Towards a Structured Framework for Techno-Economic Analyses of Chemical Recycling Technologies

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The role of chemical recycling (CR) as a valuable complementary strategy to mechanical recycling in closing the carbon cycle for carbon-containing waste is currently being discussed in political, economic, and social spheres. However, CR deployment is hindered by uncertainties regarding its environmental impacts and costs compared to conventional waste treatment and chemical production routes. While methods for assessing CR's environmental impacts are the focus of socio-political debates and investigations, techno-economic analyses (TEA) to evaluate costs of CR remain scarce. To contribute to a standardized framework for assessing the economic viability of CR technologies, this article draws on life cycle assessment and TEA literature to develop a six-stage TEA process for CR. A checklist is also presented to support transparent and comprehensive analyses.

Keywords: Chemical recycling, Costs, Indicators, Techno-economic analysis, Waste

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1 Introduction

Chemical recycling (CR) is generally used to describe a range of technologies from solvent-based purification, depolymerization, liquefaction to gasification [1, 2]. In enabling the conversion of carbon-containing waste into valuable base chemicals, which can subsequently be used as feedstock for the chemical industry, CR could complement conventional mechanical recycling techniques. It enables the recirculation of non-recyclable carbon-containing waste back into the production cycle [3–6], thereby contributing to sustainability by closing the carbon cycle for carbon-containing waste.

However, the deployment of CR projects is hindered by uncertainties regarding their environmental impacts as well as costs compared to conventional waste treatment and chemical production routes [6–8]. To address the former, the contribution of methodologies such as life cycle assessment (LCA) and the mass-balance approach to enable a determination of the environmental impacts associated with CR are being heavily debated in the socio-political spheres [9–15], as well as being the focus of numerous scientific investigations [1, 16]. In contrast, techno-economic analyses (TEA) to evaluate the costs of CR remain underrepresented in extant literature.

TEA represents an integrated evaluation methodology that combines technological and economic aspects to analyze the feasibility, cost-effectiveness, and sustainability of an industrial process, product, or service [17, 18]. The technical component involves evaluating the technical performance, including the generation of process design and input/output data. The economic component builds upon these data to assess financial characteristics, such as economic profitability and risks. Conventional TEA indicators are represented by the total capital investment or the net present value [17]. However, as environmental considerations and carbon taxes gain importance for industrial decision-makers, integrated indicators like carbon abatement costs are incorporated into the realm of TEA [3, 19–21].

Extant applications of TEA in the context of CR deployment exhibit substantial ambiguities in their methodological choices and reporting standards (cf. Sect. 2). Unlike LCA where ISO standards are available to guide evaluations of environmental impacts, TEA studies of CR technologies are generally not conducted according to standardized and proven guidelines. As a result, the application of varying numbers and types of indicators generated according to differing methodologies have led to diverging conclusions

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regarding the economic feasibility of CR technologies and the conditions necessary for a business case. Moreover, heterogeneity in the reporting focus and structure of TEA reports hinder the comparability and easy interpretation of TEA results for the readers, emphasizing the need to minimize such heterogeneity whenever feasible [1, 5].

To contribute to a standardized framework for assessing the economic viability of CR technologies from a process-based perspective (i.e., single process plant), this article draws on the four phases of LCA processes as indicated in the ISO standards [22, 23] and also on TEA literature [1, 17, 18] to propose a six-stage TEA process for CR. Specifically, the contribution of this research is to build and expand on the ideas and basic structure presented by Keller et al. [1], with the central aim of providing a comprehensive yet concise guideline to facilitate future economic assessments of CR and similar processes. In the following paragraphs, after a brief introduction of CR technologies and their integration into the conventional waste treatment and chemical production pathways as the context for TEA application, the proposed six-stage TEA process is described and discussed in detail. The article concludes with a checklist, which is developed to support TEA in the CR context.

2 State of the Art

The standardization of research methods promotes reproducibility, comparability, efficiency, and quality control in scientific investigations, ultimately enhancing the rigor and impact of empirical studies [24, 25]. However, the existing literature on TEA applications for chemical recycling technologies reveals a limited degree of standardization, as indicated by Tab. 1. Specifically, the applied TEA indicators

Table 1. Overview of TEA investigations on CR [1].

Year, Source	Waste fraction	CR Technology	Data sources		Main product substitution	Ref. waste treatment	Applied TEA indicators	Result type
			Process inventory	Market inventory				
2022 [19]	LWP	Gasification	Modeling	Literature (CRP)	Olefins	TT and MBT	TCI, NPV, PP, CAC	Comparative plant profit
2021 [26]	PET	Depolymerization	Modeling	Literature (CRP)	TA	NBT	MSP, TCI, OC	Absolute product MSP
2021 [27]	PE	Depolymerization	Modeling	Literature (CRP)	Olefins, benzene	TT & landfilling	PC	Absolute PC
2021 [30]	MSW	Gasification	Experimental	Literature (CRP)	Electricity/hydrogen	NBT	TCI, NPV, IRR, PP	Absolute plant profit
2021 [61]	LWP	Gasification	Modeling	Literature (CRP)	Hydrogen	NBT	TCI, OC, EP, MSP	Absolute MSP and plant profitability
2021 [28]	MSW	Pyrolysis	Experimental and modeling	Literature (CRP)	Pyrolysis oil	NBT	TCI, PC	Absolute PC
2021 [31]	LWP	Pyrolysis/depolymerization	Literature	Literature, quality losses considered	Virgin plastics	MR	PC	Comparative PC
2021 [3]	rMSW	Gasification	Modeling	Literature (CRP)	Olefins	TT & MBT	TCI, NPV, PP, CAC	Comparative plant profit
2020 [29]	LWP	Pyrolysis	Industry	Literature (CRP)	Naphtha	NBT	NPV, IRR, PP	Absolute plant profit
2020 [62]	Plastic	Pyrolysis	Modeling	Modeling	Olefins	NBT	Unit NPV	Process optimization
2018 [63]	Plastic	Pyrolysis	Modeling	Modeling	Pyrolysis oil	NBT	ACC, NPV, PO	Absolute plant profit
2016 [64]	PET	Depolymerization	Experimental	Literature (CRP)	Polyester	NBT	BE point	Absolute plant profit
2011 [65]	Tires	Pyrolysis	Experimental	Literature (CRP)	Pyrolysis oil	NBT	ACC, PC	Absolute PC
1998 [66]	Plastic	Pyrolysis	Literature	Literature (CRP)	Pyrolysis oil	NBT	TCI, TPC, ROI	Absolute plant profit

