D9.3 “TEA AND ENERGY EFFICIENCY ASSESSMENTS”

Acronym:
NEO-CYCLE

Project Title:
Upcycling of NdFeB magnets in the EU for green applications

Grant Agreement No:
101138058

Call:
HORIZON-CL4-2023-TWIN-TRANSITION-01

Funded by the European Union

NEO-CYCLE has received funding from the European Union under grant agreement No 101138058.

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Deliverable 9.3	**TEA and energy efficiency assessments**
Associated WP	**WP No.9**
Associated Task(s)	**Task 9.3**
Due Date	**M18**
Date Delivered	**11/02/2026**
Prepared by	**UNITO**
Partners involved	**UNITO, HOLOSS**
Authors	**Giovanni Andrea Blengini, Sara Di Felice, Chiara Gilardi**
Reviewers	**IDE team**
Deliverable Version	**1.0**
Dissemination Level	**PU/SEN**
Keywords	**Techno-economic assessment, energy efficiency assessment, indicators, profitability indicators, technical indicators, economic indicators**

DOCUMENT REVISION HISTORY

Version	Date	Description of change	List of contributor(s)
No.1	06/02/2026	First draft	UNITO, HOLOSS
No.2	26/02/2026	Final draft	UNITO

DISCLAIMER

The NEO-CYCLE project received funding from the European Union's Horizon Europe Research and Innovation Programme under Grant Agreement No 101138058.

ABBREVIATIONS

CapEx = Capital expenditure
COGM = Cost of goods manufactured
COGS = Cost of goods sold
CRMA = Critical Raw Material Act
EBIT = Earnings Before Interest and Taxes
EC = European Commission
EEA = Energy Efficiency Assessment
EI = Energy Intensity
EnMs = Energy Management System
EnPIs = Energy Performance Indicators
FCI = fixed capital investment
FU = Functional Unit

IEA = International Energy Agency
SA = Sensitivity Analysis
IRR = Internal Rate of Return
ISBL = inside battery limits
KPIs = Key Performance Indicators
LCA = Life Cycle Assessment
LCC = Life Cycle Costing
MSP = Minimum selling price
NPV = Net Present Value
OpEx = Operating expenditure
OSBL = outside battery limits
PB = Payback Period
PDCA = Plan-Do-Check-Act
PFD = process flow diagram
REEs = Rare Earth Elements
ROI = Return on Investment
SCC = Solid-State Chlorination
SEC = Specific Energy Consumption
SENE = Electrochemical Nd extraction
TEA = Techno-Economic Assessment
TRL = Technology Readiness Level
UA = Uncertainty Analysis

SUMMARY OF DELIVERABLE

Within the context of the European green and digital transition and the growing attention to the security of supply of critical raw materials, there is an increasing need for analytical tools capable of supporting the development and assessment of emerging technologies from the earliest stages of their life cycle. In this framework, **Techno-Economic Assessment (TEA)** and **Energy Efficiency Assessment (EEA)** represent key approaches for coherently analyzing feasibility, potential performance, and the main trade-offs associated with new industrial processes, particularly in contexts characterized by low levels of technological maturity. In light of these considerations, this report focuses on the analysis of the **methodological structure** of TEA and EEA evaluations and on the definition of the **relevant indicators** applicable within the NEO-CYCLE project. Quantitative assessments will follow throughout the upcoming project phases, when greater availability of data and a higher level of technological maturity will be achieved.

Building on the state of the art and the main methodological frameworks available in the literature, **Chapter 2** presents the existing frameworks and indicators for TEA and EEA and defines the methodological reference adopted for the application of these analyses to the processes developed within the NEO-CYCLE project.

Chapter 3 represents the methodological core of the TEA approach adopted within the NEO-CYCLE project and describes the developed processes, outlining the assessment boundaries and the common assumptions underlying both TEA and EEA. This chapter also systematically defines the required input flows, the cost items considered, and the quantitative elements needed for the calculation of the selected indicators.

Chapter 4 is dedicated to the development of the EEA within the NEO-CYCLE project and presents the set of indicators identified for the preliminary evaluation of the energy performance of the analyzed processes. The chapter also lays the groundwork for the future selection of additional indicators and for the development of quantitative and comparative analyses in the subsequent phases of the project.
Overall, this report establishes a coherent methodological foundation for the future application of TEA and EEA within the NEO-CYCLE project, to be progressively refined as the project advances and additional data become available.

TABLE OF CONTENTS:

SUMMARY OF DELIVERABLE 4
1. Introduction 1
  1.1. European policy context and strategic relevance of permanent magnets 1
  1.2. Critical raw material, rare earth elements, and circularity challenges in Europe 1
  1.3. Overview of existing primary production and recycling routes for Rare Earth Elements and permanent magnets 2
    1.3.1. Overview of existing Rare Earth recycling and recovery pathways 3
  1.4. The NEO-CYCLE project: rationale and objectives 3
    1.4.1. Processes developed within the NEO-CYCLE project 4
    1.4.2. Relevance of NEO-CYCLE processes for TEA and EEA 4
  1.5. Report’s objectives and scope 5
2. TEA & EEA existing modelling framework 7
  2.1. Techno-economic assessment modelling framework 7
    2.1.1. Technology Readiness Level (TRL) 12
    2.1.2. Product System Analysis 13
    2.1.3. Collecting Inventory Data 14
    2.1.4. Calculating Informative Indicators 20
    2.1.5. Result and Interpretation 25
  2.2. Energy Efficiency Assessment modelling framework 28
    2.2.1. Multidisciplinary nature of energy efficiency assessment 30
    2.2.2. Energy Efficiency Indicators 32
3. Methodology of preliminary TEA within NEO-CYCLE 35
  3.1. Goal and Scope 35
    3.1.1. TEA Implementation and Calculation Tool 35
  3.2. Technology Readiness Level (TRL) 36
  3.3. Functional Unit 36
  3.4. System Boundaries 37
  3.5. Data Categories and Data Quality 37
  3.6. Inventory 37
    3.6.1. NEO-CYCLE – Process Overview 38

3.7. Indicators 46

3.7.1. Challenges in the Selection and Calculation of Profitability Indicators for NEO-CYCLE 57

4. Methodology of preliminary EEA within NEO-CYCLE 58

4.1. Energy efficiency indicators for the NEO-CYCLE project 58

5. Conclusion 59

REFERENCE 62

INDEX OF FIGURES

Figure 1: The main methodological guidelines. Adapted from Buchner et al. (2018).......... 11
Figure 2: The process flow diagrams of Task 4.1 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners.. 39
Figure 3: The process flow diagrams of Task 4.2 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners.. 40
Figure 4: The process flow diagrams of Task 4.3 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners. The flow diagrams represent the “Non-selective electrochemical leaching + OH precipitations”... 41
Figure 5: The process flow diagrams of Task 4.3 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners. The flow diagrams represent the “Selective electrochemical leaching”... 41
Figure 6: The process flow diagrams of Task 4.4.1 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners.. 42
Figure 7: The process flow diagrams of Task 4.4.2 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners.. 43
Figure 8: The process flow diagrams of subtask 4.4.1 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners.. 44
Figure 9: The process flow diagrams of subtask 4.4.2 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners.. 45
Figure 10: The process flow diagrams of Task 4.5 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners.. 46
Figure 11: The workflow of the planned interactions with project partners and the progressive development of the indicator-based assessment 62

INDEX OF TABLES

Table 1: Description of the nine TRLs for the chemical industry. Adapted from Buchner et al., 2018.. 12
Table 2: OpEx estimation methodology. Adapted from Zimmermann et al. (2020) 19
Table 3: Economic and cost -related indicators 22
Table 4: The main profitability indicators associated with each TRL. Adapted from Giacomella (2021) 24
Table 5: The most used energy efficiency indicators from the literature. Adapted from Bunse et al. (2010). 33
Table 6: technical indicators for the NEO-CYCLE project.. 47
Table 7: The main cost categories considered relevant at TRL 4 for the NEO-CYCLE project.. 52
Table 8: Preliminary selected indicators for the NEO-CYCLE project 58

1. Introduction

1.1. European policy context and strategic relevance of permanent magnets

The European Commission (EC) has identified the *Twin Transition* — green and digital — as one of the key pillars of its strategic agenda, outlining comprehensive policies and frameworks to guide Member States over the coming decades.

The *European Green Deal* (2019) aligns with the *Twin Transition* by setting objectives for carbon neutrality by 2050 and highlighting the role of digital technologies in achieving a sustainable, competitive, and resilient economy.

Raw materials constitute the foundation of this transition: they are present across all major European industrial sectors — aerospace, automotive, electronics, medical, and defense — and in all supply chains for high-tech applications.

However, although Europe is among the world leaders in manufacturing products such as wind turbines, hard drives, electric motors, LEDs, and more, it does not have a significant primary production of rare earth elements.

As a result, 98% of its total demand for rare-earth magnets is met through imports, particularly from China, making the supply chain highly vulnerable to geopolitical, economic, and market risks.

The European decarbonization strategy for 2030 and 2050 requires the deployment of low-emission energy production. In this context, permanent magnets based on Nd, Fe, and B represent the most energy-efficient choice for the development of electric motors and beyond, thanks to their superior magnetic properties, and they remain essential components in the development of new technologies.

Nevertheless, the limited availability of resources, combined with the environmental impacts associated with their extraction, processing, and purification, poses a critical challenge for the energy transition.

For this reason, the EU aims to secure the supply of these materials in the coming years to strengthen the resilience and strategic autonomy of the rare-earth and magnet value chains in Europe, as also formalized in the recent *Critical Raw Materials Act* (CRMA).

1.2. Critical raw material, rare earth elements, and circularity challenges in Europe

CRMs are materials characterized by high economic importance and a high risk of supply disruption for a given country or geographical area, such as the European Union. Their criticality arises from a combination of factors, including the geographical concentration of production, limited substitution possibilities, growing future demand, and geopolitical vulnerabilities. In this context, the European Commission regularly assesses the level of material criticality and updates a list of CRMs reflecting the economic and industrial characteristics of the EU.

Within the framework of the major structural transformations currently underway, the green and digital transitions, the demand for many CRMs is rapidly increasing. Among these, Rare Earth Elements (REEs) play a central role in a wide range of key technologies and applications, such as electric vehicles, wind turbines, electronics, and, in particular, permanent magnets.

REEs comprise a group of seventeen elements with similar chemical and physical properties. Despite the term “rare”, these elements are relatively abundant in the Earth’s crust; however, the main challenges related to their availability are associated with their low concentration in ore deposits and the complexity of the separation and purification processes. Some elements, particularly the so-called heavy rare earth elements, occur at even lower concentrations, resulting in higher economic costs and greater environmental impacts associated with their extraction.

Thanks to their unique magnetic properties, REEs are used in numerous high-value-added sectors, especially in the production of permanent magnets. Neodymium-iron-boron (NdFeB) permanent magnets currently represent the highest-performing technology available on the market, due to their high performance-to-weight ratio, high coercivity, and good resistance to high temperatures.

The European Union nevertheless remains highly dependent on imports of REEs and permanent magnets, as supply chains are strongly concentrated outside Europe. The development of a European primary production supply chain is hindered by several factors, including the lack of know-how and technologies, regulatory constraints, environmental considerations, and the need for substantial investments accompanied by long development times. In this context, circular economic strategies and material recovery pathways play a key role as complementary alternatives to primary production, contributing to addressing both supply security challenges and environmental sustainability concerns.

1.3. Overview of existing primary production and recycling routes for Rare Earth Elements and permanent magnets

This chapter provides an overview of the state of the art of the main primary production and recycling routes for REEs and permanent magnets, to contextualize the processes developed within the NEO-CYCLE project.

The description focuses on process-related aspects and on the main technological, energy, and economic challenges that are relevant for the subsequent preliminary TEA and EEA.

1.3.1. Overview of existing Rare Earth recycling and recovery pathways

In response to the environmental and economic limitations of primary production, several circular economy strategies have been developed to recover REE from end-of-life products and production scraps. These approaches aim to reduce dependence on primary resources and to mitigate supply risks associated with highly concentrated global markets.

Rare Earth recycling nevertheless faces several challenges, including:
- low concentrations of REE in final products;
- variability in magnet composition and lack of labelling;
- difficulties in dismantling end-of-life products;
- limited availability of dedicated infrastructure.

Collection and dismantling stages represent particularly critical steps, as permanent magnets are often embedded in complex products, such as electric vehicles and electronic equipment. As a result, manual or semi-automated disassembly processes are often required, involving highly specialized personnel or advanced machinery.

Recycling routes in the Rare Earth and permanent magnet sector can generally be classified into *short-loop* and *long-loop* approaches, depending on the extent of material processing before reintroduction into the value chain.
Short-loop recycling refers to processes that enable the production of new magnets from scrap material without separating individual REEs. An example is hydrogen decrepitation, which uses hydrogen to break down magnets into a powder that is subsequently pressed to form new magnets.
Long-loop recycling, by contrast, involves the complete chemical processing of end-of-life magnet scrap to recover rare earth oxides. This approach includes both conventional techniques, such as pyrometallurgical and hydrometallurgical processes, and innovative technologies, such as bioleaching.

In many cases, a combination of techniques is adopted, for instance, using pyrometallurgical treatment as a pre-processing step to facilitate subsequent separation stages.
Short-loop recycling is generally faster and less environmentally intensive, while long-loop recycling offers greater flexibility and enables the recovery of higher-quality outputs. Nevertheless, even under highly optimistic recycling scenarios, the total output would not be sufficient to meet the continuously growing demand for Rare Earth Elements, implying that a certain share of primary production will remain necessary.

1.4. The NEO-CYCLE project: rationale and objectives

The EU-funded NEO-CYCLE project has been conceived as a technological and systemic response to the main challenges of the permanent magnet value chain. NEO-CYCLE addresses one of the most critical issues of the European transition: the near-total lack of circularity in production systems and, consequently, the absence of internal recycling capacities and secondary production of NdFeB magnets.

Within the project, the objective is to develop and demonstrate sustainable processes for the recovery, separation, and upcycling of NdFeB permanent magnets from end-of-life products, such as hard disk drives and other electronic equipment, by valorizing waste streams that are currently underutilized.

The recycled materials are intended to be reintegrated into strategic industrial applications, thereby contributing to the creation of a more circular, resilient, and competitive European ecosystem.

1.4.1. Processes developed within the NEO-CYCLE project

The processes developed within the NEO-CYCLE project are positioned within the Rare Earth and permanent magnet value chains as advanced recycling and recovery solutions aimed at valorizing waste streams that are currently underutilized.

The feedstocks considered primarily include NdFeB permanent magnets recovered from end-of-life products, such as hard disk drives and other electronic equipment.

In this context, the innovative processes analyzed in the project include the ***Solid-State Chlorination (SSC)*** process and ***the Electrochemical Nd extraction (SENE)*** process, both developed as complementary approaches for magnet recovery and described in the following sections.

1.4.2. Relevance of NEO-CYCLE processes for TEA and EEA

The application of techno-economic and energy efficiency assessment tools to the processes developed within NEO-CYCLE is particularly relevant, as it enables:

- A systematic analysis of the main process variables influencing technical, economic, and energy performance.
- Support for comparisons between alternative process configurations.
- The identification of potential criticalities and relevant trade-offs with a view to future industrial scalability.

In this context, the present report provides a methodological reference framework for the application of TEA and EEA to the NEO-CYCLE processes, laying the groundwork for future quantitative assessments that may be developed in later project stages, once greater availability of data and a higher level of technological maturity have been achieved.

2.4.2.1 *From Life* Cycle Approaches to Techno-Economic Assessment

In the context of the assessment of technologies and processes, such as within the NEO-CYCLE project, different analytical tools may be adopted depending on the objective of the analysis and the level of technological maturity considered; in some cases, these tools may also be complementary or comparable.
Life Cycle Assessment is aimed at evaluating the environmental performance over the entire life cycle of a product or process, focusing on the environmental impacts associated with material and energy flows. Life Cycle Costing, on the other hand, addresses the economic dimension, estimating the overall monetary costs incurred throughout the life cycle, including investment, operational, maintenance, and end-of-life costs.

Techno-Economic Analysis differs from these approaches in that it integrates the economic assessment—also supported by LCC-type analyses—with the evaluation of the technical performance of the process and the system. TEA considers aspects such as process efficiency, scalability, and TRL, and is aimed at assessing the techno-economic feasibility and development potential of new or emerging technologies. For this reason, while LCA and LCC are more frequently applied to consolidated or already implemented systems, TEA is particularly suitable for the early stages of technological development, supporting research and development activities and the definition of future industrialization strategies.
For these reasons, beyond cost estimation, TEA explicitly incorporates market-related considerations, allowing for the assessment of market prospects and competitive advantages in view of potential commercialization. Moreover, TEA includes a structured technology assessment, enabling the comparison of alternative technological scenarios and the identification of the most promising technology implementation pathways. Finally, the application of sensitivity analysis within TEA supports decision-makers in understanding the influence of key parameters and assumptions on the results, thereby contributing to the identification of critical uncertainties and the development of informed risk mitigation strategies.

