



From indicators to interventions: Economic assessment of circular strategies for informed policy design

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ABSTRACT

While the circular economy (CE) is a central sustainability objective, its implementation in industrial value chains remains challenging. This calls for targeted policy interventions under fiscal and regulatory constraints. Although environmental - and to some extent social - indicators are widely used to assess circular strategies (CSs), economic assessments that capture policy and price (P&P) scenarios and inter-organizational cost dynamics remain underdeveloped. This paper introduces the Comparative Economic Assessment of Circular Economy (CEACE), a process designed to evaluate the cost-effectiveness of CSs across entire national value chains and derive policy recommendations. By quantifying and disaggregating circular life-cycle costs across actors and over time and by introducing the Circular Cost Effectiveness Index (CCEI), CEACE reveals economic “winners” and “losers” and identifies strategic leverage points for cost-effective and minimally intrusive policy interventions. Applied to the Swiss expanded polystyrene (EPS) insulation sector, the framework demonstrates how Swiss P&P scenarios are insufficient to increase the financial attractiveness of environmentally desirable CSs. This study establishes CEACE as a systematic process. It identifies cost-effective and environmentally desirable CSs. Thereby it contributes to evidence-based policy design to accelerate the transition to a sustainable CE.

1. Introduction

The Circular Economy (CE) has gained significant traction as a promising pathway toward enhanced sustainability by addressing resource depletion and mitigating environmental impacts associated with traditional linear economies (Ellen MacArthur Foundation, 2022; UNECE, 2022). CE integrates resource-focused strategies, such as reduce, reuse, and recycling (see e.g., Potting et al., 2017), within broader sustainability frameworks encompassing environmental, economic, and social dimensions. While some scholars argue that the CE has matured into a distinct and coherent research field with its own frameworks and methodologies (Geissdoerfer et al., 2017), others remain critical, emphasizing that CE's practical implementation often falls short of its theoretical promises and may obscure unresolved systemic challenges (Korhonen et al., 2018; Pauliuk, 2018). The latter statement might partially originate from the fact that the practical

implementation of circular strategies (CSs) - ranging from early 3R concepts to more systemic 10R-ladders (Potting et al., 2017) - continues to pose considerable challenges for policymakers and industry alike. Research indicates that the sustainability benefits of specific CSs are not inherently guaranteed, thus necessitating comprehensive environmental, social, and economic assessments to verify their effectiveness (Haupt and Hellweg, 2019; Blum et al., 2020; Pieroni et al., 2019).

Considerable attention has been devoted to developing sustainability indicators across micro, meso, macro¹ scales, including contributions from both academia and private actors such as the Ellen MacArthur Foundation and Circularity Gap. However, translating these indicators into actionable policy remains challenging (UNEP, 2024). Studies highlight persistent uncertainty in identifying intervention points within complex value chains, particularly under resource constraints (Pauwels et al., 2024). This highlights the need for approaches that can identify cost-effective intervention points within specific national value chains to

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¹ Micro refers to individual products or components, meso to industrial value chains or organizational networks, and macro to entire economic systems such as national or regional economies.

Table 1
R-strategies. based on Potting et al. (2017).

| Level | R-strategy | Logic |
|-------|---------------|---------------------------------------------|
| R0 | Refuse | Avoid product altogether |
| R1 | Rethink | Intensify use (sharing, multifunctionality) |
| R2 | Reduce | Increase efficiency in production/use |
| R3 | Reuse | Use product again for same purpose |
| R4 | Repair | Fix product to extend life |
| R5 | Refurbish | Restore and update |
| R6 | Remanufacture | Use parts in new product |
| R7 | Repurpose | Use product/parts for new function |
| R8 | Recycle | Reprocess materials |
| R9 | Recover | Energy recovery |

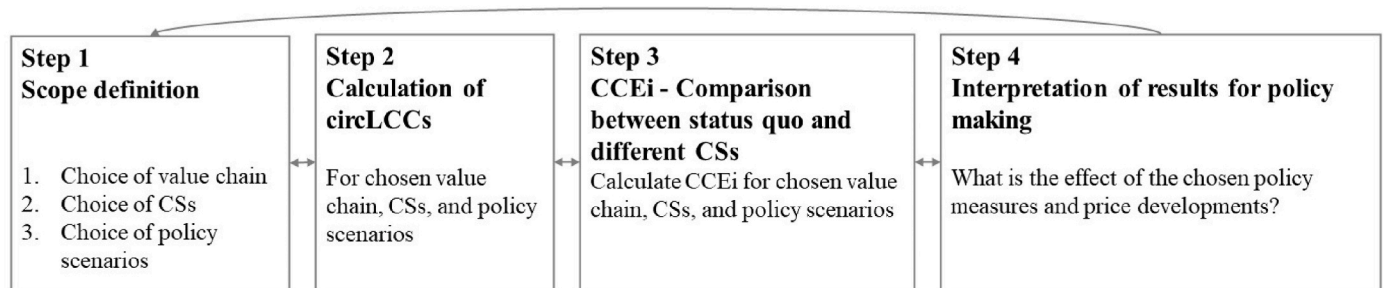


Fig. 1. The 4 –step, iterative CEACE process for policy making. → = feedback loops. CEACE = Comparative Economic Assessment of Circular Economy, CSs = Circular Strategies, circLCC = Circular Life-Cycle Costing, CCEi = Comparative Circular Economy Indicator.