focus on different dimensions of economic criteria, making direct comparisons challenging. For instance, various studies examine the total cost of a product by considering different factors, such as total production costs or the minimum selling price [26–28]. Other studies concentrate more on the profitability of a production plant investment by calculating indicators like the net present value or the internal rate of return [3, 29, 30]. Additionally, even among studies that use the same focus, the individual inclusion or exclusion of specific cost positions leads to disparate results. While some research approaches employ comprehensive calculation frameworks that incorporate detailed labor requirement or risk estimations [28], others rely on simplified calculation schemes that are suitable for comparative assessments within a study but not for inter-study comparisons [31]. Furthermore, in addition to the variability in calculation schemes for indicators, there is a lack of provision and reporting of primary and secondary data in the field [29]. To address these irregularities and associated challenges, a sophisticated framework is required to enhance the impact of research on the economic profitability of CR.

3 Integration of CR in Conventional Waste Treatment and Chemical Production Systems

Generally, CR can be classified under four technological routes, namely solvent-based purification, depolymerization, liquefaction, and gasification, which, inter alia, differ in terms of their main recycling products [1, 32–37]:

- *Solvent-based purification* includes processes that recover high purity polymers for direct reintegration in the plastic production process without a polymerization step. It can be carried out through selective dissolution or recovery using either vaporization or precipitation. These processes take place at a temperature range of 90–280 °C and target waste fractions with high content of the targeted soluble plastic type. Note that as solvent-based purification is primarily a physical solution its declaration as CR is debatable.
- *Depolymerization* includes processes that involve the cleavage of chemical bonds within polymer structures to produce smaller units or monomers as feedstock for conventional polymerization of virgin-grade polymers. It can be carried out through the application of solvents (i.e., solvent-based depolymerization), catalysts (i.e., catalytic depolymerization), or using thermal processes (i.e., thermal depolymerization). Depolymerization processes take place at temperatures between 80–280 °C and are primarily applicable for condensation and addition polymers especially polyethylene terephthalate (PET), polyurethane (PU), polyamide (PA), and polystyrene (PS).
- *Liquefaction* includes processes that produce a liquid hydrocarbon mixture directly from the waste feedstock, which can be subsequently processed to steam cracker feedstock, and/or for the recovery of BTEX aromatics. The conversion generally takes place at temperatures between 350–600 °C. Applicable plastic-containing waste for different liquefaction concepts differ with relevant parameters being fractions of standard packaging polymers (especially polyethylene/PE and polypropylene/PP), other plastic fractions (especially PET and polyvinylchloride/PVC), non-plastic combustible fractions (especially organics) and inert fractions (especially metals).
- *Gasification* includes processes that produce a synthesis gas (i.e., syngas) with carbon monoxide and hydrogen as the main components. These gases can be utilized individually or as intermediates for the production of plastics or other chemicals/fuels (e.g., methanol, olefins, ammonia). Gasification processes range from fixed-bed, fluidized-bed, entrained-flow processes, to a mixture/combination. Heat supply can be autothermal, allothermal (including plasma), or a mixture/combination, and conversion occurs at temperatures between 1000–1600 °C. Besides plastics and non-plastic fractions, gasification is also suitable for mixed waste fractions, i.e., unsorted and/or contaminated waste fractions, plastic waste residues from mechanical recovery, and other challenging waste fractions (e.g., pretreated municipal solid waste, shredder fractions, carbon- and glass-fiber composites, sewage sludges, agricultural waste).

In view of their applicability for different carbon-containing waste, the four CR routes are integrated differently in the conventional waste treatment and chemical production value chains. These value chains depicted in Fig. 1 are crucial as a reference for comparative TEA, as further discussed in Sect. 4.3. Note that the conventional waste treatment system presented in Fig. 1 is based on the German context. Its applicability to other countries – especially those where waste separation, collection, and recycling are not implemented – is therefore limited.

4 Six-stage TEA Process for CR Technologies

The framework presented encompasses six distinct stages (i.e., technology characterization, waste feedstock characterization, goal and scope definition, indicator selection, inventory development, and indicator calculation, adjustment and interpretation) that are sequentially executed and described in detail below.