1.5. Report’s objectives and scope

This report provides the methodological framework for assessing the techno-economic and energy efficiency of the processes developed within the NEO-CYCLE project.
Since the extraction of rare earth elements from end-of-life hard disk drives has not yet been implemented at an industrial scale, it is essential to conduct this preliminary TEA and EEA to evaluate its economic viability and technical feasibility. Within the NEO-CYCLE project, the TEA and EEA serve as strategic tools to support technological development, assess process feasibility, and guide research and development (R&D) activities.
Based on these objectives, the present report adopts a preliminary methodological assessment framework to analyze the techno-economic and energy performance of the processes developed within the NEO-CYCLE project. The assessment is in an early stage of technological development, in line with the current maturity level of the proposed solutions and with

the availability of data generated within the project.

Consequently, the methodological choices adopted in this report are designed to support research and development activities, process optimization, and strategic comparison between alternative configurations, rather than to provide a fully detailed or investment-grade evaluation.

The results derived from the application of the proposed methodological framework should therefore be interpreted as indicative and exploratory, as they are aimed at identifying the main primary performance drivers, trade-offs, and potential areas for improvement.

Within this framework, TEA and EEA are treated as complementary components of a common structure, consistent with the principles adopted in LCA/LCC assessment, sharing consistent system boundaries, functional units, and coherent modelling assumptions.

The TEA and EEA activities, which are carried out within the framework of WP9, contribute to providing a coherent analytical basis for the integration of the technical, economic, and energy dimensions of the processes developed within the project, and are primarily addressed to relevant stakeholders, including project partners, European institutions, and other parties interested in the development of sustainable supply chains for rare earth elements and permanent magnets.

2. TEA & EEA existing modelling framework

In recent years, within the context of the innovation-driven transformation taking place in Europe, the growing focus on environmental sustainability, resource security, and industrial competitiveness has highlighted the need for analytical tools capable of supporting this transition. In particular, such tools are required to inform strategic decision-making at early stages of technological development and to guide future choices.

In this context, TEA and EEA have progressively emerged as fundamental and often complementary tools for analyzing the feasibility of processes, their performance, and potential criticalities during development, before their implementation at an industrial scale.

Following the adoption of the European Green Deal, these approaches have been widely applied within industrial research and publicly funded programs to support the development of solutions aligned with decarbonization objectives, energy efficiency targets, and circular economy principles.

TEA combines technical and economic aspects to evaluate the feasibility, competitiveness, and potential impact of a technology or project. It is therefore based on technical inputs, and variations in these inputs are directly reflected in the corresponding economic outcomes. TEA also provides a detailed understanding of the main cost drivers, key technical performance indicators (KPIs), as well as the benefits and risks associated with the implementation of a given technology. For these reasons, it represents an essential tool to support strategic planning and decision-making processes.

EEA, by contrast, provides quantitative insights into the energy performance of processes, contributing to the identification of improvement potential and possible trade-offs among different technological configurations.

In the context of emerging processes characterized by a low technology readiness level (TRL), such as those addressed within the NEO-CYCLE project, the combined use of TEA and EEA plays a particularly relevant role. The objective, in this case, is not to deliver definitive estimates or investment-grade results but rather to support research and development activities, guide design choices, and explore alternative technological solutions.

To date, however, the literature lacks a coherent and harmonized theoretical discussion on the methodological setup of TEA and EEA, which remains relatively weak and fragmented.

2.1. Techno-economic assessment modelling framework

To date, TEA is not an analysis governed by an ISO standard, but rather it remains a flexible methodology defined according to the TRL, the purpose of the analysis, data availability, and the type of decision it is intended to support.

As a result, several approaches and operational guidelines have been developed and pub-

lished by research institutions and standardization bodies to define a common methodological framework (Gupta et al., 2022).
Although a specific standard does not govern TEA, its methodological framework is commonly structured according to a life cycle–based logic, aligned with the principles outlined in ISO 14040 and ISO 14044, including: i) goal and scope definition, ii) life cycle inventory, iii) impact assessment, and iv) interpretation (Buchner et al., 2018).

In the literature, several methodological workflows have been proposed for conducting a TEA, depending on the analysis purpose and the TRL.
At early stages of development, simplified frameworks are often adopted to support exploration and comparative analyses. Box 2.1 summarizes a representative three-phase TEA framework frequently referenced in the literature (Gupta et al., 2022).

Box 2.1 - Key methodological aspects related to existing TEA methodological workflows

In Gupta et al. (2022), a three-phase summary of the main TEA models proposed in the literature is presented.

1. Phase 1- Scale-up flows
   The first phase consists of plausibly estimating industrial-scale mass and energy flows for a process that has not yet been implemented at such a scale. This requires the decomposition of the process into subsystems and the development of models representing each component (e.g., equipment, instrumentation and control systems, structures, and utilities).
   At this stage, many process parameters are derived from laboratory-scale data and are therefore affected by significant uncertainty and are not yet consolidated at an industrial scale. Scaling relationships are thus commonly applied to estimate the performance of the industrial version of a process developed at laboratory scale (Kobos et al., 2020).

2. Phase 2 – Cost and revenue estimation
   The second phase focuses on the estimation of costs and revenues associated with the process modelled at an industrial scale. Costs are generally classified into capital, operating, and maintenance costs.
   Capital costs can be further distinguished into fixed capital and working capital, required for plant construction, as well as interest accrued during construction, while operating costs are typically divided into fixed costs (e.g., contracts, maintenance, depreciation) and variable costs (e.g., labor, utilities, and overheads) (Scott, 2015).

Revenue estimation is based on the value of the output products, considering market conditions within the reference scenario.

3. Phase 3 – Techno – economic evaluation and interpretation
   In the third phase, TEA parameters are analyzed by distinguishing between process-related (technical) parameters and economic parameters. Technical parameters refer to engineering attributes such as process yields and the consumption of energy and reagents. Economic parameters relate to the characteristics of the inputs (e.g., the content of valuable materials to be recovered), the prices of reagents, raw materials, and output products, as well as all market-related assumptions. In this context, cost estimation and market analysis can be regarded as the "inventory" of the TEA (Buchner et al., 2018).

In line with this life cycle–oriented logic, Buchner et al. (2018) proposed a conceptual TEA framework consistent with the main methodological guidelines available in the literature (Fig. 1).

These guidelines commonly describe TEA as a structured sequence of phases, including:

- Definition of the technology readiness level;
- definition of the assessment objective and scope, system components, and analytical boundaries;
- evaluation of technical and economic feasibility, cost structure;
- assessment of profitability;
- evaluation of risks and uncertainties through sensitivity and scenario analyses;
- presentation and interpretation of results, and discussion of potential implementation pathways.

Such comprehensive and articulated frameworks are generally applied at more advanced stages of technological development, when sufficient data is available to support detailed quantitative analyses. In the case of emerging technologies, however, these frameworks are often adapted into simplified and modular structures that prioritize a clear definition of objectives and scope, a consistent structuring of the inventory, and the identification of informative indicators, while postponing detailed indicator calculation and result interpretation to later stages of technological development.

Based on the findings from the literature, the main limitations of these methodological workflows—which are also particularly relevant in the context of this deliverable—are related to the level of uncertainty associated with the analyses, which is strongly dependent on data

availability and on the current level of technological maturity of the processes. The characterization of uncertainty represents a critical challenge: for theoretical processes and laboratory-scale systems, uncertainty can be high and difficult to quantify.
At these stages, uncertainty is primarily addressed through scenario analysis (Gupta et al., 2022), by rerunning the assessments using different sets of values for the key parameters, which are often categorized into three groups: low, reference, and high.

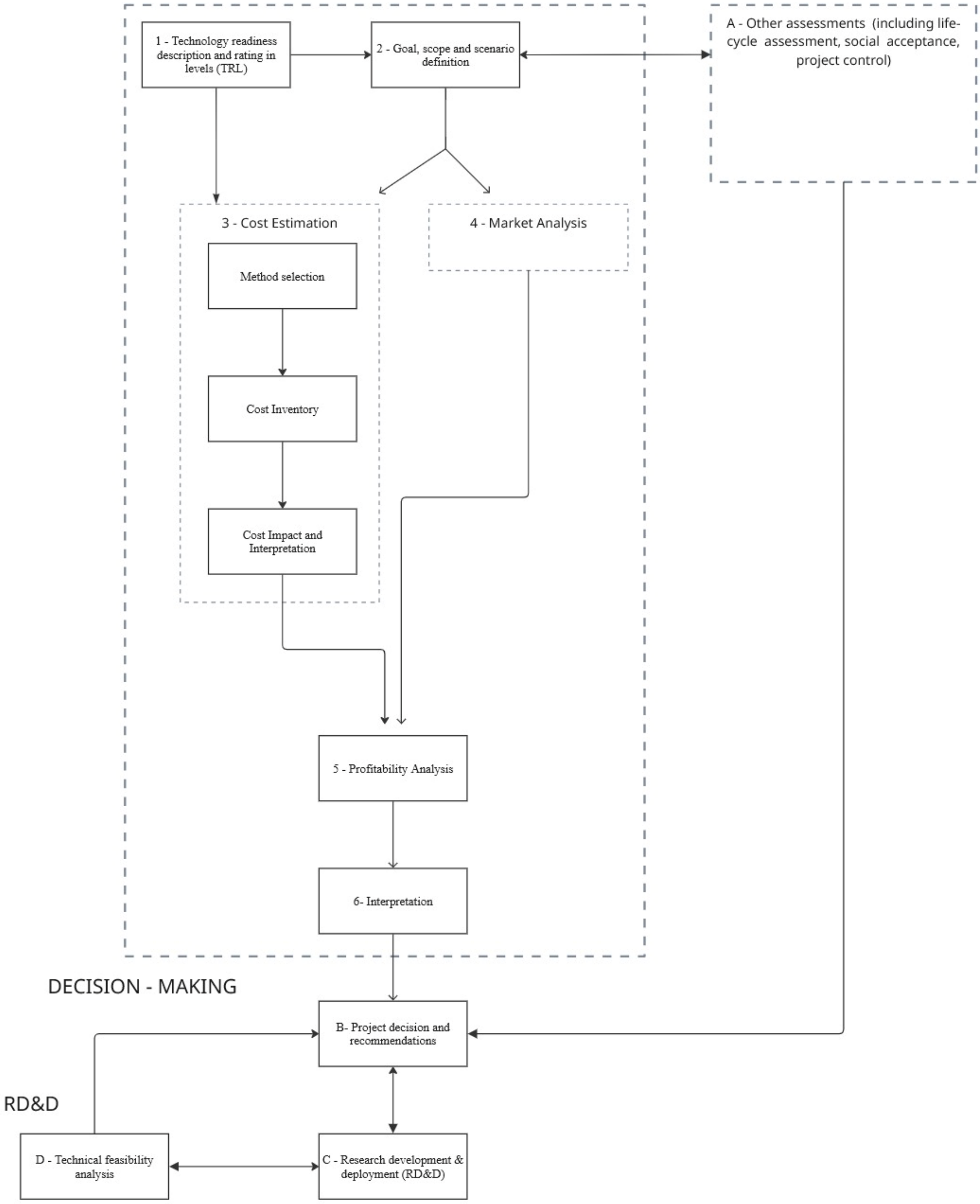

Figure 1: The main methodological guidelines. Adapted from Buchner et al. (2018)

2.1.1. Technology Readiness Level (TRL)

Within the context of research and development projects, TRLs represent a widely used tool to describe the degree of technological maturity. The assessment is performed through a nine-level scale, covering the entire innovation pathway, from the initial concept to the operational application of technology. To date, the criteria used for assigning TRLs are not always fully defined and unambiguous. This lack of clarity can make it difficult to compare technologies belonging to different disciplines and may introduce elements of uncertainty or ambiguity into the assessments. In the chemical industry, the TRL scales proposed by NASA are widely adopted as a reference; however, the need for further specification and adaptation to the specific application context has been increasingly recognized (Buchner et al., 2018).

In general, the TRL scale should reflect the level of knowledge and information available for the technology under assessment. Nevertheless, the initial and final stages of the technological development process cannot be identified in a fully objective manner. For this reason, the boundaries of the scale are defined based on alternative criteria, often linked to the specific objectives that research activities are intended to address. As a result, the criteria used to evaluate TRLs may vary depending on the purpose of the analysis. From a general perspective, technology is commonly considered mature when it is able to operate within an economically relevant environment and to sustain market-related activities in an economically viable manner.
Table 1 presents the titles, descriptions, tangible outcomes, and typical operational environments associated with the nine TRL levels in the chemical industry.

Table 1: Description of the nine TRLs for the chemical industry. Adapted from Buchner et al., 2018.

TRL	**Title**	**Description**	**Tangible work result**	**Workplace**
1	Idea	Opportunities identified, basic research translated into possible applications	Idea/rough concept/ vision/ strategy paper	Sheets of paper
2	Concept formulated	Technology concept and/or application formulated	Technology concept formulated, list of solutions, future R&D activities planned	Sheets of paper
3	Proof Concept	Applied laboratory research started, functional principle/reaction (mechanism) proven, predicted reaction observed	Proof of concept (in laboratory)	Laboratory
4	Preliminary Process Development	Concept validated in laboratory environment, scale-up preparation started, and conceptual process design	Documentation of reproduced and predicta-	Laboratory/ miniplant

			ble (quantitative) experiment results, first process ideas	
5	Detail Process Development	Shortcut process models found, simple property data analyzed, detailed simulation of process and pilot plant using bench scale information	Simple parameter and property data, process concept alternatives evaluated	Laboratory/ miniplant
6	Pilot Trials	Pilot plant constructed and operated with low-rate production, products tested in application	Working pilot plant	Pilot plant, technical center
7	Final Engineering	Parameter and performance of pilot plant optimized, (optional) demo plant constructed and operating, equipment specification including components that are type conferrable to full-scale production	Optimized pilot plant, (optional) working demo plant, sample production, finalized and qualified system and building plan	Pilot plant, technical centre, (optional) demo plant (potentially incorporated in production site)
8	Commissioning	Products and processes integrated in organizational structure (hardware and software), full-scale plant constructed, and startup initiated	Finalized and qualified system and building plan	Production site
9	Production	Full-scale plant audited (site acceptance test), turn-key plant, production operated over the full range of expected conditions in industrial scale and environment, performance guarantee enforceable	Full-scale plant tested and working	Production site

The definition of more detailed qualitative and quantitative criteria, however, requires further scientific investigation.

2.1.2. Product System Analysis

The identification of *system elements* and *system boundaries* plays a primary role in TEA, as well as in LCA, and follows the same principles defined by ISO 14040:2006. Their definition enables the identification of input and output flows, supporting the understanding of interconnections among different system elements across various stages of project development (Zimmerman et al., 2018).

In accordance with the guidelines proposed by Zimmerman et al. (2018), the analysis of the results can be carried out both at the overall system level and at the level of individual system elements. In particular, within the TEA, the system is decomposed into system elements, whereas in the LCA, the analysis is structured around unit processes. This distinction enables a clearer identification of the most critical stages, the main areas for improvement, and supports a more transparent interpretation of trade-offs between economic performance and environmental impacts, especially from the perspective of integrating different assessment approaches.

System boundaries are used to delimit the processes to be considered, to clarify what is included in the analysis, and to ensure transparent and consistent comparisons with benchmark systems and other TEA studies. Among the most adopted system boundary settings are *gate-to-gate*, *cradle-to-gate*, and *cradle-to-grave*, which respectively indicate the inclusion or exclusion of the different stages of the project life cycle. The narrower *gate-to-gate* approach primarily focuses on specific modules of project development, whereas the broader cradle-to-grave approach encompasses all life-cycle stages, from raw material extraction to final disposal or recycling (Torabi & Ahmadi, 2020).
Consequently, the definition of the functional unit and the *process flow diagram* (PFD) also represent a common and fundamental component of TEA. The process flow diagram may include mass and energy balances of the process and, when data are available, allow a direct estimation of certain cost items, such as operational costs.
However, the PFD represents a more detailed form of product system characterization and, therefore, cannot always be fully defined during the preliminary phases of the study, when data availability is limited.

2.1.3. Collecting Inventory Data

The collection of inventory data represents one of the most critical and decisive aspects of the TEA process. In order to calculate the selected indicators in a consistent and meaningful way, the quality and level of detail of the data must be appropriate to the objectives of the study. The need to estimate certain parameters in the absence of consolidated data can, in fact, limit the reliability of the results and the robustness of the conclusions.
Within a TEA, inventory data can generally be classified into three categories: i) **process-specific data**, ii) **average data**, and iii) **generic data**.