establish financial incentives for businesses (Holly et al., 2023).

While environmental and social indicators address the overall sustainability potential of a CS, economic feasibility determines whether an - i.e., environmentally - desirable CS² will be adopted by industry or requires policy support. Balancing environmental and economic impacts is central to the CE literature, as it is underpinned by the premise to decouple environmental impacts from economic growth through new business opportunities (Bocken et al., 2016). Assessing the economic performance of desirable CSs across national, industrial value chains can reveal how costs³ are distributed among actors and how this affects their economic attractiveness. Comparing alternative CSs under different policy and price (P&P) scenarios can further indicate the financial implications of policy interventions.

The literature on circularity indicators, is extensive. While a growing body of work proposes indicators and assessment frameworks to compare CSs across environmental, economic, and social dimensions, most approaches remain either environmentally focused, product-level, or static in time, limiting their relevance for strategic decision-making (Ahmed et al., 2022; Calzolari et al., 2022; Ferrante et al., 2025). Recent reviews highlight that economic CE indicators rarely integrate temporality, neglect end-of-use impacts of existing stocks, and are seldom operationalised at the industrial value-chain (meso) level, despite this scale being critical for implementation and policy design (Kulakovskaya et al., 2022b). This gap is problematic from a policy perspective, as policymakers require systematic, comparable, and forward-looking assessments of alternative CSs at the value-chain level to design cost-effective interventions, anticipate lock-ins, and prioritize strategies with the greatest diffusion potential. Addressing this gap motivates the present study and leads to the research question: "How can circular strategies systematically be compared on an industrial value chain level, and thereby support policymakers in designing

Table 2
Nomenclature for the CEACE process.

| <i>circLCC</i> | circular life-cycle costs | <i>c</i> | unit process cost |
|----------------|-------------------------------------|-----------|-------------------------------------------|
| α | mass ratio parameter | <i>i</i> | unit process in the production phase unit |
| C_{NP} | cost of a newly produced product | <i>j</i> | process in the use phase |
| C_D | cost of a disposed product circular | <i>k</i> | unit process in the EOU phase |
| C_{prod} | cost in the production phase cost | <i>d</i> | discount factor |
| C_{use} | cost in the use phase | <i>r</i> | discount rate |
| C_{EOU} | cost in the end-of-use phase | <i>t</i> | year |
| <i>q</i> | unit process quantity | <i>LT</i> | product lifetime |

cost-effective interventions for the their broader diffusion?" To address this question, we first develop a methodology to (a) assess costs across value chains and (b) integrate P&P scenarios that influence these costs, thereby enabling the identification of effective policy measures for facilitating the transition toward desirable CSs. This overall process for policy making, we label as Comparative Economic Assessment of Circular Economy (CEACE). Second, we demonstrate the process' application with real data on different alternative CSs for the expanded polystyrene (EPS) thermal insulation industry in Switzerland. We have chosen this case due to the high environmental impacts of insulation material, current uncertainty about economically feasible CSs in the industry, and the long lifespans of construction products, which amplify the significance of current policy interventions, but understand the proposed method as sector-independent.

The paper is structured as follows. Section 2 provides a background on the current state of literature on value-chain level economic CE indicators and their use for policy making. Section 3 describes the CEACE process and its development, while Section 4 applies CEACE to the Swiss EPS insulation value chain by employing two P&P scenarios. Section 5 discusses the CEACE process' relevance for policymakers and investors, and its limitations. While, Section 6 concludes.

² A desirable circular strategy is beneficial in environmental and social terms, e.g., a recycling process that keeps scarce, non-toxic, non-renewable material in the cycle, while at the same time is less CO2-intensive and prohibits child labor.

³ Costs include all costs occurring during the production such as material, labour or logistics; the use and the end-of use of a product.