4.1 Technology Characterization

The characterization of the investigated CR technology acts as an orientation for subsequent assessment steps. In this first stage, four technical dimensions are recommended for consideration:

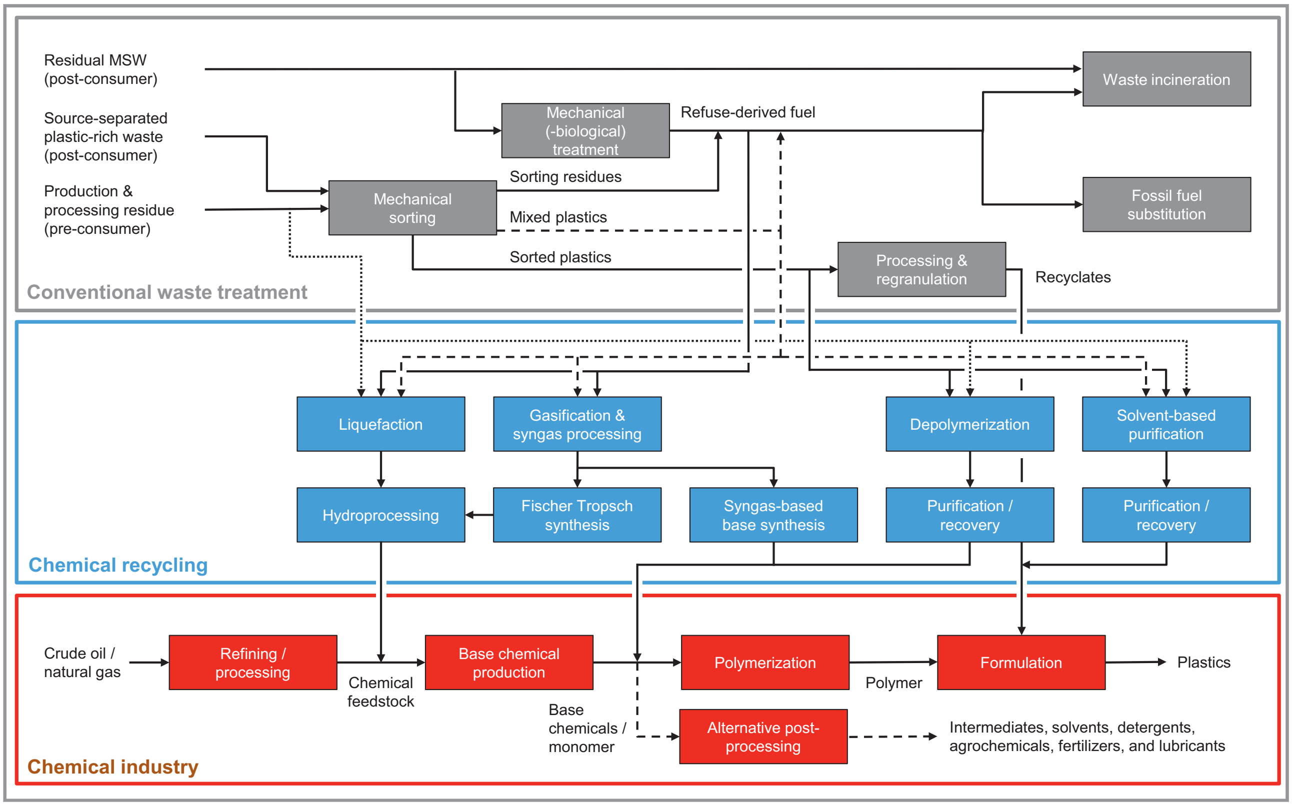

Figure 1. Integration of CR into conventional waste treatment and chemical production value chains based on Keller et al. [1].

1) *Fundamental process description*: A detailed description of all individual process steps, including all important technical parameters is recommended [18]. This can be complemented with technical drawings (i.e., process flow diagrams, block flow diagrams, and piping/installation diagrams) and mass/energy balances to increase the clarity of the descriptions and understanding of the functionality of the CR technology by the intended audience. In addition to defining the range of applicable waste feedstock including potentially necessary pretreatment steps, a discussion of realized applications is also recommended (i.e., realized plants in industry and research). Please note that detailed documentation of systematic frameworks for process development, such as the engineering design process, can provide a valuable source of data and information for process descriptions and system boundary definitions in TEA for CR.
2) *Assignment to one of the four main CR technological routes*: This will support a systematic and structured approach to understanding and analyzing the CR process and its characteristics, such as temperatures, required process agents, and suitable feedstock. Additionally, it will facilitate communication and information sharing among researchers, practitioners, and stakeholders, providing a clear reference point for accessing relevant knowledge, research findings, and resources related to the technology. Moreover, it enables comparative assessments with other CR processes, even for study recipients with limited technical knowledge. A consideration of the robustness against feedstock heterogeneity and an analysis of the CR product spectrum is also recommended to support the classification process and to ensure its reliability.
3) *Integrability in existing chemical production and waste treatment systems*: This supports the determination of opportunities and challenges for the integration in existing production and waste treatment value chains, including required interface technologies for pre-treatment of waste feedstock as well as post-processing/refining of CR products and by-products. In cases where reduced CR product quality prevents direct substitution of conventional chemical products/intermediates, potential post-processing/refining steps to improve product quality should be considered. In cases where reduced CR product quality is accepted despite lower substitution rates (e.g., pyrolysis oil replaces small amounts of naphtha in a conventional steam cracking process), sensitivity analysis of substitution rates is recommended.
4) *Classification of technological maturity*: The technological maturity of CR routes differs. While solvent-based processes are mostly at laboratory scale, liquefaction and gasification systems are at pilot, demonstration, and/or commercialized scales [38–42]. This difference in technological maturity has implications on data

availability and TEA design [17, 18], and is thus a critical step in the characterization of CR technologies. Specifically, the classification of technological maturity not only supports the choice of economic indicators and the design of corresponding calculation methods, but also provides indications whether study aims are reasonable, which are targeted audience groups, and how the TEA study should be reported [17]. A widely applied concept for the classification of the technological maturity is the technology readiness level (TRL). Drawing on [17, 18, 43, 44], nine TRLs are summarized in Tab. 2, including corresponding data availability and TRL-specific study aims and audience groups. An example of TRL utilization in the CR context is provided by Solis & Silveira [45] for eight individual cases.