Process-specific data are those known with a reasonable degree of certainty and derived from direct measurements, experimental results, or detailed design information; their use significantly increases the reliability of the assessment results. However, this type of data is not always available, particularly in the case of emerging technologies characterized by a low TRL. In such contexts, it is often necessary to rely on assumptions based on data from analogous, more mature processes or on information available in the literature.
Average and generic data, by contrast, do not originate from direct measurements of the

process under study, but are obtained through estimates, sector-average values, or reference databases. Although their use introduces a higher level of uncertainty, such data are commonly employed in preliminary TEAs and are often indispensable to enable exploratory analyses in the early stages of technological development. The combination and availability of the different data types, therefore, directly influence the quality of the analysis and the achievable level of detail.

In the case of preliminary studies, which are typically characterized by high uncertainty, data collection may follow an iterative approach. When indicators are found to be particularly sensitive to specific parameters, as highlighted by sensitivity or scenario analyses, the inventory can be progressively refined by focusing on the most influential parameters to improve the overall consistency and robustness of the results. The technical and economic data collected for the life cycle inventory may also be useful for the TEA inventory. However, the required level of data quality and detail may vary depending on the objectives and the scope of the assessment.

Overall, the inventory summarizes all relevant technical and economic parameters and the main assumptions of both the product and benchmark systems; in addition, information related to market characteristics, the value chain, the analyzed scenario, and the reference context (temporal, regional, and economic) is collected and transparently documented.
During the goal and scope phases, the system elements to be included in the analysis and the level of detail at which they are assessed are defined; for each data point, quality requirements are then established according to the assessment objective. Data quality must be verified and documented throughout the data collection phase.
Standardized methods exist to evaluate the influence of individual data points on the TEA results, that is, to determine whether a given parameter and its variations contribute quantitatively to the calculated indicators (e.g., operational expenditures), such as sensitivity analysis and uncertainty analysis, which generally belong to the interpretation phase (see the description in Chapter 2.1.5).

One of the main challenges practitioners may encounter during data collection for a TEA is the difficulty of accessing confidential cost and market price data held by technology providers or users, which often results in incomplete data sets. Moreover, even when data on industrial performance and costs are available in the literature, the underlying assumptions are frequently not clearly stated. This leads to issues in terms of transparency and credibility of TEA results, particularly in the case of more mature technologies.
Therefore, it is important to explicitly state any difficulties encountered in acquiring confidential data.

The guidelines defined by Zimmermann et al. (2020) recommend the following measures to facilitate data collection when confidential inputs are required:

1. organization of workshops with industry experts to comment on academic research and gather qualitative and quantitative inputs;
2. collection and aggregation of confidential data from multiple entities in order to ensure anonymity;
3. presentation of relative relationships between data points rather than absolute values in the TEA report;
4. collection, anonymization, and provision of data by a trustworthy third party;
5. selective sharing or publication of basic results related to industrial process design and simulations.

2.1.3.1. Cost structure

The data required for a TEA includes both technical and economic information. Technical data describe the flows of materials and energy between the different process units composing the analyzed system, while economic data include elements such as raw material costs, energy costs, investment costs, and operating expenses. In particular, the most considered economic data relates to capital expenditure (**CapEx**), operating expenditure (**OpEx**), and, in some cases, general overhead costs (Scown et al., 2021).

- CapEx refers to costs associated with non-consumable components, such as investments in production plant equipment, engineering costs, and working capital.
- OpEx includes costs related to the operation and provision of a product, such as material and energy flow costs and labor costs.
- General expenses include costs that cannot be specifically allocated to a manufacturing operation, such as administration, marketing and sales, or general research costs.

Other costs that can be quantified include the cost of goods manufactured (**COGM**) and cost of goods sold (**COGS**), which are particularly useful for manufacturing projects.

When real data is not available, cost estimation methods are applied to estimate the costs of a planned plant. Such methods are widely described in the relevant literature.

Another relevant economic element is the *minimum selling price* (**MSP**) of the reference product. This can be determined directly based on market data or estimated using a cost-plus approach, which involves adding a profit margin to the production costs. Alternatively, more articulated cost models can be developed to estimate the production cost of the reference product and to analyze the extent to which customers' willingness to pay and non-production costs influence the current market price.

The MSP is a metric commonly reported in published TEAs and is determined based on the unit price required to achieve a Net Present Value (**NPV**) equal to zero over a predefined plant lifetime, given a specified Internal Rate of Return (**IRR**) (Scown et al., 2011).

Regarding technical data, the methodological approach adopted in TEA follows a logic analogous to that used in LCA, based on the coherent definition of material and energy flows and their quantification within the defined system boundaries. According to the project's TRL, at this stage, a preliminary estimate of costs is recommended (Giacomella, 2021).

Capital Expenditure

As previously stated, CapEx refers to the initial investment required for the design, construction, installation, and commissioning of a plant. An accurate estimation of these costs is particularly challenging in the research, development, and laboratory stages, mainly because: i) process development does not yet provide sufficiently detailed data; and ii) the analyzed processes belong to different technological fields.

CapEx can be divided into fixed capital investment (**FCI**) and additional cost items, such as working capital, start-up expenses, and contingencies. FCI includes the core plant (*inside battery limits*, **ISBL**) and the infrastructure required to connect it to the outside (*outside battery limits*, **OSBL**). Both ISBL and OSBL comprise tangible cost items (*direct costs*), such as equipment and piping, as well as intangible cost items (*indirect costs*), including construction supervision and insurance.

In general, methods for estimating CapEx differ according to the availability and level of detail of the data. The literature identifies several groups of methods for estimating FCI and ISBL costs, which are summarized below:

- **Short methods**: estimate costs based on one or a few key parameters, often using cost–capacity curves or scaling factors;
- **Parametric techniques**: derive costs from the main process characteristics (e.g., number and type of process steps), and can be applied at both low and high levels of detail;
- **Factored methods**: estimate overall costs by applying multiplication factors to equipment costs, using either global factors or item-specific factors;
- **Unit cost line-item methods**: allow for detailed cost estimation of individual equipment items based on rigorous process design;
- **Cost transformation methods**: adapt the CapEx of similar plants to the case under study, typically based on capacity, location, or time, for example, through scaling rules (such as the six-tenths rule) or economic indices (e.g., CEPCI).

Operational Expenditure

OpEx can be further distinguished into *fixed* and *variable costs*. Variable costs depend on the amount of production volume; on the other hand, fixed costs do not directly depend on the amount of product produced but can indirectly be influenced by it.

The inclusion or exclusion of specific cost items depends on the objective of the assessment and on the availability of relevant data. In many preliminary TEAs, especially in the absence of detailed project-specific information, the analysis focuses primarily on identifying economic hotspots and assessing the potential feasibility of the developing technology, sometimes omitting cost items that are less relevant at this stage, such as certain overhead expenses.

Two key terms in OpEx estimation are *cost increment* and *factored estimation*. A cost increment means the amount of money that covers an assigned cost item (mostly per functional unit). Factored estimation describes the procedure of multiplying a cost item by a factor for the estimation of another cost item.

In the following box, the main methodological approaches described by Zimmermann et al. (2020) for the estimation of OpEx are presented, with reference to the individual cost items, including raw materials, energy and utilities, fixed operating costs, and general and freight expenses.

Box 2.2 - OpEx estimation methodology

Variable OpEx

1- Raw Material Cost

Raw material costs are determined on the basis of the mass balance. In the early stages of research, material demand can be estimated from preliminary experimental results or, in the case of reaction processes, based on reaction stoichiometry or conceptual process design. As the maturity of the process increases and more reliable mass balances become available, cost estimation is progressively based on actual mass flows.

Raw material prices can be obtained from primary or secondary sources. The use of supplier-specific prices is preferable; however, this is often challenging, particularly for projects under development that do not yet have established relationships with suppliers or that are still in the early stages of defining commercial conditions.

2- Energy, utilities, and other costs

Energy and utility costs are based on the energy balance, which is constructed from the measured energy consumption of the analyzed process. During research phases, especially at laboratory scale, the estimation of these costs may be simplified, provided that such simplifications are properly justified.

If energy costs are considered of minor importance, they may be estimated as a share of the total raw material costs. Similarly, if utilities or other variable costs are deemed of limited relevance, these costs may be estimated as a percentage of the total energy costs.

Energy prices can be obtained from databases similar to those used for raw material prices.

Fixed OpEx

Fixed operating costs can be estimated by drawing on data from comparable plants, by applying correction factors or specific correlations, or by directly calculating individual cost items. In more advanced stages of project development, the use of factored approaches for estimating fixed OpEx is generally recommended, applying such factors to CapEx or to the main OpEx components.

It should be noted that no standardized quantitative method exists to assess the degree of similarity between plants and, consequently, to rigorously derive appropriate cost increments. In the deployment phase, all major fixed OpEx items should therefore be estimated in a detailed and independent manner.

General expenses and freight

The main market-related costs are represented by the COGS, which is obtained by adding general expenses and any freight or delivery costs to the COGM, which includes both CapEx and OpEx.

During the research phases, general expenses are often estimated using a factored approach, whereas in more advanced development and deployment phases, company-specific values may be applied.

The following table, adapted from Zimmermann et al. (2020), summarizes the OpEx estimation methodologies, the required data, and the corresponding data sources as a function of the project's technological maturity, distinguishing between the research, development, and deployment phases.

Table 2: OpEx estimation methodology. Adapted from Zimmermann et al. (2020)

Technological maturity	**Research**	**Development**	**Deployment phase**
Material	- Based on stoichiometry, measured mass flows, or design/simulation	- Based on measured mass flows or design/simulation	- Based on measured mass flows or design/simulation
Energy, utilities & other variable OpEx	- Based on measured energy flows or design/simulation - Factored estimation - Cost increments from similar plants	- Based on measured energy flows or design/simulation - Cost increments from similar plants	- Based on measured energy flows or design/simulation

Fixed OpEx	- Simple factored estimation - Cost increments from similar plants	- Detailed factored estimation - Cost increments from similar plants	- Detailed factored estimation - Separate calculation of fixed OpEx items
General expenses & freight	- Factored approach	- Factored approach or company-specific	- Company – specific
Main price data and sources	- Price data: market average - Sources: few, secondary	- Price data: market-average - Sources: multiple, secondary	- Price data: process specific - Sources: few, primary (supplier quotes)

2.3.1.2 *Market analysis*

Market analysis is generally conducted in parallel with cost estimation, as the two activities represent equivalent inputs for subsequent TEA phases and are closely interrelated. The objective of this passage is to assess the economic feasibility of the project by analyzing the economic conditions of the sectors and studying competitors, which allows to identify, when possible, the benchmark of the sector, or the “best in class” to compare the object of the study to as a way to assess both technical and economic performance (Lamberts-Van Assche et al., 2021). Market analysis is also a tool to collect data, as material costs and certain production factors are directly derived from market conditions, while cost ranges help define the reference context, considering that price represents a relevant dimension of market segmentation.

For subsequent profitability analyses, benchmark identification, sales price, and sales volume represent the main market parameters, as indicated by guidelines at the project’s current TRL (Giacomella, 2021). Sales price and sales volume of the product can be derived from the benchmark analysis.

2.1.4. Calculating Informative Indicators

Indicators are the metrics used to evaluate the *criterion* of interest (e.g., profitability), that is, the aspect to be assessed, which is defined during the initial phase of the study. They can be technical, economic, or techno-economic in nature when they incorporate both technical and economic aspects of the production process.
The selection of indicators represents one of the most critical phases of the analysis, as it depends on the specific objectives of the study; for this reason, the lack of standardization in the selection criteria constitutes a significant obstacle both to the evaluation of results and to the comparison with similar technologies.

The main categories of indicators considered in TEA studies generally relate to technical performance, cost structure, and profitability.
The selection of indicators is guided by three fundamental principles:

1. the methods adopted must be consistent with the goal and scope of the study;
2. indicator selection must be justified and appropriately motivated;
3. all assumptions and equations must be transparently stated.

Therefore, the selected indicators and their corresponding calculation methods must be consistent with data availability, which is closely linked to the level of technological maturity. As maturity increases, the reliability of both estimation methods and process and economic data also increases. For technical indicators, the level of technical detail increases with technological maturity, as does the robustness of the economic assumptions. Depending on the maturity level, simpler or more complex indicators may therefore be selected.

In the early stages of research, quantitative assessments are often not performed due to the high level of data uncertainty; instead, qualitative evaluations, such as multi-criteria ranking, are adopted.
Indicators may also include or exclude temporal variability, thus distinguishing between *static* indicators (which exclude time-related variability) and *dynamic* indicators. In the early research phases, when quantitative assessments are carried out, static indicators are generally preferred, as they do not require detailed data and are easier to calculate. In later stages, once the market perspective has been completed through the projection of external sales volumes, it becomes possible to calculate an absolute profit; moreover, the product definition is sufficiently accurate to allow the prediction of future revenues and the use of dynamic economic indicators.

2.1.4.1 Technical Indicators

Technical indicators are used to describe process performance from an operational perspective and therefore aim to answer questions such as: *Does the process operate effectively? How efficient is it from a techno-physical standpoint? At which stages do the main performance losses occur*?
These indicators typically include parameters related to material and energy efficiency, such as process yields, conversion efficiencies, specific energy consumption, and material losses along the different operational steps.

In the research phases, where theoretical stoichiometry or laboratory experiments allow the definition of the *mass balance*, it is possible to calculate a static profit derived from product sales (revenues) and the associated costs; these costs may already include materials and other cost items.

These types of indicators are not uniquely standardized within the TEA literature but are selected according to the type of process under investigation and the objectives of the study.

At low TRL, technical indicators are often characterized by high uncertainty, but they could be essential for identifying technological bottlenecks and potential improvement margins.

2.1.4.2 Economic and cost-related indicators

Economic and cost-related indicators are primarily used to describe the internal cost structure of the process. They generally refer to CAPEX, OPEX, and their main components.

Table 3: Economic and cost -related indicators

Indicator	Unit	Description
Cost per unit of product	€/kg product	Total cost normalized to the functional unit
Total CAPEX	€	Total investment required for plant construction
Total OPEX	€/year	Total annual operating cost
OPEX share by category	%	Relative contribution of OPEX components

2.1.4.3 Profitability indicators

Profitability analysis, in the context of process development and demonstration, supports decision-making related to the allocation of financial resources across different research activities. Specific profitability indicators are calculated values associated with investments—defined as the expenditure of money for a specific purpose—and represent monetary gains or losses in comparison with an alternative investment.
The selected profitability indicators are intended to show how much and when an economic activity can generate a profit. For this reason, they strongly depend on the stage of technological development of the process, since cost estimates—which constitute a fundamental

component of these indicators—are themselves a function of technological progress and the availability of process-specific data.

Profitability indicators can be classified into **static** and **dynamic indicators**.
Static indicators do not account for time dependence and consider a single period or an average over multiple periods; therefore, alternative reference investment is effectively the absence of any investment. These indicators are typically calculated at low TRLs, when only preliminary insights into the potential profitability of an investment are required, for instance, for processes still at pilot or pre-pilot scale (Buncher et al., 2018). Among the most common static indicators are relative profit, payback period, and ROI.
Dynamic indicators, on the other hand, account for the time preference of cash flows. Consequently, the reference alternative investment is an investment in the capital market with an equivalent risk profile. The most relevant dynamic profitability indicator is the NPV.
In the chemical sector—or for chemical processes—as reported by Buchner et al. (2018), costs are generally calculated on an annual basis and are often allocated to the amount of product(s) produced within the same period, resulting in parameters expressed with a “value per mass” dimension.
In general, the profitability indicators presented below—derived from Buchner et al. (2018) and Giacomella (2021) —are based on the same underlying principle: profit is defined as the difference between revenues and costs. Accordingly, these indicators combine cost-related information with assumptions regarding selling prices, sales volumes, and other economic parameters.

One of the most used profitability indicators is the *payback period* (**PB**), defined as the time required for an operation to recover the initial investment. Depending on the technological maturity of the process, either a static or a dynamic payback period can be calculated.
Another commonly adopted indicator is *relative profit*, a dimensionless indicator representing the gain per unit sold after subtracting allocated operating and capital costs. *Absolute profit* can also be calculated, corresponding to the total amount generated by a plant over a specified period, given a certain production level.
ROI, NPV, IRR, and EBIT are more advanced profitability indicators, and their use at early stages of technological maturity is not recommended. IRR is always accompanied by the calculation of NPV for the same investment, as it does not provide information on the achievable absolute profit, resulting in a loss of information.
In addition to the quantitative profitability indicators presented, other economic factors of interest may exist that are difficult to translate into monetary measures and are therefore assessed qualitatively (e.g., the availability of skilled personnel).

During the research phases, the use of static indicators is recommended, as they normalize profit with respect to costs. Normalized values facilitate comparison among alternatives and support the formulation of recommendations. Once the addressable market volume is known, it becomes possible to calculate absolute profit. At these stages of development, dynamic indicators can be introduced, thus moving towards the calculation of NPV. This indicator, in fact, serves as a structural basis for more detailed profitability analyses during the implementation phases.

During the development phases, experimental activities lead to updated assumptions and evolving perspectives on market development, within which profitability indicators must be progressively refined. To date, the selection of profitability indicators lacks standardization, including in the magnet market, particularly at early stages of technological maturity. The use of different indicators makes it difficult to understand, reproduce, and compare techno-economic assessments (TEAs) for similar processes.
In the calculation of dynamic profitability indicators, one of the most significant challenges is the selection of an appropriate discount rate. It would be preferable to choose a rate that represents an investment in the capital market with the same risk profile as the considered technological investment, rather than relying on an average capital market rate.

A further challenge is the forecasting of future cash flows. If the market is not well understood or if it is a new market, cash flows are highly uncertain, with a significant risk of error. Developing an understanding of scenario conditions and forecasting future cash flows requires market knowledge that can typically only be acquired after substantial progress in technical development.

Table 4 presents the main profitability indicators associated with each TRL, as derived from Buncher et al. (2018) and Giacomella (2021). These sources recommend the use of specific indicators depending on the degree of advancement in scenario definition, market analysis, and the accuracy of cost estimates.

Table 4: The main profitability indicators associated with each TRL. Adapted from Giacomella (2021)

TRL	Development stage description	Objective of the assessment	Development phase	Profitability indicators
TRL 1	Idea or basic principle for a product, process, or application	Screening and comparison of ideas and concepts	Research	- No quantitative indicators - Multi-criteria ranking
TRL 2	Formulated technological concept and theoretical mass balances	Preliminary comparison between alternative pathways	Research	- Theoretical gross margin - Relative gross profit (normalized)

TRL 3	Start of process development; preliminary process flow assumptions	Assessment of the economic plausibility of the concept	Research	- Relative profit - Specific profit
TRL 4	Process validated at laboratory scale	Preliminary estimation of profitability and investment recovery	Development	- Static profit - Static PB - Static ROI
TRL ≥ 5	Process validated at pilot scale	Support the investment decision-making	Development	- NPV - Dynamic PB - Dynamic ROI - IRR - EBIT

2.1.4.4 Techno-economic indicators

At more advanced stages of technological development and in the presence of lower uncertainty in data and analyses, indicators may also combine technical, economic, and environmental aspects of the assessed technology.

2.1.5. Result and Interpretation

The interpretation phase represents the core of a TEA, as it is essential to ensure that the outputs of the analysis are consistent with the objectives of the study, the TRL of the processes, and the assumptions adopted during the modelling phase. This phase includes **uncertainty**, **sensitivity**, and **scenario analyses**, which are carried out after the calculation of the selected indicators. This iterative approach is completed if the inventory can address the goal of the assessment sufficiently.

A key challenge in the interpretation stage is assessing the information provided by indicators and corresponding criteria, in order to satisfactorily answer the questions posed by the assessment goal.

A central aspect of result interpretation concerns the *analysis of uncertainty* (UA). This type of analysis allows the assessment of the uncertainty associated with the model output, defined as any result or indicator of interest for the baseline case and for additional scenarios relevant to the decision-making process. In the context of TEA, such outputs may include calculated profitability indicators (e.g., NPV, IRR).

In particular, in contexts characterized by low TRL levels and limited availability of process-specific data, the uncertainty associated with the results may be high. In such cases, uncertainty analysis is primarily based on sensitivity analyses of the selected indicators with respect to the main assumptions and the most uncertain parameters, rather than on point estimates.

Sensitivity analysis (SA) makes it possible to evaluate how variations in input parameters—such as energy consumption, process yields, or unit costs—affect the TEA results, that is, how sensitive the model output is to changes in one or more input variables. Uncertainty analysis (UA) and sensitivity analysis are therefore complementary, as SA helps to understand how output uncertainty is generated and to identify the key input variables that contribute most significantly to overall uncertainty (Saltelli et al., 2000).
In the case of preliminary TEAs, the interpretation of results may also include qualitative comparisons between different process configurations or hypothetical scenarios, where available, to assess potential trade-offs. This is particularly relevant because the application of complex analytical methods may introduce a significant level of noise into the results.
It is therefore necessary to identify the most influential parameters to support the prioritization of data collection efforts and process optimization activities in subsequent research and development phases.

The framework proposed by Langhorst et al. (2022) for the analysis of uncertainty and sensitivity of the calculated indicators is as follows:

1. Characterization of uncertainty
2. Uncertainty analysis
3. Sensitivity analysis
4. Improving data quality by an iterative approach

2.1.5.1 Uncertainty analysis

In this phase, the objective is to identify the overall variation in the model output caused by uncertainties associated with the input data or with the model itself. To this end, several methods are available, which are selected depending on the source and the nature of the uncertainty.
In literature, uncertainties are generally classified into three main categories:

- Quantitative uncertainties in input variables, arising from measurement errors or expert-based estimates (data accuracy), as well as stochastic uncertainties related to the probability distributions of the variables.
- Uncertainties in the model structure and process representation, that is, related to the extent to which the model faithfully represents the interrelationships of the real system.
- Contextual and scenario uncertainties, arising from methodological choices made by the practitioner during the definition of the goal and scope of the analysis.

In principle, uncertainty is expected to decrease as the level of technological maturity increases, due to improvements in data quality and availability, as well as to a more comprehensive understanding of the processes and technologies.

2.1.5.2 Sensitivity analysis

In this phase, the key variables on which efforts should be focused are identified, with the aim of reducing overall uncertainty and improving the quality of inventory data or impact assessment results. The identification of key variables can be initiated already at early stages of technological development; however, a more detailed decomposition requires the availability of data that typically becomes accessible only at higher levels of technological maturity.

Sensitivity analysis can be classified into local and global approaches. Local sensitivity methods are generally simpler and faster to apply, as they involve varying one input variable at a time. In contrast, global sensitivity methods allow the attribution of output variance to the different input variables and enable the quantification of interaction effects between two or more variables.

2.1.5.3 Interpretation of Indicators

Once the different checks on the indicators have been performed, the resulting information and trends are interpreted to address the original questions defined by the objectives of the assessment. Interpretation should be carried out in accordance with the definition of each indicator, with particular attention to the limitations described. Typically, results are compared with alternative values, for instance, based on selected reference systems.

Specific thresholds are defined for the indicators, to which a particular form of local sensitivity analysis—referred to as threshold analysis- is applied to identify the threshold values of key input variables at which the indicator results lead to a change in the main conclusion. The break-even point represents the threshold at which a project becomes profitable (Langhorst et al., 2022).
According to Langhorst et al. (2022), and considering the individual profitability indicators:

- Static profit and static ROI: the indication is positive if the value is greater than zero or meets the required target value; when comparing alternatives, the higher value is preferred; in efficiency form, the threshold value is equal to 1.
- Static payback period: the indication is positive if the payback period is shorter than the expected lifetime of the plant; when comparing alternatives, a shorter payback period is preferred.

- NPV and dynamic ROI: the indication is positive if the value is greater than zero or meets the required target value; when comparing alternatives, the higher value is preferred.
- IRR: the indication is positive if the value is higher than the interest rate of a capital market investment with an equivalent risk profile, or if it exceeds a predefined target value; IRR should be interpreted in conjunction with the corresponding absolute profitability indicators.
- Dynamic payback period: the indication is positive if the payback period is shorter than the expected lifetime of the plant; when comparing alternatives, a shorter payback period is preferred.

2.2. Energy Efficiency Assessment modelling framework

In the context of climate change, uncertainty in energy supply, and rising energy prices, the need to develop sustainable and circular industrial processes, as well as to mitigate the environmental impacts of production activities, makes energy efficiency a key success factor and a strategic priority in the short term (Bunse et al., 2011; IPCC, 2018). Consequently, the energy efficiency of industrial processes emerges as one of the fundamental drivers for emission reduction and for improving the overall sustainability of production systems (May et al., 2017).

From the perspective of manufacturing companies, the main drivers for introducing energy efficiency improvements can be grouped into three key factors:

- Rising energy prices;
- The introduction of new environmental regulations and the associated costs related to CO_2 emissions;
- changes in customer purchasing behavior towards “green” and energy-efficient products and services.

In this context, the interest of the European Union and the industrial sector in energy management has increased significantly, leading the EU to strengthen its regulatory framework in the environmental and energy domains. The first publication of the ISO 50001 standard in 2011 provided a strong impetus to research in this field, contributing to increased awareness among companies regarding energy consumption and consequently stimulating the development of new methods and tools aimed at improving energy performance while simultaneously identifying energy-saving opportunities.

The international standard updated in 2018 by the *International Organization for Standardization* – **ISO 50001:2018** – defines the requirements for Energy Management Systems

(**EnMS**) and provides a structured framework for managing energy use and consumption within organizations.
The standard specifies requirements applicable to energy use and consumption, including measurement, documentation, and reporting activities, which contribute to improving energy performance.
ISO 50001:2018 has been designed to be compatible with and integrable into other management systems, in particular ISO 14001 for environmental management, thereby promoting a systemic approach to the sustainability of processes and organizations.

The adoption of an EnMS compliant with ISO 50001 offers several benefits, including:

- Reduction of energy costs;
- increased energy awareness and enhanced staff engagement;
- improved decision-making based on energy consumption data;
- reduction of environmental impacts and greenhouse gas emissions;
- more efficient and transparent resource management, resulting in competitive advantages.

These benefits are applicable to organizations of any size and across all sectors.
In the context of projects such as NEO-CYCLE, ISO 50001 provides a relevant methodological reference for structuring energy assessment activities, even though system certification is not yet an objective.
In light of the European and national regulatory framework (e.g., Legislative Decree 102/2014), ISO 50001 currently represents one of the main reference solutions for energy management.

The EnMS is based on the Plan-Do-Check-Act (**PDCA**) continuous improvement cycle, which integrates energy management into existing organizational practices:

- PLAN: analysis of the organizational context and energy consumption, identification of significant energy uses, definition of energy performance indicators, baselines, objectives, and action plans;
- DO: implementation of action plans, operational and maintenance management, training, and integration of energy performance considerations into design and procurement activities;
- CHECK: monitoring, measurement, and analysis of energy performance, internal audits, and management reviews;
- ACT: implementation of corrective actions and continuous improvement of both the EnMS and energy performance.

Although ISO 50001:2018 provides a comprehensive framework for energy management, it does not prescribe specific methods or indicators for assessing energy efficiency at the process or system level. The standard defines *what* organizations are required to establish—such as energy reviews, *energy performance indicators* (**EnPIs**), baselines, and continuous improvement mechanisms—but leaves open *how* energy performance should be quantitatively evaluated.

In this context, EEA represents a key analytical component supporting the implementation of an Energy Management System.
EEA methodologies provide models, indicators, and evaluation frameworks to analyze how energy is used within processes, machines, and production systems, thereby enabling the definition of meaningful EnPIs and the identification of significant energy uses.
Several studies highlight that EEA approaches complement ISO 50001 by translating its requirements into operational tools capable of supporting decision-making, technology comparison, and performance monitoring (Giacone and Mancò, 2012; Schulze et al., 2016; Menghi et al., 2019).
In development projects such as NEO-CYCLE, where the focus is on emerging technologies' processes, ISO 50001 serves as a methodological reference, while EEA provides the analytical framework for evaluating energy performance.

2.2.1. Multidisciplinary nature of energy efficiency assessment

As highlighted in the literature, the validation of models for EEA can lead to economic benefits, increased transparency of energy consumption – including real-time monitoring – and improved energy awareness within the analyzed system, providing manufacturing companies with a comprehensive and pragmatic method to measure, control, and improve energy efficiency in production systems (Bunse et al., 2011; Menghi et al., 2019).

In light of these considerations, EEA requires a multidisciplinary approach (Johansson and Thollander, 2018). The energy performance of any production process does not depend exclusively on machinery or measured energy consumption, but is also influenced by managerial and organizational factors, such as corporate decisions and strategies, production management practices, and technical aspects.
For this reason, EEA cannot be addressed through a single isolated technical model but requires the adoption of methods and tools capable of supporting both energy evaluation and collaboration among the various stakeholders involved (Giacone and Mancò, 2012).

2.2.1.1 *Measurement of energy efficiency and modelling frameworks*

A common approach in the literature is the adoption of hierarchical modelling frameworks, in which energy consumption and energy efficiency are analyzed at different system levels.

1- Process level: energy use is directly linked to the physical mechanisms responsible for material transformation or value creation. Indicators at this level aim to quantify the relationship between useful energy and process output. However, strictly process-related energy often represents only a fraction of the overall energy consumption (Wang et al., 2013).
2- Machine level: energy consumption includes both process energy and the energy required for the operation of auxiliary and peripheral components, such as cooling systems, pumps, control units, and supporting services. Several studies show that energy not directly related to the core process can represent a dominant share of total consumption, particularly in advanced technologies or systems characterized by intermittent operation (Fysikopoulos et al., 2014).
3- Higher levels (plant, site, or production line): energy efficiency is strongly influenced by organizational and operational factors, including equipment utilization rates, idle times, production planning strategies, and start-up and shutdown procedures. In this context, a significant portion of energy losses is associated with non-value-adding activities rather than with purely technological inefficiencies (Wang et al., 2013).

Although many of the reviewed studies are specific to individual manufacturing sectors, the approaches analyzed converge towards a common workflow for conducting an EEA, which is consistent with the logic adopted in LCA, LCC, and TEA studies.
The typical workflow of an EEA is summarized in Box 2.2, which outlines the main operational phases commonly adopted.

Box 2.3 – Methodological workflow for Energy Efficiency Assessment

Goal and system boundary definition

The first step consists of defining the goal and system boundaries, including the energy flows considered, the temporal resolution, and the level of aggregation of the analysis. This phase is essential to ensure consistency and comparability with the results.

Energy characterization and modelling

This step combines direct measurements and modelling approaches. Due to the practical difficulties in monitoring all energy flows, hybrid approaches integrating experimental data, theoretical formulations, and statistical models are frequently adopted. These approaches allow the estimation of process energy, auxiliary consumption, idle energy, and start-up losses.

Data normalization

A key step of the EEA is data normalization, which is required to evaluate energy performance over time or across alternative scenarios. In this context, the use of energy baselines and EnPIs is widely recommended, particularly in energy management–oriented applications.

Indicator calculation and aggregation

Energy indicators are calculated at different system levels (process, machine, production line and subsequently aggregated according to the objectives of the analysis, enabling a structured interpretation of energy performance.

Benchmarking and improvement assessment

Finally, EEA supports benchmarking and improvement assessment activities, enabling the comparison of technological or operational alternatives and the identification of potential energy savings.

2.2.2. Energy Efficiency Indicators

Measuring the energy consumption of a process enables the assessment of optimization potential and supports the visualization of verifiable benefits resulting from the implementation of improvement measures.

The development and application of energy efficiency indicators depend on the purpose for which they are used and on the specific industrial sector considered. In general, indicators are ratios describing the relationship between an activity and the energy required to perform it.

Among the most used indicators are Energy Intensity (EI) and Specific Energy Consumption (SEC). SEC is currently the most widely applied indicator, with output expressed either in physical or economic units.

However, the interpretation of these indicators strongly depends on several factors, including:

- System boundaries;
- Production mix
- Equipment load level

For both indicators, energy consumption can be measured in different ways (Phylipsen et al., 1997), such as:

- Demand for primary energy carriers;
- Net available energy;
- Purchased energy;
- Associated CO_2 emissions

Other indicators define efficiency as the ratio between useful energy and total energy input, either in instantaneous form or integrated over the process cycle. These indicators allow a clear distinction between value-adding energy and auxiliary or idle energy consumption.

Due to the variety and complexity of industrial processes, a wide range of structural and explanatory indicators exists (IEA, 2007a). The International Energy Agency (IEA) provides in-depth analytical tools based on a hierarchical indicator pyramid that includes both disaggregated and aggregated data. Nevertheless, although numerous studies have addressed energy efficiency indicators at the national or sectoral level, a limited number of studies focus on the single company, plant, or process level.

Table 5 summarizes the most used energy efficiency indicators reported in the literature, specifying their respective units of measurement, the type of indicator (e.g., economic, hybrid, thermodynamic, physical, macroeconomic, statistical, or engineering-based), and the main fields of application. These indicators cover different levels of analysis and serve different objectives, ranging from consumption transparency to structured energy performance evaluation. Their selection and application strongly depend on system boundaries, data availability, aggregation level, and the purpose of the analysis (Phylipsen et al., 1997; Bunse et al., 2010).

Table 5: The most used energy efficiency indicators from the literature. Adapted from Bunse et al. (2010).