4.2 Waste Feedstock Characterization

The detailed characterization of the considered waste feedstock is a prerequisite for subsequent TEA steps. Three aspects are recommended for consideration:

Table 2. Technology readiness levels (TRL) [17, 18, 43, 44].

No.	Notation	Description	TRL-specific study aims (SA) and audience groups (AG)	Data availability	Accuracy intervals for investment estimation
1	Idea generation	Includes the identification, analysis, and definition of potential fields of application (e.g., waste fractions)	SA: Identification of meaningful and effective application cases; evaluation of technological improvements; R&D funding; decision support AG: Academics, funding institutions, industry representatives	Qualitative expert data	Order of magnitude estimates based on data from similar processes (±30–50 %)
2	Concept generation	Covers patent research to differentiate the chemical recycling technology under consideration from existing technologies		Basic mass balances	
3	Proof of concept	Proves the basic technical functionality of the concept using laboratory studies that test, i.a., all involved chemical processes		Capital expenditures	Preliminary estimates based on limited process design details (±30 %)
4	Preliminary process development	Includes the development of computerized models based on insights gained from the laboratory studies	SA: Comparative evaluations with conventional treatment concepts; decision support for regulatory incentives; decision support for investments into pilot/demonstration plants AG: Academics, industry representatives, policymakers	Additional assumptions including, for instance, required labor hours	Definitive estimates based on accurate process design details (±10–15 %)
5	Detailed process development	Covers the further development of process simulations to design a working pilot plant			Detailed estimates based on completed process design and firm quotes for equipment (±5–10 %)
6	Pilot plant trials	Includes the construction and testing of a pilot plant based on the developed process models		Pilot plant validation data	Check estimates based on actual engineering experience (±5–10 %)
7	Demonstration plant trials & full-scale engineering	Involves the construction of a demonstration plant based on insights and data obtained from the pilot plant trials	SA: Assessment of options for technology improvements; decision support for investments into full-scale commercial plants; assessments of sustainability impacts associated with systemic technology diffusion AG: Industry representatives, the general public	Demonstration plant validation data	
8	Construction and start-up of a commercial plant	Includes the construction of a full-scale commercial plant and its integration into extant production chains at the plant site		Full-scale commercial plant validation data	
9	Continuous operation of a commercial plant	Covers the testing of the full-scale commercial plant for a variety of operation conditions			
9+	Technology diffusion and learning	Generates additional insights and improvements to the technology via diffusion and application at various sites			

- *Waste origin*: This is closely connected to the geographical scope of the study and supports decisions about reference waste treatment processes and reference chemical production processes for benchmarking.
- *Waste quantity*: This is closely linked to the definition of the functional unit (i.e., the quantitative performance of the investigated CR system) and assumptions regarding the dimensioning of a CR plant that can substantially impact its profitability [3, 19].
- *Waste characteristics*: A comprehensive and structured analysis of material and fuel characteristics facilitates the traceability of the TEA, in addition to delivering valuable data for potential computerized process modeling in the inventory development stage. Relevant material characteristics include fractional composition (e.g., plastics, organics, metals, problematic compounds, additive contamination) and elementary composition (e.g., carbon content, fossil carbon content, water content). Fuel characteristics include the lower calorific value and compactness of considered waste fraction. Note that a significant difficulty in waste characterization originates from the impact of consumer behavior, which varies by region and time. This variability may also affect the expected product yields over the lifetime of the plant.

4.3 Goal and Scope Definition

The goal and scope definition stage defines all important framework conditions that will have a significant impact on the TEA results and how they should be interpreted. Drawing on accepted standards for LCA [22, 23], this stage is recommended to include definitions of the following:

- *Study aims*: These enable effective and efficient conduct of the entire analysis as they specify the central purpose for the analysis and research questions which are addressed (i.e., informative value) [17, 18]. Study aims are closely linked to the TRL [18]. Tab. 2 provides recommendations for defining study objectives based on the TRL.
- *Intended audience*: Differing audience groups will have different background knowledge and therefore different needs for the documentation and reporting of the TEA results. As displayed in Tab. 2, the TRL can support the identification of audience groups for the assessment and correspondingly the design of the reporting [18].
- *Geographical scope*: The geographical (or spatial) scope narrows the geographical region where the CR system is assumed to be realized [46]. It determines the availability and form of data including sources for market prices of supplies and plant equipment. As data can vary significantly between world regions, countries, and even regions within a country, the geographic scope of the analysis should be clearly defined. This will also ease the transference of TEA results and insights for CR implementation in different geographical locations.
- *Temporal scope*: This refers to the time horizon in which the TEA including its generated insights are valid [46]. Two factors are relevant in defining the temporal scope in the CR context. First, many CR concepts are still at low TRL with significant improvement potential in the near future [45]. Second, data for TEA (e.g., market prices for equipment, supplies, or products) are subjected to fluctuations and should thus be updated regularly. The temporal scope for CR investigations is therefore recommended to be kept at a reasonable and rather short range.
- *Functional unit*: This defines the waste volume that can be processed annually by the CR system under investigation (i.e., single plant or a system of plants) and thus influences the basic assumptions regarding plant scaling. While a generous scaling usually leads to reduced costs due to cost efficiency effects, the maximum CR system size could be limited by waste feedstock availability in a region. Technical limitations associated with different CR processes also play an important role. Hence, waste availability for the geographical region under consideration (i.e., geographical scope) and individual process characteristics should be considered when determining the functional unit.
- *System boundaries*: A clear definition of the CR system boundaries improves traceability and comparability of TEA results. As indicated in Sect. 4.1, process steps can include the pretreatment of waste feedstock or the upgrading of CR products. As these could be associated with significant capital costs, their consideration (or lack thereof) will strongly influence TEA results [47].
- *Benchmark system*: "Mono-technological" TEA with absolute results (i.e., the technology is profitable/feasible) are associated with significant uncertainties due to diverse factors including strongly fluctuating energy/resource prices over time/space. Relative results and conclusions (i.e., technology A is more profitable/feasible than reference technology B) from comparative assessments are often considered more reliable and offer additional advantages, such as providing increased decision-making benefits [1, 18]. As CR technologies serve two purposes, i.e., waste disposal and production of basic chemical feedstock, the selection of a suitable reference technology is a major challenge. Depending on factors such as systemic framework conditions, data availability, or indicator choice, either a conventional (or best available technique) waste treatment or chemical production plant/system or a combination of both should be taken as reference. Whereby the choice of a reference waste treatment technology mostly depends on the addressed waste feedstock and geographical scope, the choice of a reference chemical plant mainly depends on the main CR products. Please note that in comparative assessments, differing TRL levels can create data asymmetries that compromise result quality. To address this, thorough analysis and discussion of these asymmetries is necessary. Additionally, during the indicator selection phase, emphasis should be placed on the technology with the