Indicator	**Indicator Type**	**Application**	**Unit/Formula**	**Reference**
Energy Intensity	Economic	Aggregated level	Energy consumption/economic term	Phylipsen et al., 1997
Specific energy consumption	Physical	Energy use/physical unit of production	Process level, cross-country comparison, sector level	(Farla et al., 1997) (IEA, 2007a)
Economic energy efficiency	Economic	Measure in terms of market value	Energy input in monetary terms/output in monetary terms	(Patterson, 1996)
Energy efficiency measurement	Economic	Activity of a sector	Energy consumption/value added or value of shipments	(Farla et al., 1997)
Thermal energy efficiency of equipment	Physical	For single equipment	Energy value available for production/input energy value	(IEA, 2008a)
Energy consumption intensity	Physical	Broader than thermal indicator: companies, etc	Energy consumption/physical output value	(IEA, 2008a)

Absolute amount of energy consumption	Physical	With the indication of production volumes	Energy value	(IEA, 2008a)
Thermodynamic energy efficiency	Thermodynamic	Measurements derived from the science of thermodynamics	Actual energy usage related to an ‘ideal’ process	(Patterson, 1996)
Industrial energy intensity	Physical	Comparison of efficiency data on a sub-sector	Energy use/unit of industrial output, e.g., GJ/t	(IEA, 2007a)
Energy performance indicators	Statistical	On plant level	Percentile ranking of the energy efficiency	Boyd et al., 2008)

3. Methodology of preliminary TEA within NEO-CYCLE

3.1. Goal and Scope

Within the context of the NEO-CYCLE project and of the present report, the TEA is applied at an early stage of technological development, characterized by a TRL 4 and a limited availability of process-specific data. The processes analyzed have not yet been implemented at an industrial scale; instead, they are still under development in a laboratory environment and are therefore affected by a high degree of uncertainty, particularly concerning process performance, technical characteristics, and associated economic parameters.
Consequently, the scope of preliminary TEA developed in this report is not to perform a complete and detailed evaluation typically aimed at estimating economic profitability, calculating financial indicators, or carrying out a direct comparison with industrial reference processes. Instead, the present report seeks to define, at the current state of knowledge, a coherent and transparent methodological framework capable of providing preliminary indications to project partners and of facilitating a structured and forward-looking technical dialogue, consistent with the current stage of technological development and intended to evolve.

In particular, the TEA within NEO-CYCLE is aimed at:

- identifying the main techno-economic drivers of the analyzed processes;
- providing useful indications to guide research and development (R&D) activities and future exchanges with the involved partners;
- highlighting potential critical issues and relevant trade-offs, where assessable at the current stage, in view of a future industrial scalability.

Within this approach, some key phases that are typical of a complete TEA, as described in Chapter 2, such as a detailed profitability analysis, market analysis or benchmarking against alternative technologies, are not addressed in the present assessment and may be developed in subsequent phases of the project, when a larger amount of data at a higher level of technological maturity becomes available.
The scope of the present preliminary TEA report includes the definition of specific techno-economic indicators suitable for an exploratory assessment, primarily aimed at providing qualitative insights. In particular, the analysis focuses on cost breakdowns and the relative contributions of the main cost categories, intending to identify the key economic drivers of the analyzed processes. Advanced financial indicators and detailed market analyses are outside the scope of the present study and may be addressed in future stages of the project, as data quality improves and the level of technological maturity increases.

3.1.1. TEA Implementation and Calculation Tool

-

The TEA is implemented through a dedicated calculation tool developed in Microsoft Excel, designed to facilitate data exchange with project partners and to support iterative updates of the analysis throughout the project duration.
At this stage, where available, default values derived from scientific literature and publicly available databases may be used in the absence of process-specific data. Depending on data availability and information quality, these values may be replaced or updated.

The tool interface has been designed to ensure a transparent and user-friendly structure and is based on an interface available online and published by AssessCCU (n.d).

3.2. Technology Readiness Level (TRL)

As reported in the literature (Buchner et al., 2017; Giacomella, 2021), applied research activities related to process development are typically positioned within the early levels of the TRL scale, namely TRL 1 to TRL 4, and no clear-cut boundary currently exists between research and development phases in terms of TRL. Progression from one TRL to the next requires an increasing availability of technical, operational, and economic information, which allows the uncertainty associated with process development to be progressively reduced.

Within the context of the present report, the TRL of the processes under analysis has been defined as TRL 4, corresponding to *laboratory validation of the technology*. This choice is justified by the fact that NEO-CYCLE activities are conducted at laboratory scale and already involve a systemic development of the processes, rather than isolated or purely conceptual investigations.

The attribution of TRL 4 is also consistent with the objectives of the project, which aim at a progressive advancement of technological maturity towards higher TRL levels, up to TRL 6 in subsequent project phases, in view of a future industrial-scale application, as also outlined in the project planning and amendment documents.

Based on this assumption, the methods for cost estimation and the techno-economic indicators considered are selected and applied—where feasible—in a manner consistent with the current level of technological maturity. These elements will be progressively refined and expanded throughout the project, as the technological development of the process advances and as data quality and availability improve.

3.3. Functional Unit

The functional unit (FU) represents the reference parameter to which the results of the study are related, namely the quantity or unit of measure with respect to which impacts and performance indicators are calculated.

In the present report, the functional unit is defined as 100 g of NdFeB permanent magnets. The selection of the functional unit is consistent with that adopted for the EEA and for the LCA/LCC analyses, in order to ensure methodological alignment among the different assessment tools and to enable the comparability of results with respect to a common functional reference and time horizon.

3.4. System Boundaries

System boundaries define which stages are included in the study, thereby delineating the process under analysis and isolating it from those parts that are excluded.

In the present report, the system is analyzed according to a “**gate-to-gate**” configuration, whereby only specific process modules within the facility under development in the project are included. Upstream activities related to raw material collection and recovery, as well as downstream stages related to product use and end-of-life management, are excluded from the analysis (Torabi & Ahmadi, 2020).

For preliminary TEA studies, such system boundaries are commonly adopted, particularly in contexts characterized by low TRL and processes still under development at laboratory scale. Similarly to the functional unit definition, the selected system boundaries are consistent with those adopted in the EEA and in the LCA/LCC analyses, in order to ensure methodological alignment among the different assessment tools and to enable the comparability of results.

3.5. Data Categories and Data Quality

At this phase of the study, the use of generic data is consistent with the preliminary objective of the present TEA and is justified by the need to provide indicative and orientation-oriented insights rather than definitive quantitative results.
In order to ensure transparency and traceability, the data will be classified according to their origin and quality, distinguishing between project-specific data, literature-based data, and estimated values.

3.6. Inventory

In the following section, all processes related to WP4 of the NEO-CYCLE project are presented and described through process flow diagrams.

Considering the dual objective of the report, namely, to analyze the processes under consideration from both a technical and an economic perspective, the inventory is structured through tables dedicated to material input and output flows, as well as cost inventory tables,

including materials, labor, and equipment.
These inventory data, including diagrams and tables, were collected by HOLOSS in collaboration with partners from WP4 and subsequently shared with the consortium as part of a collaborative effort to minimize the workload on individual partners.

3.6.1. NEO-CYCLE – Process Overview

Within WP4, innovative processes have been developed for the recovery of permanent magnets from end-of-life hard disk drives, with particular focus at this stage on the recovery of neodymium (Nd).

WP4 is structured into four tasks, each addressing a specific stage of the process chain:

- Task 4.1: Waste inventory and magnet characterization
- Task 4.2: Nd extraction via solid-state chlorination
- Task 4.3: Electrochemical Nd extraction
- Task 4.4: Metal extraction and selective separation
- Task 4.5: Refining metal recovery

3.6.1.1 Task 4.1 “Waste inventory and magnet characterization.”

Within the context of this task, a process flow has been developed for the preparation and characterization of rare-earth-based permanent magnets derived from end-of-life hard disk drives. As illustrated in Figure 2, the input material consists of magnets supplied by Ecoreset, which represent the common initial feedstock for the subsequent experimental activities developed within WP4.

The process includes the following main steps:

- demagnetization, required to ensure safe handling of the material and its suitability for subsequent mechanical operations;
- crushing and milling, through which the demagnetized magnets are converted into a powder with appropriate granulometric characteristics;
- digestion using aqua regia, aimed at the complete solubilization of the elements present in the sample.

The resulting liquid phases are subsequently analyzed by ICP-OES/MS to determine the elemental composition of the material. In parallel, a portion of the milled solid material is allocated to structural and compositional characterization, while a representative fraction of the magnet powder is used as input material for the extraction processes developed in Tasks 4.2 and 4.3.

The final output of Task 4.1 mainly consists of analytical data, which provides the basic information required for the design, interpretation, and evaluation of the subsequent recovery stages, as well as of the demagnetized magnet powder destined for downstream processing. In this sense, Task 4.1 represents an enabling preliminary stage, closely linked to the development of neodymium extraction processes addressed in Tasks 4.2 and 4.3.

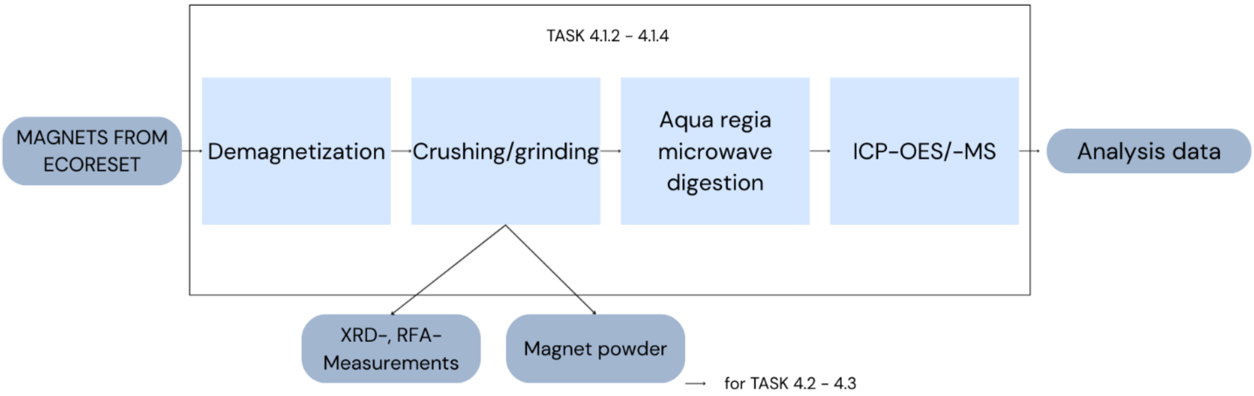

Figure 2: The process flow diagrams of Task 4.1 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners.

3.6.1.2 Task 4.2 "Nd extraction via solid-state chlorination (SSC)"

Task 4.2 is dedicated to the development of an innovative Nd extraction process based on a Solid-State Chlorination approach. The input material consists of the magnet powder obtained in Task 4.1, derived from magnets supplied by Ecoreset, which represents the common feedstock for the extraction activities developed within WP4. The powder, produced through the preparation steps described above, is then fed into the SSC reactor, which represents the core of the process. During the chlorination stage, the material reacts with ammonium chloride (NH_4Cl), used as the chlorinating agent, enabling the selective conversion of the elements of interest into chlorinated species.

As a by-product of the SSC process, the formation of ammonia (NH_3) in the gas phase is observed. The main output of Task 4.2 consists of a chlorinated magnet powder, which represents the input material for the subsequent process steps developed in Task 4.4. In parallel, the process generates a leaching residue, which may originate both from Task 4.2 and from downstream stages, and which requires dedicated management in the subsequent phases of the project.

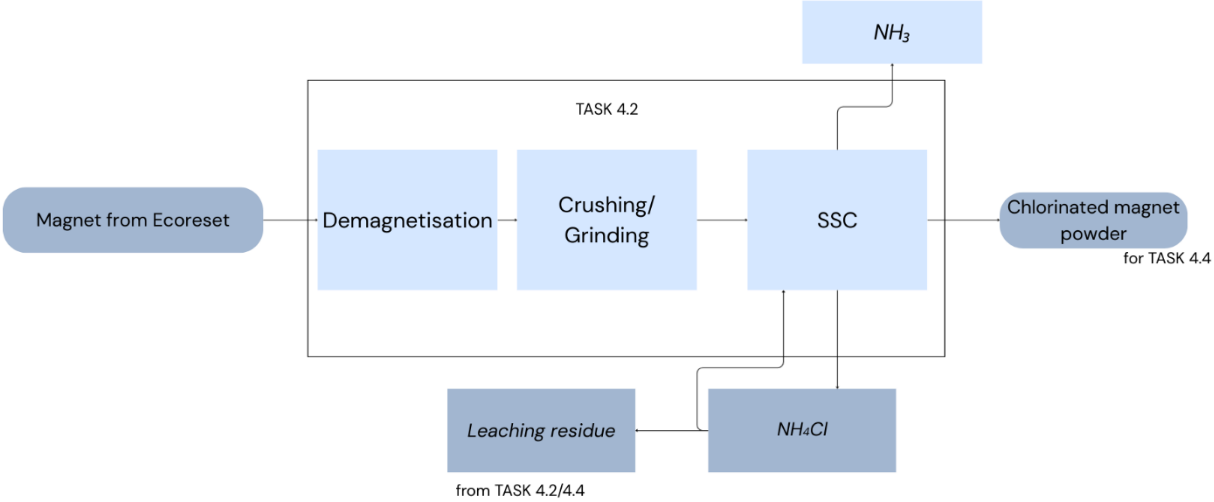

Figure 3: The process flow diagrams of Task 4.2 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners.

3.6.1.3 Task 4.3 “Electrochemical Nd extraction”

Task 4.3 explores alternative approaches for Nd extraction based on electrochemical processes, assessing both non-selective and selective configurations.

In the non-selective configuration (Figure 4), the magnets constitute the input material and are subjected to an electrochemical leaching step, which enables the transfer of the metallic elements into solution. The resulting slurry is subsequently subjected to filtration, separating a liquid phase from a solid phase. During this step, a fraction of the iron is removed in the form of iron oxy-hydroxide residues, which may also contain fractions of Nd and other trace elements.

The leaching solution is then sent to the subsequent stages of the process (Task 4.4). The solid residue is further treated through acid leaching, followed by a second filtration step, to recover additional amounts of neodymium and other metals of interest. This results in a leaching solution enriched in Nd and Fe, as well as a final solid residue, mainly composed of magnetite.

In parallel, the process diagram (Figure 5) includes a configuration based on selective electrochemical leaching, which is currently under investigation. In this case, the process is designed to promote the selective dissolution of neodymium while limiting the co-transfer of iron into solutions. Following leaching and filtration, a leaching solution predominantly containing Nd is obtained and directly sent to Task 4.4, together with an iron-rich solid residue, separated as sludge or secondary solid.

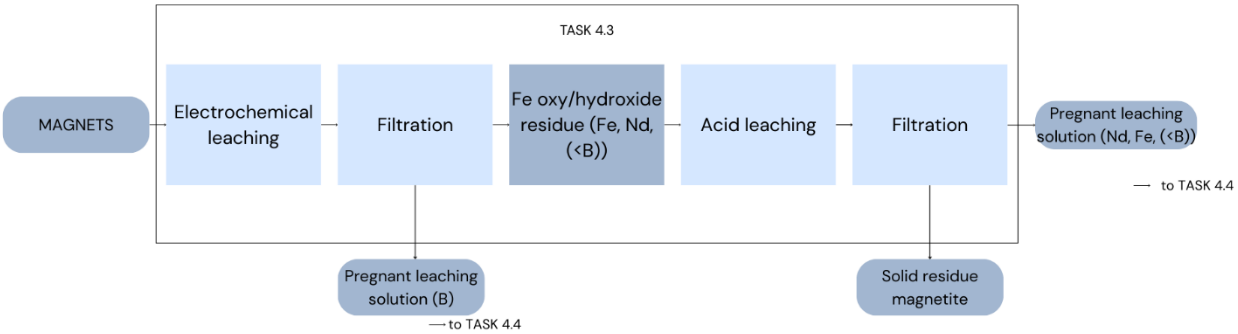

Figure 4: The process flow diagrams of Task 4.3 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners. The flow diagrams represent the "*Non-selective electrochemical leaching + OH precipitations*".

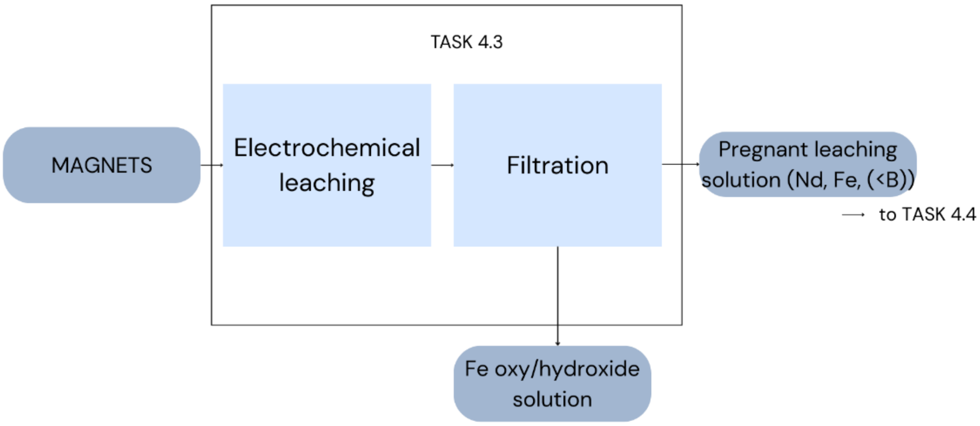

Figure 5: The process flow diagrams of Task 4.3 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners. The flow diagrams represent the "*Selective electrochemical leaching".*

3.6.1.4 Task 4.4 "Metal extraction and selective separation."

Task 4.4 is dedicated to the extraction and selective separation of metals, with particular emphasis on the separation and purification of Nd from the process streams generated in the upstream tasks. This task represents the downstream stage of the WP4 process chain and integrates the treatment of both solid and liquid outputs produced in Tasks 4.2 and 4.3.