lower TRL to ensure all data needs in the indicator calculation stage can be fulfilled.

4.4 Indicator Selection

Techno-economic indicators objectify the economic benefits of a technology/concept and have different complexity levels [17]. They can be classified as basic qualitative indicators (Level 1), indicators that do not consider capital costs (Level 2), capital cost indicators (Level 3), comprehensive profitability indicators (Level 4), and multidimensional indicators (Level 5). TRL are closely linked to data availability (see Tab. 2). In the following, the five levels of economic indications are discussed using examples, among others, from Buchner [17]:

Level 1 – Basic Qualitative Indicators
At initial TRL (i.e., 1–2) where basic quantitative data such as detailed mass/energy balances are typically not available [17], multi-criteria decision analysis (MCDA) can capitalize on available expert knowledge to evaluate a CR technology against a reference technology [48]. Following the identification of important characteristics as the basis of evaluation (e.g., feedstock availability, estimated investments, or potential use of the recycled products), experts/stakeholders are interviewed to quantify and weigh them. Weighted scores for CR and conventional technologies can then be determined using Eq. (1). Please note that the classification of MCDA results as TEA indicators is a matter of debate. However, they are regarded as such here because they can aid in integrating economic characteristics into the early phase of technology development, laying the groundwork for all subsequent stages.

$$\text{Aggregated score} = \sum_{items} \text{single score} \times \text{weight} \tag{1}$$

Level 2 – Indicators That Do Not Consider Capital Costs
Once basic mass/energy balances are available (i.e., TRL 2–3), the relative gross profit (RGP) can be used to enable initial rough estimates of operational profitability by relating revenues via obtained gate fees or CR product sales to material and energy costs (see Eq. (2)) [17]. As a normalized measure, RGP cannot support absolute statements about a CR plant. Rather, it enables rough comparative evaluations of the operational profitability of CR against conventional treatment/production techniques. Note that RGP excludes distinctly important cost factors such as capital or labor costs. Hence, if the CR technology is expected to deviate strongly from conventional technologies in these aspects, the application of RGP should be accompanied by comprehensive analysis and discussion of potential deviations. In general, there are significant uncertainties associated with using indicators at early stages of technology development for decision-making, as there is still insufficient data to reliably calculate a TEA.

$$RGP = \frac{\text{revenues} - \text{material and energy costs}}{\text{material and energy costs}} \tag{2}$$

Level 3 – Capital Cost Indicators
The total capital investments include all costs associated with the construction and commissioning of a CR plant [47]. The assessment can be based on data obtained from similar processes, engineering, or engineering experience from existing plants, with increasing certainty (refer to Tab. 2 for accuracy estimations for different data sources based on [49]). A detailed analysis is typically conducted at TRL 3–4 when process flow diagrams, block flow diagrams, piping/installation plans, and equipment lists for the most relevant plant equipment (e.g., reactor vessels, heat exchangers, filters, pumps, electric installations, conveyor belts) are available. Based on Peters et al. [47], investment appraisals include adjustments of price data for equipment extracted from literature or obtained from plant equipment manufacturers.

For scaling adjustments, an established approach is the application of a power factor to the capacity ratio, with a degression coefficient to account for economies-of-scale (see Eq. (3)). Subsequently, markup factors can be used to incorporate additional direct costs (e.g., instrumentation and controls, piping, property costs) or indirect costs (e.g., engineering and supervision, legal expenses), as discussed by Peters et al. [47]. Finally, it is necessary to estimate and include working capital (e.g., costs of raw materials carried in stock, cash kept on hand for operating expenses). Note that capital costs can also be combined with RGP for a first profitability assessment using the relative profit indicator as described by Buchner et al. [17]. This approach can also incorporate more advanced methods to consider operational process costs, which leverage additional available data compared to Level 2.

$$TCI = \left(\sum \text{equipment price} \left(\frac{cap_{plant}}{cap_{ref}} \right)^{\text{degression coef}} \right) \text{markups} + \text{working capital} \tag{3}$$

Level 4 – Comprehensive Profitability Indicators
A consideration of the time value of money (i.e., interest) in the determination of economic profitability can support decisions for investment/project deployment [17]. One widely utilized indicator is the net present value (NPV), which is the sum of all discounted cash flows over the lifetime of a project or technology (see Eq. (4)) [17]. Cash flows include all expenses and incomes that trigger a monetary transaction (e.g., initial investment at the beginning of the construction period, replacement investment, supply costs, labor costs, or the revenues generated from gate fees or products). As the NPV requires an extensive dataset including reliable estimates for capital expenditures, supply needs, and additional costs such as labor or insurances costs, it is typically applied at TRL 4 and higher. Suggestions on types of cash flows to include and methods for inclusion are provided in Peters et al. [47]. Besides NPV, another

indicator that considers interest is the dynamic payback period [1].

$$NPV = \sum_{\text{project years}} \frac{(\text{revenues} - \text{operational costs} - \text{capital costs})_{\text{current year}}}{(1 + \text{dicount rate})^{\text{current year}}} \tag{4}$$

Level 5 – Multi-Dimensional Indicators
At high TRL (i.e., TRL 5 and above), increased data availability can support multi-dimensional assessments where, e.g., both economic and environmental impacts associated with a CR technology can be evaluated. One example is the levelized costs of carbon abatement (LCCA), defined by Eq. (5) as the total costs associated with reducing a certain amount of climate-effective carbon emissions over the lifetime of a project or technology [50]. This requires detailed economic and environmental data for both the CR technology and the conventional reference technology (i.e., status quo) to calculate annual deviations in costs (i.e., operational and capital costs reduced by revenues) and emissions.

$$LCCA = \frac{\sum_{\text{project years}} \frac{\text{cost deviation}}{(1 + \text{dicount rate})^{\text{current year}}}}{\sum_{\text{project years}} \text{emission deviation}} \tag{5}$$

4.5 Inventory Development

Following the selection of suitable economic indicators, required inventory data for indicator calculation is gathered in this stage. As illustrated in Fig. 2, two types of data can be distinguished namely process and market data [18].

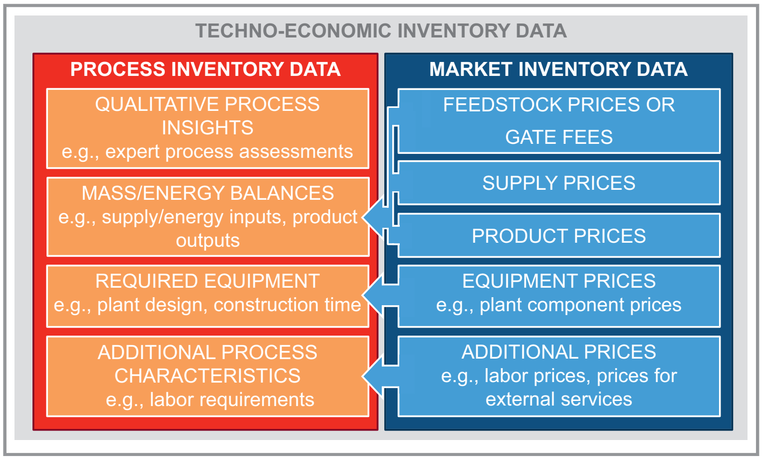

Figure 2. Individual components of techno-economic inventories.

4.5.1 Process Inventory Development

Qualitative data
At low TRL where little is known about the CR process, initial assessments depend on educated evaluations by experts along key criteria (e.g., robustness of the technology against feedstock heterogeneity and impurities) to determine the applicability and profitability of the considered technology.

Mass and energy balances
This comprises all relevant inputs and outputs for a CR process in a concise and transparent tabular form [1]. The former mainly includes waste feedstock and supply inputs while the latter includes product and by-product outputs. At lower TRL, mass and energy balances can be derived from the basic reaction enthalpies and stoichiometries of underlying chemical processes using manual calculations or computerized process modeling [17, 43, 51]. At higher TRL, they can be generated using operating experience from pilot/demonstration/commercial plants. When preparing the balances, special attention must be paid to the use of catalysts and solvents as these account for a high proportion of total expenses in chemical processes [47]. Note that reliable mass and energy balances are also important pillars for LCA of CR technologies. There is thus a high synergy potential and LCA can provide a rich data source if techno-economic data quality demands are met.

Engineering Documentation
This gathers all information on required equipment for a CR plant, including information on the exact configuration and scaling of all plant components [1]. These can be derived from mass flow diagrams and technical drawings that are generated in the technology characterization stage whereby orientation for plant scaling is provided in the goal and scope definition stage.

Additional Process Characteristics
These characteristics encompass pertinent process attributes beyond feedstock utilization, supply utilization, product, and by-product output, and equipment requirements that are directly (i.e., manufacturing costs) or indirectly (i.e., general expenses) connected to the operation of a CR plant [47]. As presented in Tab. 3, characteristics may include labor requirements, maintenance and repair requirements, or health and safety risks associated with plant operations. Corresponding attributes are combined with market prices or assumptions in the inventory to generate estimates regarding labor costs, maintenance and repair costs, or insurance expenses, for instance.

Table 3. Additional plant characteristics based on Peters et al. [47].