The input materials to Task 4.4 include:
- chlorinated magnet powders obtained from the solid-state chlorination process developed in Task 4.2;

- leaching solutions containing Nd and other metals (e.g., Fe and B), generated by the electrochemical leaching processes investigated in Task 4.3.

Therefore, two main separation routes have been considered, as illustrated in Figures 6 and 7.

The first configuration (DS route) is applied to non-selective leaching solutions originating from Task 4.3 and involves a precipitation step using Na_2SO_4, followed by filtration and washing, enabling the recovery of neodymium in the form of a double salt. The product can subsequently be subjected to calcination, yielding Nd_2O_3 as a final or intermediate product. In parallel, the process generates a Fe- and B-containing solution, which requires further treatment in continuity with the approaches developed in the upstream tasks.
It is important to consider that optimization activities currently ongoing within WP4 may lead to a modification of this process configuration. Therefore, the scheme reflects the configuration adopted at the time of drafting.

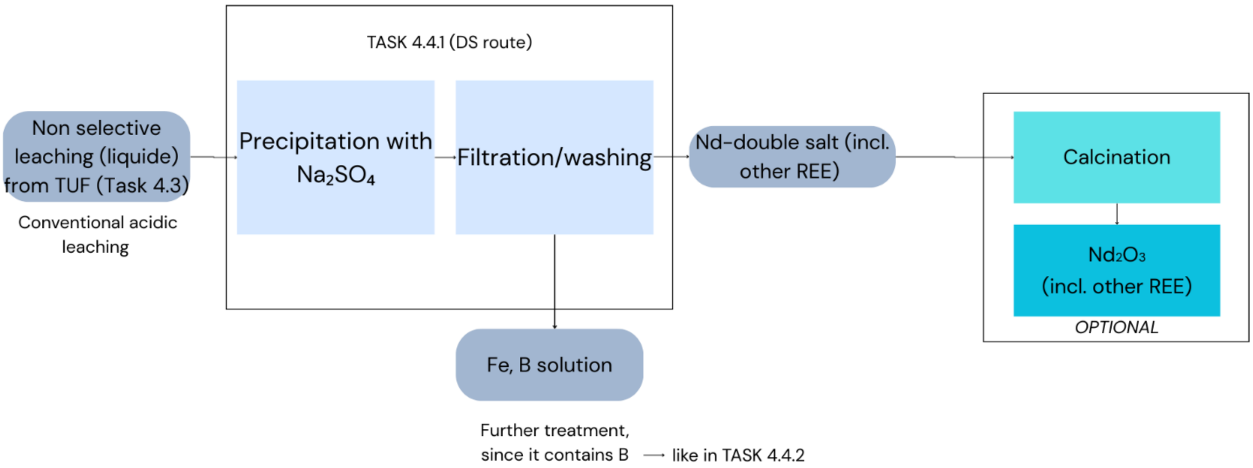

Figure 6: The process flow diagrams of Task 4.4.1 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners.

The second configuration (oxalate route) is applied to selective leaching solutions obtained in Task 4.3 and is based on a precipitation step using oxalic acid, which allows the selective recovery of Nd in the form of Nd oxalate. Also in this case, the product may undergo an optional calcination step to obtain Nd_2O_3. Fe management is achieved through a pH increase, leading to the formation of Fe $(OH)_3$ and the generation of a wastewater stream containing trace amounts of other metals.

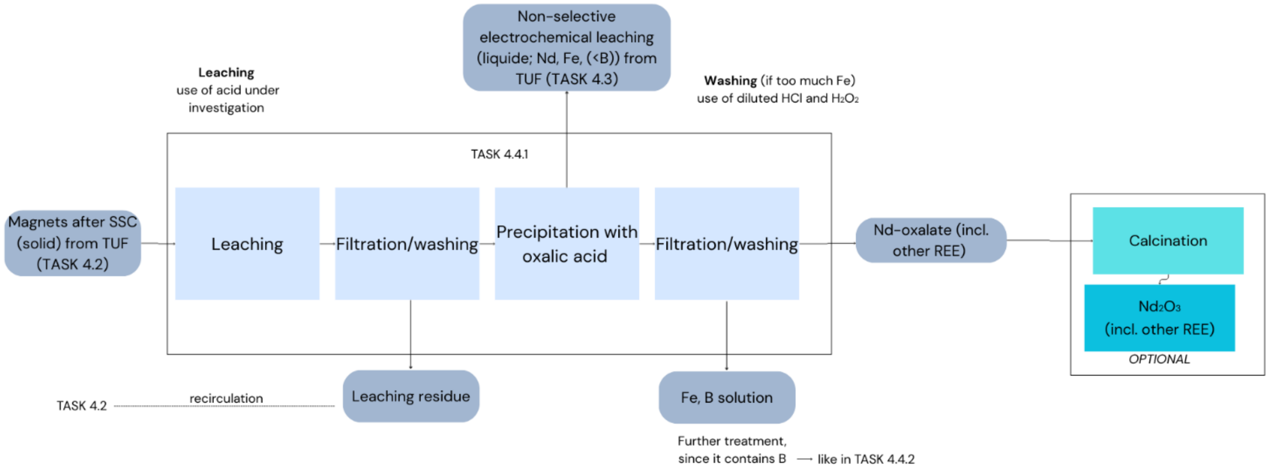

Figure 7: The process flow diagrams of Task 4.4.2 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners.

Subtask 4.4.1 – Separation of Nd/Fe

Within Subtask 4.4.1, a process flow has been developed for the separation of neodymium from iron and other co-leached elements. As illustrated in Figure 8, the solid material derived from the SSC process (Task 4.2) is initially subjected to a leaching step, using acidic solutions that are currently under investigation.

The resulting suspension is subsequently subjected to filtration, enabling the separation of a solid leaching residue and a solution containing the dissolved metals. The process liquor is then treated by precipitation with oxalic acid, which allows the selective recovery of neodymium in the form of Nd oxalate, potentially containing other rare earth elements. The precipitate is subsequently subjected to filtration and washing in order to remove residual impurities; if a high iron content is detected, additional washing steps using diluted HCl and H_2O_2 may be applied. The solid Nd oxalate product can finally be subjected to an optional calcination step, yielding Nd_2O_3 as a final or intermediate product.

In parallel, the process generates secondary streams, including Fe- and B-containing solutions and leaching residues, which may require further treatment or recirculation strategies, in continuity with those developed in the upstream tasks.

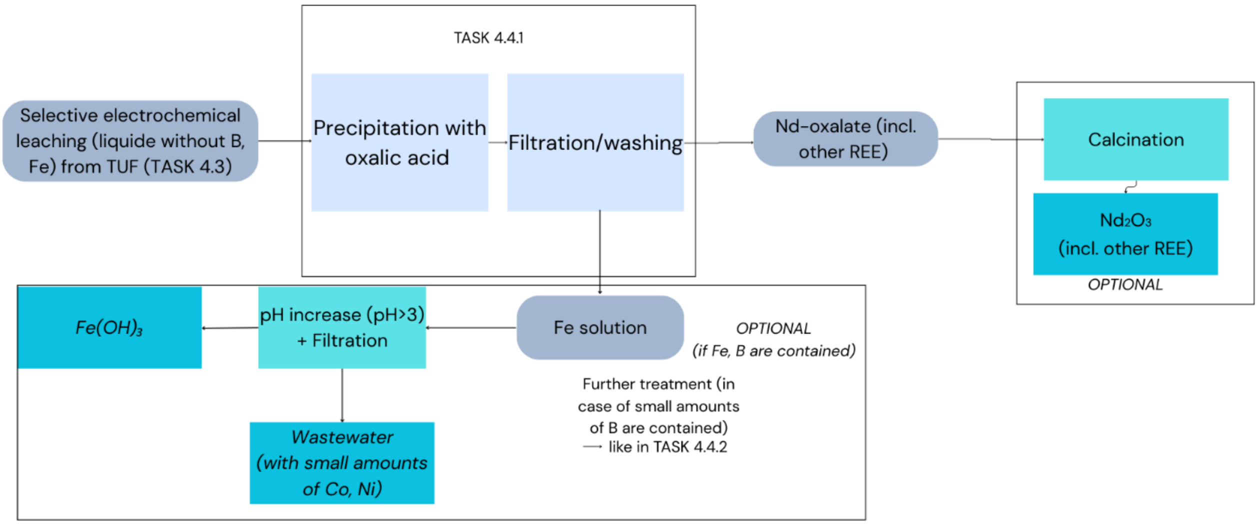

Figure 8: The process flow diagrams of subtask 4.4.1 (WP4) activities, collected by HOLOSS in co-operation with WP4 partners.

Subtask 4.4.2 – Separation of Fe/B

This subtask is dedicated to the development of a process flow for the separation of Fe and B from the liquid streams generated in the upstream extraction stages, to manage and valorize the metallic by-products associated with neodymium recovery.

As illustrated in Figure 9, the input material consists of a liquid stream originating from Task 4.3, which is subjected to a preliminary treatment (pretreatment) to adjust its chemical characteristics. The process initially involves an increase of the pH to values in the range of approximately 6.5 to 7, enabling the selective precipitation of iron in the form of ferric hydroxide ($Fe\ (OH)_3$). The precipitate is subsequently separated by filtration, while the resulting liquid phase is enriched in boron.

The B-containing solution is then subjected to a pH decrease ($pH < 5$), followed by a precipitation/crystallization step, aimed at recovering boron in the form of boric acid. A subsequent filtration allows the separation of the solid product from the residual process solution.

The boron recovered as boric acid may be further treated through an optional calcination step, yielding B_2O_3 as a final or intermediate product. Depending on the composition of the stream and the presence of impurities, an additional purification step (e.g., based on ion exchange) may be required, the need for which is currently under investigation.

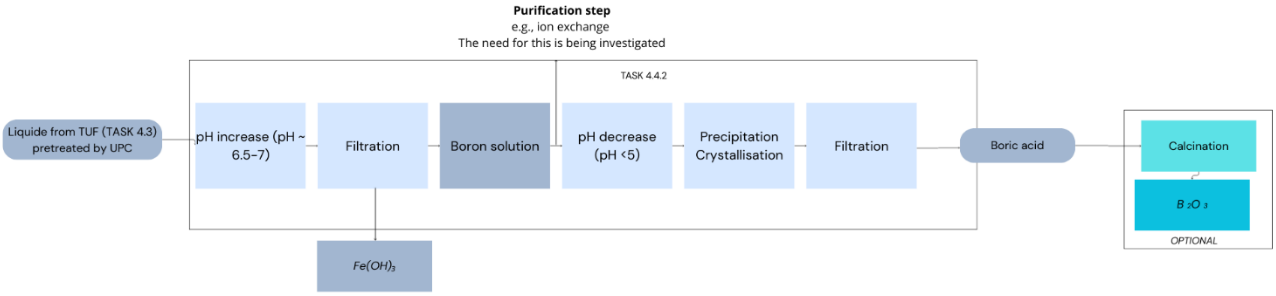

Figure 9: The process flow diagrams of subtask 4.4.2 (WP4) activities, collected by HOLOSS in co-operation with WP4 partners.

3.6.1.5 Task 4.5 “Refining metal recovery.”

Task 4.5 is dedicated to the development of a process flow for the final purification of recovered materials, to obtain products with a level of purity suitable for the intended end uses. This task represents a cross-cutting and flexible stage within the process chain, applicable to both solid and liquid materials obtained from the upstream tasks of WP4.

As illustrated in Figure 10, the input material consists of an impure material derived from the extraction and separation stages developed in Tasks 4.2, 4.3, and 4.4. The process initially includes a dissolution or leaching step, intended to render the material suitable for the subsequent purification operations.
The core of Task 4.5 consists of the application of a purification method, the specific configuration of which is currently under definition, depending on the required purity level and the composition of the input material. The options under consideration include, for example, ion exchange, solvent extraction, and selective precipitation or crystallization, which are developed and optimized within the relevant task.

Downstream of the purification stage, the process includes separation, filtration, and washing steps, enabling the recovery of the purified material as the main output. In parallel, process liquid streams are generated, which may be directed to recirculation, contributing to a reduction in overall reagent consumption and an improvement in process efficiency.

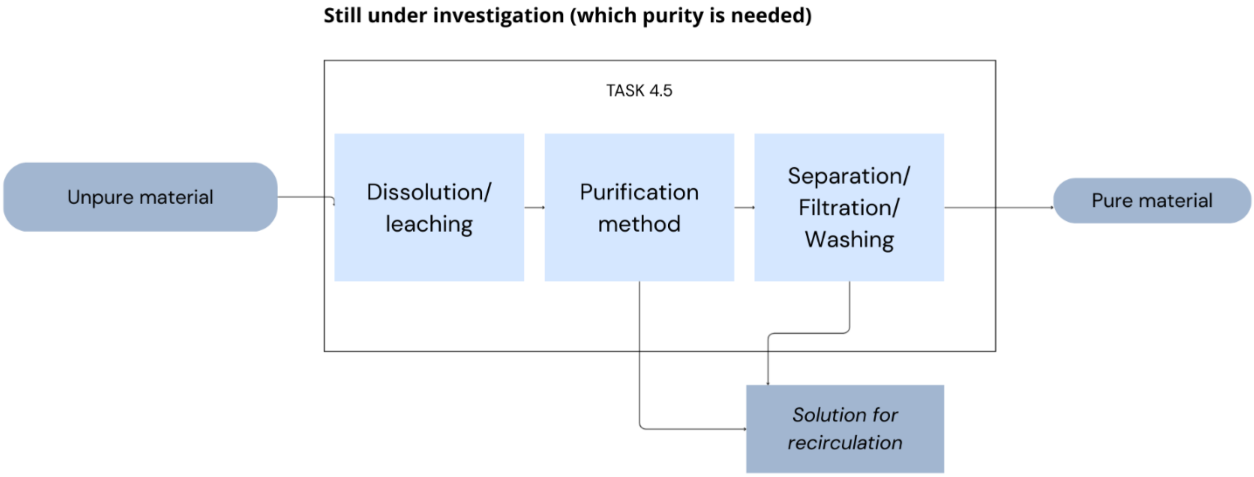

Figure 10: The process flow diagrams of Task 4.5 (WP4) activities, collected by HOLOSS in cooperation with WP4 partners.

3.7. Indicators

Based on the processes described in the previous section and on the TRLs considered within the NEO-CYCLE project, the selection of indicators has been carried out in accordance with the recommendations reported in the literature. With specific reference to profitability indicators, the methodological framework proposed by Giacomella (2021) has been adopted, which links specific indicators to the degree of technological maturity of the process.
At the current state of knowledge, the indicator formulations are presented mainly from a methodological and qualitative perspective, as a sufficient level of data detail to allow for a complete quantification of all the involved parameters is not yet available.

The objective of this section is therefore twofold: on the one hand, to present the formulations and calculation criteria of the selected indicators; on the other hand, to support the involved partners in understanding the type of data required to achieve the objectives of this report. These data are expected to be provided by month 24, in particular with reference to the activities of WP4, to enable the subsequent quantitative application of the selected indicators, the results of which will be reported in Deliverable 10.2.

In Box 4.1, all the indicators selected for the subsequent quantification phase are reported, including technical, economic, and cost-related indicators, as well as profitability and techno-economic indicators.

Box 4.1 – Selected indicators for TEA analysis

In this box, the selected indicators related to technical aspects, economic and cost-related, profitability, and techno-economic aspects are summarized.

Technical Indicators

Based on the considerations discussed in Section 2.1.4.1, the technical indicators selected at this preliminary stage are reported below to assess the process performance of the recovery pathways developed within WP4, in coherence with TRL 4.
Table 6 summarizes the technical indicators considered in this report and, for each of them, the typical unit of measurement and the TEL at which they become applicable.

Table 6: technical indicators for the NEO-CYCLE project

Technical indicator	Description	Unit	TRL applicability	Reference
Process yield	Preliminary assessment of process effectiveness	%	4 - 6	Towler & Sinnott, 2013
Recovery efficiency	Evaluation of recovery performance	%	4 - 6	911Metallurgist., 2013
Product purity	Assessment of product quality	% or wt.%	4 - 6	*IUPAC*, (2025). Winkelnkemper and Schembecker., 2010.
Specific material consumption	Identification of material efficiency	kg/kg product	4 – 6	Estimated based on mass balance data
Specific energy consumption	Assessment of energy efficiency	kWh/kg product	4 – 6	Lawrence et al., 2019 Giacone and Mancò, 2012
Process capacity	Evaluation of scalability and productivity	Kg/h	5 – 6	Ogle et al., 2014

Process availability	Assessment of operational reliability	%	5 – 6	OEE, n.d.