No.	Category	Characteristic	Indications for data generation	Rough annual cost estimations
1	Manufacturing characteristics	Operating labor requirements	Equipment specifications; plant output; reference plants	–
2		Operating supervision requirements	Operating labor requirements	15 % of operating labor costs
3		Maintenance and repairs	Equipment and building properties	11 % of equipment costs + 3.5 % of building costs
4		Operating supplies	Equipment properties	15 % of maintenance and repair costs
5		Laboratory charges	Labor requirements for quality control	15 % of the operating labor
6		Patents and royalties	Patent positions in question	–
7		Depreciation	Types and costs of used equipment, and regional regulations	–
8		Financing	Equity ratio	–
9		Local taxes	Regional regulations	2 % of the fixed capital investments
10		Property insurances	Process type and available protection facilities	1 % of the fixed capital investments
11		Rent	Value of rented property	10 % of the value of rented property
12		Overheads	Manufacturing process and its scale	60 % of the aggregated costs for operating labor, operating supervision, and maintenance and repairs
13	General characteristics	Administration	Salaries and wages for administrators, secretaries, accountants, etc.	20 % of the operating labor
		Distribution and marketing	Recycling product characteristics	–
		Research and development	Salaries and wages for research and development personnel	–

4.5.2 Market Inventory Development

In contrast to the process inventory, the market inventory is highly flexible and closely connected to the current economic framework conditions. Therefore, it should be carefully aligned with the geographical and temporal scopes defined in the goal and scope definition stage.

Feedstock Prices

Depending on its quality, homogeneity, and the general market demand, a feedstock can achieve positive or negative prices on the market [52, 53]. For example, pure plastic streams from lightweight packaging sorted from material recovery facilities are usually sold as secondary raw materials at increased prices [53]. In contrast, heterogeneous carbon waste feedstock with reduced qualities can usually obtain a waste treatment gate fee [54]. While numerous references for waste treatment price conditions in different countries are provided in the literature (e.g., Neuwahl et al. [54], Cimpan et al. [53]), an individual price analysis – e.g., market research via expert interviews – for the geographic region under consideration is recommended to account for fluctuations across time and space [55].

Supply Prices

The market inventory also includes prices for process supplies such as energy prices, prices for basic raw materials, and catalysts. Of these, energy price data is easily obtainable, e.g., from EU publications of energy prices for EU member states. Data for basic raw materials is available in the European PRODCOM and the UN COMTRADE databases, with detailed physical and monetary trade statistics for numerous countries worldwide that can be used for price estimations. Additionally, Zimmermann et al. [18] list a number of online price data sources that can be used for rough initial price estimations at lower TRLs. These include, e.g., the online marketplace Alibaba with a focus on the Asian market, but also commercial price information services such as ICIAS or ICS Market with a global focus. Finally, expert interviews are an efficient way to obtain additional price information.

Product Prices

Price assumptions for CR products are challenging. Though they have the same qualities as conventional chemical products, it is uncertain whether the market may be willing to pay a price premium for them. To arrive at plausible assumptions for CR products, the benchmarking approach described by Buchner et al. [17] is recommended. This consists of three steps namely benchmark product identification, benchmark product price analysis, and market trade value calculation. First, all conventionally produced benchmark product alternatives are identified. Second, price assessments for these alternatives are conducted, e.g., using UN COMTRADE. Third, an average price level for the conventional product alternatives and a surcharge factor to account for the sustainability value of recycled products – to be determined using market research and expert interviews – is set. Note that if no surcharge factor can be determined, the conservative assumption is that CR and conventional products achieve the same prices on the market.

Equipment Prices
Prices of individual CR plant equipment items can be found in textbooks, governmental reports, scientific papers, or in reports released by operating companies. Textbooks that include explicit equipment price information include Couper [56], Sinnot & Towler [49], Turton et al. [57], and Peters et al. [47]. Depending on the timeliness of the data and geographic origin, adjustments may be necessary. Price indices such as the Chemical Engineering Plant Cost Index (CEPCI) are recommended to be applied for temporal price adjustments [58]. Additionally, geographical price deviations can be considered using a location factor approach as described by Sinnot & Towler [49]. Any data gaps for custom-made equipment can then be estimated using expert knowledge.

Additional Prices
Additional price information is gathered from various sources to evaluate additional cost components associated with the process characteristics outlined in Tab. 3. For example, labor prices, which are combined with labor requirements to calculate labor costs, can often be obtained from governmental reports, utilizing data on average annual salaries for different professional groups. Corresponding data for countries within the European Union are publicly available in EUROSTAT statistics [59]. Expert interviews can be conducted to acquire pricing information for other items such as insurance prices or local tax rates. If detailed price information is unavailable, Tab. 3 provides a summarized list of suggestions for initial estimations of individual cost components based on Peters et al. [47]. However, at later stages of technology development (i.e., higher TRL), such rough estimates should be replaced by detailed cost calculations based on initial experiences gained from cost records of operating facilities.

Please note that the presented data sources refer to past or current prices. To enhance the quality of assessment results, future prices or product market volumes can be estimated using techniques such as linear regression analysis, estimations based on macroeconomic figures (e.g., gross domestic product forecasts, population development), or expert forecasts [49, 60].

4.6 Indicator Calculation, Adjustment, and Interpretation

In this last TEA stage, indicators chosen in Sect. 4.4. are calculated using process and market inventory data gathered in Sect. 4.5. using appropriate computerized models and tools. Additionally, indicators are normalized, weighted, and aggregated to facilitate their interpretation against the backdrop of defined study aims in Sect. 4.3. Finally, sensitivity and scenario analyses are recommended to address uncertainties whereas validity checks can increase the audience's confidence in the applicability of the TEA results.

Normalization
Normalization approaches support the conversion of multiple TEA indicator results with different units into comparable measures without units [18]. An example is the expression of results as a proportion of a target value or value achieved by a reference case (i.e., achieved value divided by the optimum or target value). Additionally, normalization facilitates meta-assessments of results from different studies.

Weighting
Aggregating multiple indicator results to a single score can contribute to resolving potential inconsistencies and contradictions in different indicator results and support the ease of comparative technology comparisons [18]. As different indicators may have different relevance/importance, a weighting step is recommended before aggregation. Suitable weights can be determined using expert/stakeholder surveys/interviews.

Uncertainties
Uncertainties can refer to the process itself or systemic framework conditions. To evaluate uncertain data and assess their impacts, sensitivity analysis (i.e., variation of individual parameters) to assess uncertainty with regards to individual technical assumptions (e.g., energy/product yield efficiencies, energy consumption) and scenario analysis (i.e., variation of parameter sets) to assess uncertainties regarding systemic assumptions including changes in reference energy systems or regulatory frameworks are recommended [17].

Validity Checks
TEA results can be validated against data from technology providers. This however is often limited as CR is an emerging concept and/or for confidentiality reasons. To check the plausibility of TEA results, a validation of central cost positions by experts in the field is therefore recommended. Independent critical reviews can help to identify mistakes and incorrect assumptions in the analysis. The inclusion of at least one expert reviewer with a background in the field of chemical engineering to check the validity of applied process balances [18] as well as at least one expert with background knowledge in the waste treatment and chemical

production systems in which the CR technology is to be implemented is therefore recommended. The validity check can be designed as an iterative process, comparable to the peer review process in scientific journals. A TEA checklist to ensure that key aspects of the analysis have been considered sufficiently is proposed in Fig. 3.

5 Documentation and Reporting

A complete and accurate documentation of the TEA study is paramount as the precise documentation and reporting of all analysis stages, all applied data, the key assumptions, and the used methods can facilitate understanding, avoid

No.	Process Steps	Yes	No	N.A.
Technology characterization				
1	A basic process description is included			
2	The technology is assigned to a process technical principle			
3	The integrability of the technology into extant systems is discussed			
4	The technical maturity is assessed			
Waste feedstock characterization				
5	The waste origin and quantity are defined			
6	The central material and fuel characteristics are analyzed			
Goal and scope definition				
7	The study aims are defined			
8	The intended audience is specified according to the TRL			
9	The geographical scope (e.g., region or country) is set			
10	The temporal scope (i.e., temporal validity of results) is set			
11	The functional unit is defined			
12	The system boundaries are defined and graphically visualized			
13	The benchmark system is defined			
Indicator selection				
14	The TEA indicators are selected based on the TRL and reported			
15	The TEA indicator calculation methods are selected and documented			
16	The inventory data requirements are defined			
Inventory development				
17	All required process inventory data (e.g., mass/energy balances, equipment requirements) is gathered based on the applied indicator(s)			
18	All required market inventory data (e.g., feedstock gate fees, prices for equipment/supplies/products) is gathered based on applied indicator(s)			
Indicator calculation, adjustment, and interpretation				
19	The results from multiple indicators are normalized and weighted to reduce the assessment complexity and to facilitate comparisons between individual chemical recycling technologies and/or applications			
20	Sensitivity analyses are conducted to reduce uncertainties in assessment assumptions			
21	Scenario analyses are conducted to investigate the impact of framework conditions such as governmental regulations			
22	All relevant qualitative and quantitative assessment results including implications for study aims and recommendations for study recipients are reported			
23	A validity check is conducted			
Documentation and reporting				
24	The TEA assessment report is clearly structured (e.g., according to the TEA stages)			
25	The TEA report is understandable for the intended audience			

Figure 3. Techno-economic analysis checklist based on Keller et al. [1]. TEA: Techno-economic analysis. TRL: Technology readiness level.

ambiguity, and reduce the peril of misinterpretations [18]. If confidentiality reasons hinder the full disclosure of utilized data, graphical visualization including aggregated bar plots or Sankey diagrams can be used to support result presentation without revealing process efficiencies entirely [1]. Furthermore, the language use in the report should be carefully aligned with the intended audience to ensure efficient transference of study results and insights [18].

6 Conclusion

In this article, a structured and standardized framework is proposed for assessing or reevaluating the economic viability of CR technologies. Drawing on LCA and TEA literature, a six-stage TEA process is proposed, and a checklist is developed to support transparency, comprehensiveness, and reliability of TEA in the CR context, as well as in suitable other contexts (e.g., recycling processes, waste treatment processes, or chemical production processes). Please note that detailed methods for generating inventory data for CR applications are not presented here, but can be found in the LCA literature, which utilizes similar datasets. Future research is encouraged to explore additional synergies between TEA and LCA (e.g., further development of integrated indicators, combined process simulation and assessment), and to further develop the presented framework by aligning TRL levels more closely with the recommendations for TEA practice. Despite these and other research opportunities, the presented framework facilitates the generation of consistent economic knowledge, enabling decision-makers to assess the contribution potential of CR to sustainability through closing the carbon cycle.

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Abbreviations

ACC	Annualized capital costs
BE	Break-even
CAC	Carbon abatement costs
CEPCI	Chemical Engineering Plant Cost Index
CR	Chemical recycling
CRP	Conventional reference products
ED	Energy demand
EP	Economic potential
FCI	Fixed capital investment
IRR	Internal rate of return
LCA	Life cycle assessment
LCCA	Levelized costs of carbon abatement
LWP	Lightweight packaging
MBT	Mechanical-biological treatment
MCDA	Multi-criteria decision analysis
MF	Mass flows
MR	Mechanical recycling
MSP	Minimum selling price
MSW	Municipal solid waste
NBT	No benchmark technology
NPV	Net present value
OP	Operating costs
PA	Polyamide
PE	Polyethylene
PET	Polyethylene terephthalate
PO	Pay-out
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinylchloride
RGP	Relative gross profit
ROI	Return on Investment
TA	Terephthalic acid
TCI	Total capital investment
TEA	Techno-economic analysis
TPC	Total production costs
TRL	Technology readiness level
TT	Thermal treatment.

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