In the case of NEO-CYCLE, which focuses on the recovery and purification of secondary materials, indicators based on mass and energy balances have been selected, as they are commonly used to assess the technical efficiency of such processes.

Process Yield

The process yield expresses the amount of product obtained per unit of input material and provides a first indication of the overall effectiveness of the process.
At the current stage, the data required are: i) the mass flow rate of the input feedstock; ii) the mass of final product obtained.

$$Process\ yield = \frac{Mass\ of\ product\ obtained}{Mass\ of\ feedstock\ processed}$$

Recovery efficiency

The recovery efficiency quantifies the fraction of the target material effectively recovered with respect to the amount originally present in the feedstock. This indicator can be particularly relevant for secondary raw material recovery processes.
At the current stage, the data required are: i) chemical composition of the feedstock; ii) mass of target material in the recovered product; and iii) analytical data along the process steps.

$$Recovery\ efficiency = \frac{Mass\ of\ target\ material\ recovered}{Mass\ of\ target\ material\ in\ the\ feedstock}$$

Grade of product purity

Product purity expresses the concentration of the target component in the final product and is a key parameter determining the potential end-use and market value of the recovered material.
At the current stage, the data required are: i) compositional analysis of the final product, and ii) identification and quantification of impurities.
The key factors that could be influencing the parameters are: I) the efficiency of separation and purification steps; ii) the presence of impurities and co-recovered elements; and iii) the process selectivity.

$$Purity = \frac{Mass\ of\ target\ component}{Total\ mass\ of\ the\ product}$$

Specific material consumption

Specific material consumption measures the number of reagents, solvents, or functional materials required per unit of product and provides an indication of the material efficiency of the process.

At the current stage, the data required are: i) the inventory of material inputs; ii) the mass of product obtained; and iii) the information on material recovery or reuse.

$$Specific\ material\ consumption = \frac{kg\ reagent}{kg\ product}$$

Specific energy consumption

Specific energy consumption quantifies the energy required to produce one unit of product and represents a key link between technical performance and energy efficiency assessment. At the current stage, the data required are: i) electricity/thermal energy consumption by unit operation; and ii) production rate of the process.

$$Specific\ energy\ consumption = \frac{total\ energy\ consumed}{total\ of\ product\ obtained}$$

Once all the required laboratory-scale data become available and the process is transferred to pilot scale, it will be possible to perform more representative comparisons aimed at assessing the technical feasibility of the process. Furthermore, at higher levels of technological maturity and with increased data availability, additional technical indicators can be calculated by introducing further variables such as time, operational stability, process reproducibility, and plant capacity.

Process capacity

Process capacity refers to the amount of product that can be produced by a process per unit of time under defined operating conditions.

The data required are: i) mass of products produced over a defined period; ii) effective operating time of the process; and iii) process operating conditions.

$$Process\ capacity = \frac{mass\ of\ product\ produced}{operating\ time}$$

Process availability

Process availability represents the fraction of scheduled operating time during which the process is effectively running and producing output. It reflects the operational reliability of the process on the pilot scale.

The data required are: i) scheduled operating time; II) actual operating time; and iii) records of downtime and interruptions.

$$Process\ availability = \frac{effective\ operating\ time}{total\ scheduled\ operating\ time}$$

These indicators selected at this preliminary stage, in view of increased data availability and project development, may be further refined and, if necessary, updated during the project, also based on the inputs and recommendations provided by the partners involved.

Economic and cost-related Indicators

The economic and profitability assessment is based on a set of cost-related indicators, selected and described in this section, which progressively support both preliminary evaluations of economic plausibility and subsequent investment-oriented analyses.

At TRL 4, these indicators are primarily used to identify orders of magnitude of costs and the main cost items, without reaching a level of detail that is not justified by the current data availability. In later stages, the same indicators will provide the basis for the construction of cash flows and for the calculation of profitability indicators.

Total CapEx

At the current state of knowledge, CapEx represents the total investment cost required for the implementation of the plant.
Depending on data availability, at this stage it is possible to include, in addition to the cost of major equipment and simplified estimates of installation costs, also indirect costs, potential financing costs, as well as tax structures and depreciation schemes.

If these elements are not included at early stages, they may be integrated at a later stage, once a higher level of information becomes available. CapEx is a key parameter for subsequent phases, as it represents the basis for the calculation of the main profitability indicators.

Total OpEx

Total OpEx represents the annual operating cost of the process. At the current state of the knowledge, OpEx can be calculated in a simplified form, without explicitly accounting for:

- detailed maintenance costs;
- full personnel costs;
- administrative costs;
- waste management costs.

At the stage of the present report, the most relevant components are:

- material cost;
- energy cost;
- process consumables.

In subsequent phases, as the TRL advances, a refined OpEx will be calculated, accounting for all relevant cost items to enable a more realistic evaluation of the industrial cost of the process.

Unit production cost (C_{unit})

This indicator represents the average cost per unit of product and is calculated as the ratio between annual operating costs and the amount of product produced in the same period:

$$C_{unit} = \frac{OpEx_{annual}}{K}$$

Where *K* represents the annual production capacity of the plant.

In preliminary analyses, this indicator represents the basis for:

- first direct comparisons with reference products and processes;
- identification of the main cost items per unit of product;
- calculation of the specific profit.

Cost of Goods Sold (COGS)

The COGS represents the industrial production cost of a product and expresses the cost incurred to produce the units effectively sold in a given period. It is derived from the annual operating costs of the process, integrating the annualized capital costs and normalizing the overall cost over the actual annual production.
For this reason, this indicator becomes meaningful only at more advanced levels of technological maturity (e.g., TRL 6), when the operational structure of the process is sufficiently defined.

Cost breakdown

The cost breakdown provides a qualitative or semi-quantitative representation of the distribution of the main cost items (materials, energy, capital, and other costs).
The qualitative cost breakdown is derived from the process description (Cap. X) and mass and energy balances, and is intended to identify the cost categories that will be progressively quantified as the project advances towards higher TRLs.

Even in the absence of consolidated numerical estimates, this indicator is particularly useful to:

- identify the cost drivers of the process;
- guide research and development activities towards the most critical stages;
- support sensitivity analyses in later phases.

Table 7 summarizes the main cost categories considered relevant at the current TRL, providing a qualitative cost breakdown and a structural framework to guide future data collection.

Table 7: The main cost categories considered relevant at TRL 4 for the NEO-CYCLE project.

COST CATEGORIES	SUB-CATEGORY	DESCRIPTION
CONSUMABLES	Reagents	e.g., chemical reagents used in extraction, leaching, separation, and purification steps
	Solvents	e.g., solvents used in process steps
RAW MATERIAL	Functional materials	e.g., magnets
INFRASTRUCTURE	Laboratory and pilot facilities	e.g., laboratory space, pilot skids
PROCESS MACHINERY AND EQUIPMENT	Main process equipment	e.g., demagnetization furnaces, reactors, leaching, separation, and purification units
	Instrumentation and control	e.g., sensors, ICP-OES/MS
PERSONNEL	Operating personnel	e.g., technicians and operators involved in process operation
UTILITIES	Electricity	e.g., electricity demand for process operation and auxiliary systems
	Thermal energy	e.g., heat requirements for process steps
	Water	e.g., process water
WASTE AND BY-PRODUCTS	Residual streams	e.g., solid residues, process wastewater
	By-product handling	e.g., handling, treatment, or potential valorization of secondary streams

Profitability Indicators

The following section presents and describes the profitability indicators considered appropriate for TRL 4 (current state of knowledge) and TRL 6 (project target). For each indicator, the analytical formulation, economic meaning, and data requirements are illustrated, in accordance with the methodological framework proposed by Buchner et al. (2018) and Giacomella (2021).

Profitability Indicators for **TRL4**

At this stage, corresponding to process validation at laboratory scale, the profitability assessment is based on static indicators, which provide a first estimation of the economic performance of the processes under steady-state operating conditions and without accounting for the time value of money. At this level, the indicators are mainly used for screening purposes and for preliminary comparison among different process configurations.

Specific Profit (€/kg product)

Specific profit is the profit generated per unit of product and equals the difference between unit revenues and allocated operating and capital costs.
According to the reference guidelines, this indicator is typically associated with TRL 3; however, for the present report, it is considered appropriate to retain it also at TRL 4, as—at the current state of knowledge—it enables a direct comparison with reference products or processes and supports the assessment of the economic plausibility of the technological concept in the presence of a more defined process.

It is calculated on a per-unit basis as the difference between unit revenues (Π_p), unit operating cost (Π_{op}), and the annualized CapEx allocated per unit of production, obtained by dividing the total CapEx by the project lifetime or recovery period (n), and the annual plant capacity (K).

$$P_{stat} = \Pi_p - \Pi_{op} - \frac{CapEx}{n * K}$$

Static Profit (€)

Static profit represents the total profit generated by the process over the considered time horizon, assuming constant operating conditions.
It is calculated as the specific profit (P_{stat}) multiplied by the annual addressable market sales volume (V) and by the project lifetime or recovery period (n).

This indicator helps to provide a first estimation of the overall economic potential of the process, despite simplified assumptions regarding production capacity and market evolution.

$$P_{stat} = n * V * (\Pi_p - \Pi_{op} - \frac{CapEx}{n * V})$$

Static Payback Period (years)

The static payback period represents the time after which an investment is amortized and starts generating net profit. Only investments with a payback time shorter than the project lifetime should be considered; when comparing alternatives, the investment with the shortest payback period is generally preferred.
The static payback period is calculated as the ratio between CapEx and the annual net profit generated by the process, expressed as the product of the annual V and the difference between Π_p and Π_{op}.

The point in time at which an economic activity starts generating net profit is defined as the break-even point.

$$t_{payback,stat} = \frac{CapEx}{V * (\Pi_p - \Pi_{op})}$$

Static Return on Investment (ROI) (%)

The ROI is an indicator used to compare efficiency in the use of invested economic resources. This indicator is generally calculated on an annual basis or as an average operating value.
For multi-period analysis, a more detailed understanding of the product and the market is required, which is consistent with a higher TRL level.
It is calculated as the ratio between the cumulative profit generated over the project lifetime and the CapEx, where cumulative profit is expressed as the product of n, the annual V, and the difference between Π_p and Π_{op}.

$$ROI_{stat} = \frac{n * V * (\Pi_p - \Pi_{op})}{CapEx}$$

Profitability Indicator for **TRL 5-6**

Based on the indications reported in the literature, starting from TRL 5, the level of process definition allows for a first description of future cash flows and market scenarios. At this stage, the uncertainty associated with cost estimates becomes comparable to the effect of discounting, making it appropriate to introduce dynamic indicators that account for the time value of money.
TRL 6, corresponding to process validation in a relevant environment and the implementation of pilot plants, represents a critical phase for investment decision-making (the so-called valley of death). In this context, the profitability assessment should necessarily include the analysis of discounted cash flows to support strategic decisions related to the continuation of technological development and the potential transition to industrial scale.

The following indicators are therefore identified as appropriate for quantification in a subsequent phase, with a view to reaching TRL 6.

Net Present Value (NPV) (€)

The NPV represents the present value of all future cash flows generated by the process over the project lifetime, discounted to the reference year.
It is calculated as the sum of the annual net cash flows — defined as the difference between Π_p and Π_{op} - discounted using an appropriate interest rate, minus the CapEx incurred in the corresponding periods. A positive NPV indicates that the investment generates a return exceeding the discount rate i assumed.

$$NPV = \sum_{t=0}^{n} \frac{V_t * (\Pi_p - \Pi_{op})_t - CapEx_t}{(1+i)^t}$$

Dynamic payback period (year)

The dynamic payback time represents the time required for the cumulative discounted cash flows to become equal to or greater than zero.

It is calculated as the first year in which the sum of all discounted net cash flows offsets the initial capital investment, accounting for the time value of money.

This indicator provides information on the risk associated with the timing of investment recovery under discounted conditions.

$$t_{payback,dyn} = t_{min}\ for\ (NPV \geq 0)$$

Dynamic return on investment (ROI) (%)

The dynamic ROI is calculated as the ratio between the total discounted cash flows generated by the process and the total discounted capital expenditure. By accounting for the time value of money, this indicator provides a measure of the efficiency of the invested capital under dynamic conditions and allows comparison between alternative investment options with similar risk profiles.

$$ROI_{dyn} = \frac{\sum_{t=0}^{n} \frac{V_t * (\Pi_p - \Pi_{op})_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{CapEx_t}{(1+i)^t}}$$

Internal rate of return (IRR) (%)

The IRR is defined as the discount rate that results in a net present value equal to zero. It represents the rate of return at which the present value of future cash inflows equals the present value of the capital investment. The IRR is commonly used to compare the economic attractiveness of different investment options and is considered favorable when it exceeds the reference market interest rate; however, it should be interpreted in conjunction with the NPV, as it does not provide information on absolute profitability.

$$IRR = i\ for\ (NPV = 0)$$

Techno-economic Indicators

Specific production cost (€/kg product)

Specific production cost represents the average total cost required to produce one unit of the final product. It includes both operating costs and, where relevant, the annualized share of capital expenditure, and is commonly used to compare alternative technologies or scenarios.

$$Specific\ production\ cost = \frac{Annual\ total\ cost}{Annual\ product}$$

Where the annual total cost comprises annual operating expenditures and, if applicable, annualized capital costs, while the annual product output is expressed in kilograms of product per year.

Specific energy cost (€/kWh product)

The specific energy cost quantifies the economic contribution of energy consumption to the production of one unit of product, highlighting the sensitivity of the process to energy prices.

$$Specific\ energy\ cost = \frac{Annual\ energy\ cost}{Annual\ product}$$

Where the annual energy cost is calculated as the total annual energy consumption multiplied by the unit energy price, and the annual product output is expressed in kilograms of product per year.

CAPEX per unit of capacity (€/kg·year^{-1})

Expresses the capital investment required per unit of installed production capacity.

$$CAPEX\ per\ unit\ of\ capacity = \frac{Total\ CAPEX}{Annual\ product}$$

Where the installed production capacity is defined as the nominal annual production capacity of the plant, expressed in kilograms of product per year.

OPEX per unit of product (€/kg product)

This indicator represents the average operating cost associated with the production of one unit of product, including both fixed and variable operating expenses.

$$OPEX\ per\ unit\ of\ product = \frac{Total\ CAPEX}{Annual\ product}$$

includes costs related to energy, consumables, reagents, labor, maintenance, and other routine operational activities, while the annual product output is expressed in kilograms per year.

Cost per unit of yield or recovery (€/kg Nd recovered)

This indicator measures the cost associated with the effective recovery of one unit of valuable material.

$$Cost\ per\ unit\ of\ yield\ or\ recovery = \frac{Annual\ total\ cost}{Annual\ recovered\ material}$$

3.7.1. Challenges in the Selection and Calculation of Profitability Indicators for NEO-CYCLE

Based on what is discussed in Chapter 2.1.4.3, the selection of profitability indicators in the preliminary TEA of emerging technologies applied to circular value chains for the recovery and valorization of permanent magnets represents one of the main methodological challenges, due to the lack of consolidated data and stable market references.
NEO-CYCLE, in fact, is embedded in a market context characterized by a high level of uncertainty, characterized by emerging technologies, still at an early stage of development, and by the transformation of the industrial value chain, for which the market cannot yet be considered fully consolidated. The potential demand for the products obtained from the processes under investigation does not depend solely on economic factors, but also on external elements such as the regulatory framework, European policies on circular economy and critical raw materials, as well as the level of acceptance by downstream user sectors. As a result, future market volumes are difficult to estimate during the early stages of technological development.

With regard to the forecasting of cash flows, in the presence of new or poorly explored markets, product selling prices, demand stability, and competitiveness with respect to conventional alternatives are subject to high variability. This uncertainty reduces the reliability of profitability indicators based on economic estimates and long-term initial assumptions.
Furthermore, the lack of sector-wide standardization in the selection of indicators makes it difficult to compare results with other studies and reference systems.
For these reasons, future market analyses developed within the NEO-CYCLE project will be the result of a dynamic process, progressively refined as technological development advances and as market conditions become better understood.

4. Methodology of preliminary EEA within NEO-CYCLE

The model adopted in this report is based on an explicit representation of the processes and of the associated material and energy flows. The modelling approach is consistent with the methodological nature of the assessment and with the current TRL of the analyzed processes.
The modelling focuses on the description of the main process units composing the systems developed within the NEO-CYCLE project, allowing for a coherent linkage between the technical, economic, and energy-related aspects of the technologies under study. This approach enables a systematic evaluation of the interactions between process performance and the corresponding economic and energy impacts, while maintaining a level of detail that is compatible with the availability of data.

4.1. Energy efficiency indicators for the NEO-CYCLE project

To assess the energy efficiency of the NEO-CYCLE project, the first subset of potential indicators has been selected to capture as much as possible the dimensions of circularity and efficiency of the project. It is important to note that significant overlap has been found among the potential indicators found in literature, so a wider list of indicators might not provide more comprehensive information. The selected indicators are presented in Table 8.

Table 8: Preliminary selected indicators for the NEO-CYCLE project

Indicator	**Indicator Type**	**Application**	**Unit/Formula**	**Reference**
Process energy efficiency Index	Physical	Process level	Effective energy/total energy	(Wang et al., 2013)
Specific energy consumption	Physical	Process level, cross-country comparison, sector level	Energy input/Physical unit of production	(Farla et al., 1997) (IEA, 2007a)
Economic energy efficiency	Economic	Measure in terms of market value	Energy input in monetary terms/output in monetary terms	(Patterson, 1996)
Lean energy indicator	Economic	Process level, sector level	Valuable energy consumed/energy consumed overall	(May et al., 2014)
Renewable energy share	Physical	Process, level, sector level	Renewable energy/Total energy	(Phylipsen et al., 2010)

The subset of energy efficiency indicators proposed in *Table 3* is not intended to be definitive; for this reason, a structured selection and validation process is required to identify a reduced subset of indicators that will be effectively applied within the project, to capture as much information as possible while avoiding redundancy. The selection process will be based on a stakeholder-driven approach and will involve the distribution of a dedicated questionnaire to the NEO-CYCLE project partners, which will focus on selecting a number of the indicators presented in *Tables 2 and 3*. Each indicator will be evaluated by partners based on a common understanding of its definition and scope as provided in the accompanying description derived from literature.

Project partners will be asked to assess and score each indicator according to a set of qualitative criteria, which will include:

- Relevance for the NEO-CYCLE project
- Data availability for the calculation of the indicator
- Perceived robustness
- Ease of interpretability

The involvement of partners representing different stages of the value chain and different aspects of the project will ensure that the final indicator set will capture multiple perspectives and avoid a purely theoretical or technical approach. The outcome of this process will be a validated and manageable set of circularity indicators that will be consistently applied across project activities.

Throughout the duration of the project, dialogue with partners will help identify any aspect regarding energy efficiency that has not been accounted for in the indicators presented in *Tables 2* and *3*. Should any relevant area emerge, novel indicators specific to the NEO-CYCLE context will be developed and assessed by partners.

5. Conclusion

Building on the recommendations reported in the literature, the present report has defined the methodological framework for the TEA and the EEA of the processes developed within the NEO-CYCLE project, in coherence with the current TRL 4. In particular, the reference processes have been described, the TRL positioning has been clarified, and the most appropriate technical, economic, cost-related, and profitability indicators have been selected as a function of the degree of technological development and project objectives.

Considering the current state of knowledge, the assessment has been primarily structured on a methodological and qualitative basis to consistently define the indicators to be applied and their corresponding formulations while avoiding the premature use of tools not supported by the level of detail of the available data. In this context, within the section dedicated to the

TEA, the report clearly distinguishes between indicators applicable at the current development stage (up to TRL 4) and indicators that will become fully meaningful once more advanced levels of technological maturity are reached (TRL 5–6).

The objective of the subsequent phases of the project, for both assessments, is to proceed with the quantification of the selected indicators, particularly the dynamic ones, to support investment-oriented decision-making and the potential industrial scalability of the developed processes. To enable such a quantitative analysis, it is, however, necessary to rely on a more detailed set of technical and economic data, including, for example, material costs, among others.

Finally, a sensitivity analysis is envisaged for the selected indicators to assess the influence of the main assumptions and the most uncertain parameters on the result of the preliminary TEA. This analysis will be developed in subsequent project phases to assess the influence of the main assumptions and the most uncertain parameters on the results of the preliminary TEA.

Regarding the EEA, this report initially presents a set of energy efficiency indicators, described in Sections 2.2 and 4.1, which mainly reflect those identified in the literature and are potentially applicable to a project such as NEO-CYCLE. However, similarly to what is envisaged for circularity indicators, a structured selection and validation process is required to identify and define a reduced subset of indicators that will be effectively applied within the project, to capture as much relevant information as possible while avoiding redundancy.

The selection process will be based on a stakeholder-driven approach and will involve the distribution of a dedicated questionnaire to the NEO-CYCLE project partners, aimed at selecting a limited number of indicators from those proposed in this report. In line with the approach adopted in Deliverable 9.2 for the identification of circularity indicators, project partners will be asked to assess and score each energy efficiency indicator according to a set of qualitative criteria, including:

- relevance for the NEO-CYCLE project;
- data availability for the calculation of the indicator;
- perceived robustness;
- ease of interpretability.

The involvement of partners representing different stages of the value chain and different aspects of the project will ensure that the final set of indicators captures multiple perspectives, avoiding a purely theoretical or exclusively technical approach. The outcome of this process will be a validated and manageable set of energy efficiency indicators, consistently applied across the different project activities.

In this regard, the contribution of the project partners is essential. In particular, the activities carried out within WP4 play a key role in the collection and validation of the data required for the subsequent quantitative application of the indicators defined in this report. To ensure temporal consistency of the analyses and compliance with the project planning, the following steps are ideally envisaged:

- the list of indicators included in this deliverable will be shared with the project partners at month 18, to collect initial feedback on the proposed set of indicators;
- over the subsequent six months, a structured dialogue with the partners will be initiated to gather further comments and preliminary data; during this phase, the types of data that will be available in the future will also be identified, to ensure the calculability of the selected indicators
- starting from month 24, a formal questionnaire will be distributed to the partners, who will be asked to rank the indicators based on several factors previously discussed;
- in the following months and until the delivery of the final deliverable, available data will be progressively collected, and the indicators will be calculated; during this phase, communication with the partners will remain a priority to ensure that the indicators accurately reflect the evolving needs of the project and that the data are accurate and up to date;
- at month 48, through Deliverable 10.2, the final results of the circularity assessment will be presented, marking the conclusion of the project.

The overall timeline and the envisaged interaction with the project partners are schematically illustrated in Figure 11.

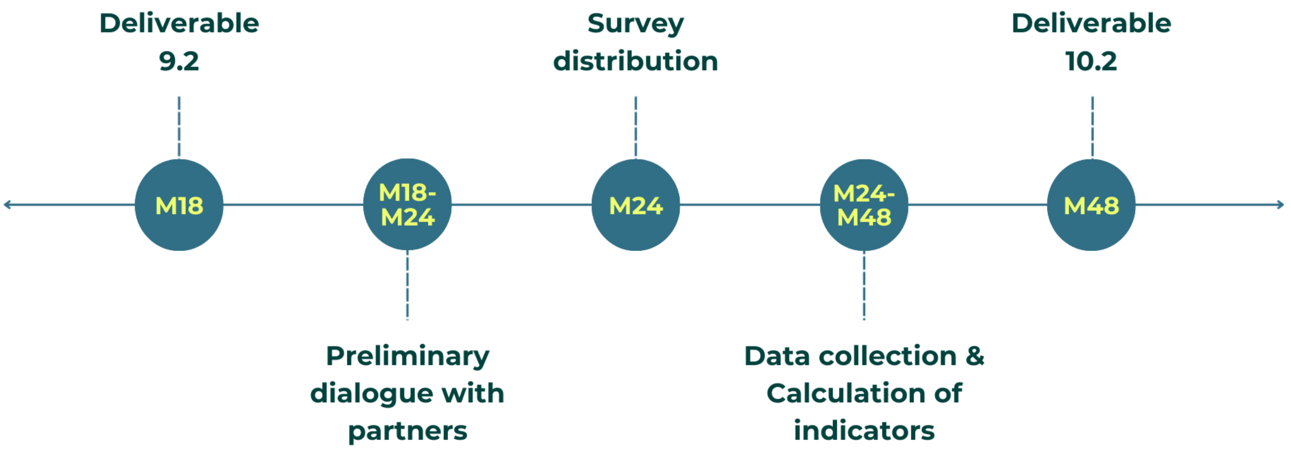

Figure 11: The workflow of the planned interactions with project partners and the progressive development of the indicator-based assessment

In parallel, a continuous dialogue will be maintained with the partner HOLOSS to progressively integrate the developed analyses, harmonize methodological assumptions, and foster the comparability of results. This approach will strengthen the robustness of the assessments and expand the scope of analysis from a system-level perspective.

Overall, the present report represents a structured and shared basis for the evolution of the TEA and EEA within NEO-CYCLE, clearly outlining both the status and the steps required to achieve a comprehensive quantitative assessment consistent with the project objectives.

REFERENCE

911Metallurgist. (2013). Metallurgical Accounting Formulas | Concentration and Recovery in Mineral Processing - 911Metallurgist. [online] Available at: https://www.911metallurgist.com/blog/metallurgical-accounting-formulas/ [Accessed Jan. 2026].

AssessCCUS (n.d.). AssessCCUS – Techno-Economic and Life Cycle Assessment for Carbon Capture, Utilization, and Storage. [online] Available at: https://assessccus.globalco2initiative.org/.

Boyd, G., Dutrow, E. and Tunnessen, W. (2008). The evolution of the ENERGY STAR® energy performance indicator for benchmarking industrial plant manufacturing energy use. Journal of Cleaner Production, 16(6), pp.709–715. doi:https://doi.org/10.1016/j.jclepro.2007.02.024.

Buchner, G.A., Zimmermann, A.W., Hohgräve, A.E. and Schomäcker, R. (2018). Techno-economic Assessment Framework for the Chemical Industry—Based on Technology Readiness Levels. Industrial & Engineering Chemistry Research, 57(25), pp.8502–8517. doi:https://doi.org/10.1021/acs.iecr.8b01248.

Bunse, K., Vodicka, M., Schönsleben, P., Brülhart, M. and Ernst, F.O. (2011). Integrating energy efficiency performance in production management – gap analysis between industrial needs and scientific literature. Journal of Cleaner Production, [online] 19(6-7), pp.667–679. doi:https://doi.org/10.1016/j.jclepro.2010.11.011.

Farla, J., Blok, K. and Schipper, L. (1997). Energy efficiency developments in the pulp and paper industry. Energy Policy, 25(7-9), pp.745–758. doi:https://doi.org/10.1016/s0301-4215(97)00065-7.

Fysikopoulos, A., Pastras, G., Alexopoulos, T. and Chryssolouris, G. (2014). On a generalized approach to manufacturing energy efficiency. The International Journal of Advanced Manufacturing Technology, 73(9-12), pp.1437–1452. doi:https://doi.org/10.1007/s00170-014-5818-3.

Giacomella, L. (2021). Techno-Economic Assessment (TEA) and Life Cycle Costing Analysis (LCCA): discussing methodological steps and integrability. Insights into Regional Development, 3(2), pp.176–197. doi:https://doi.org/10.9770/ird.2021.3.2(2).

Giacone, E. and Mancò, S. (2012). Energy efficiency measurement in industrial processes. Energy, 38(1), pp.331–345. doi:https://doi.org/10.1016/j.energy.2011.11.054.

Gupta, A., Williams, E. and Gaustad, G. (2022). The effect of time-intervals in characterizing price-related uncertainties in techno-economic analysis. Journal of Cleaner Production, 380, p.134929. doi:https://doi.org/10.1016/j.jclepro.2022.134929.

Hanne Lamberts-Van Assche and Tine Compernolle (2021). Economic Feasibility Studies for Carbon Capture and Utilisation Technologies: A Tutorial Review. Research Square (Research Square). doi:https://doi.org/10.21203/rs.3.rs-277248/v1.

IEA (2007). Tracking Industrial Energy Efficiency and CO 2 Emissions. [online] Available at: https://iea.blob.core.windows.net/assets/84e31bc6-6ebd-4026-9060-3c9ae64e4c11/tracking_emissions.pdf.

IEA (2008), Assessing Measures of Energy Efficiency Performance & Their Application in Industry, IEA, Paris https://www.iea.org/reports/assessing-measures-of-energy-efficiency-performance-their-application-in-industry, Licence: CC BY 4.0

IPCC, 2018: Global Warming of 1.5°C.An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels andrelated global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani,W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T.Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp. https://doi.org/ 10.1017/9781009157940.

IUPAC Compendium of Chemical Terminology, 5th ed. International Union of Pure andApplied Chemistry; 2025. Online version 5.0.0, 2025. https://doi.org/10.1351/goldbook.08014

Johansson, M.T. and Thollander, P. (2018). A review of barriers to and driving forces for improved energy efficiency in Swedish industry– Recommendations for successful in-house energy management. Renewable and Sustainable Energy Reviews, 82, pp.618–628. doi:https://doi.org/10.1016/j.rser.2017.09.052.

Kobos, P., Drennen, T., Outkin, A., Webb, E., Paap, S. and Wiryadinata, S. (2020). Techno-Economic Analysis: Best Practices and Assessment Tools. OSTI OAI (U.S. Department of Energy Office of Scientific and Technical Information). doi:https://doi.org/10.2172/1738878.

Lawrence, A., Thollander, P., Andrei, M. and Karlsson, M. (2019). Specific Energy Consumption/Use (SEC) in Energy Management for Improving Energy Efficiency in Industry: Meaning, Usage and Differences. Energies, 12(2), p.247. doi:https://doi.org/10.3390/en12020247.

May, G., Stahl, B., Taisch, M. and Kiritsis, D. (2017). Energy management in manufacturing: From literature review to a conceptual framework. Journal of Cleaner Production, 167, pp.1464–1489. doi:https://doi.org/10.1016/j.jclepro.2016.10.191.

Menghi, R., Papetti, A., Germani, M. and Marconi, M. (2019). Energy efficiency of manufacturing systems: A review of energy assessment methods and tools. Journal of Cleaner Production, 240, p.118276. doi:https://doi.org/10.1016/j.jclepro.2019.118276.

Ogle, R., Andrew, P. and Carpenter, R. (2014). Reactions and Separations. [online] Available at: https://www.aiche.org/sites/default/files/cep/20140859.pdf [Accessed 2026].

Patterson, M. (1996). What is energy efficiency? Concepts, issues and methodological issues. Energy Policy, 24, pp.377–390.

Phylipsen, G.J.M., Blok, K. and Worrell, E. (1997). International comparisons of energy efficiency-Methodologies for the manufacturing industry. Energy Policy, 25(7-9), pp.715–725. doi:https://doi.org/10.1016/s0301-4215(97)00063-3.

Saltelli, A., Chan, K. and Scott, E.M. (2000) Sensitivity analysis. Hoboken, NJ: Wiley.

Schulze, M., Nehler, H., Ottosson, M. and Thollander, P. (2016). Energy management in industry – a systematic review of previous findings and an integrative conceptual framework. Journal of Cleaner Production, 112, pp.3692–3708. doi:https://doi.org/10.1016/j.jclepro.2015.06.060.

Scott, M. (2015). Technical economic analysis guide-DRAFT. US Department of Energy.

Scown, C.D., Baral, N.R., Yang, M., Vora, N. and Huntington, T. (2021). Technoeconomic analysis for biofuels and bioproducts. Current Opinion in Biotechnology, [online] 67, pp.58–64. doi:https://doi.org/10.1016/j.copbio.2021.01.002.

Torabi, F. and Ahmadi, P. (2020). Techno-economic assessment of battery systems. Elsevier eBooks, pp.311–352. doi: https://doi.org/10.1016/b978-0-12-816212-5.00013-1.

Towler, G. and Sinnott, R. (2022). CHEMICAL ENGINEERING DESIGN PRINCIPLES, PRACTICE AND ECONOMICS OF PLANT AND PROCESS DESIGN THIRD EDITION. [online] Available at: https://elmoukrie.com/wp-content/uploads/2022/06/chemical-engineering-design-principles-practice-and-economics-of-plant-and-process-design-gavin-towler-ray-sinnott-3edition.pdf.

Wang, Q., Liu, F. and Li, C. (2013). An integrated method for assessing the energy efficiency of machining workshop. Journal of Cleaner Production, 52, pp.122–133. doi:https://doi.org/10.1016/j.jclepro.2013.03.020.

Winkelnkemper, T. and Schembecker, G. (2010). Purification performance index and separation cost indicator for experimentally based systematic downstream process development. Separation and Purification Technology, 72(1), pp.34–39. doi: https://doi.org/10.1016/j.seppur.2009.12.025.

www.oee.com. (n.d.). Calculate OEE – Definitions, Formulas, and Examples | OEE. [online] Available at: https://www.oee.com/calculating-oee/ [Accessed Jan. 2026].

Zimmerman, A., Wunderlich, J., Buchner, G., Müller, L., Armstrong, K., Michailos, S., Marxen, A., Naims, H., Mason, F., Stokes, G., & Williams, E. (2018). Techno-Economic Assessment & Life-Cycle Assessment Guidelines for CO2 Utilization. Doi: https://doi.org/10.3998/2027.42/145436

Zimmermann, A.W., Wunderlich, J., Müller, L., Buchner, G.A., Marxen, A., Michailos, S., Armstrong, K., Naims, H., McCord, S., Styring, P., Sick, V. and Schomäcker, R. (2020). Techno-Economic Assessment Guidelines for CO2 Utilization. *Frontiers in Energy Research*, 8. doi: https://doi.org/10.3389/fenrg.2020.00005