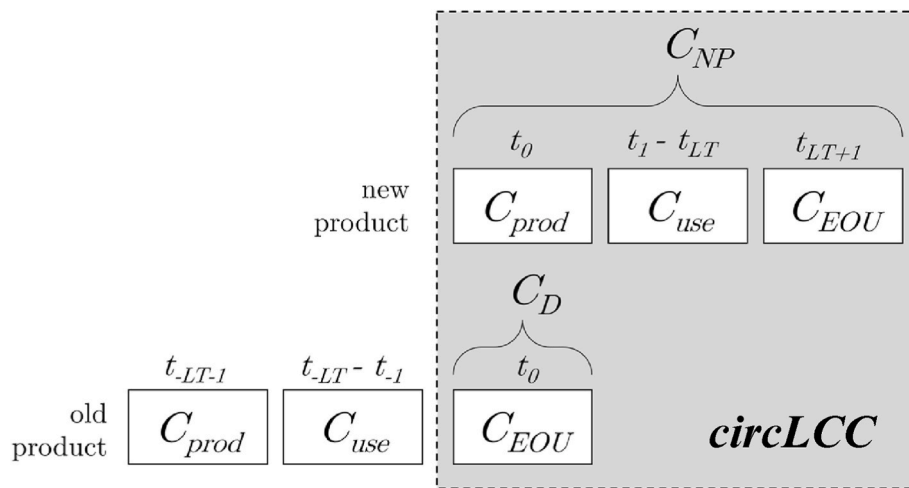


Fig. 2. Circular Life-Cycle Costing (circLCC). The shaded area represents the costs included in the calculation of circLCC. C_{prod} = cost of production, C_{use} = cost of use, C_{EOU} = cost of end of use, t = time periods when the respective costs occur ($t_0, t_1 \dots t_{LT}$, where LT = lifetime).

2. Literature review

2.1. Circular strategies (CS) and circularity indicators

The definition of different CSs is widely discussed in literature ranging from the 3R- (Reduce, Reuse, Recycle) to the 10-R concept (Potting et al., 2017). While the first originates in waste management hierarchy thinking and sustainable development discourse and has been criticized for being insufficient to distinguish value retention (Korhonen et al., 2018; Blum et al., 2020), the latter takes a more systemic approach addressing these critiques (see Table 1). In the context of this paper we

Table 3

The CEACE process. Guiding questions for the interpretation of circLCC and CCEi, and the P&P scenarios.

| Step | CEACE process step | Focus | Guiding questions for interpretation |
|------|----------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1 | Scope definition | Choice of value chain, CSs, and P&P scenarios | Which industrial value chain do we focus on? What are environmentally desirable, alternative CSs in this value chain? By what policy measures do we intend to support these alternative CSs? Or what potential price development could influence the diffusion of these alternative CSs? |
| 2 | Circular life cycle costs circLCCs | Different process steps along the value chain | Which steps in the (circular) value chain cost most? And how does the chosen P&P scenario influence this? |
| 3 | Comparative Circular Economy Indicator CCEi | Overall value-chain | Which CS is compared to the status quo financially most attractive in the future? And how does the chosen P&P scenario influence this? |
| 4 | P&P (policy and price) scenarios | Policy measures and price developments of materials, energy, disposal fees, and other relevant cost categories for the chosen value chain | What can be concluded for different P&P scenarios? Do they influence the circLCCs and the CCEi for desirable CS? What could potentially be different financial leverage points in case the influence is not as initially intended? |

Table 4

Selected CSs for the assessment. In each CSs, the amount of clean and contaminated EPS waste allocated to recycling varies depending on time (see Appendix B for material flows); the rest of EPS waste is assumed to be incinerated or landfilled.

| NAME of CSs | CSs description [Circular process(es) included in the respective CSs] | Environmental impacts [in kt CO ₂ -eq] as published in Kulakovskaya et al. (2023) for the total amount of EPS boards installed and deconstructed in Switzerland in one year | |
|------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|
| | | Year 2040 | Year 2060 |
| Baseline | Current, linear EPS production and disposal. [Incineration & Landfill] | 257 | 286 |
| Reduce | EPS bead producers increase efficiency in product manufacture by switching to electrically heated steam cracker furnaces that use renewable electricity instead of hard coal and natural gas. [Reduce] | n.a. | n.a. |
| reCleanCH | HBCD-free (clean) and HBCD-containing (hazardous) EPS waste are in two separate waste streams; only HBCD-free EPS waste is recycled in Switzerland. The recycling process is fully integrated into EPS board production. [Recycling 1] | 250 | 176 |
| reMixedCH | HBCD-free and HBCD-containing EPS wastes are in a single (mixed) waste stream; they are jointly recycled in Switzerland at a plant for HBCD-containing EPS waste. The recycling process is fully integrated into EPS board production [Recycling 1 & 2] | 190 | 156 |
| reMixedNL | Clean and contaminated EPS waste is combined into a single (mixed) waste stream and jointly transported to the Netherlands for recycling. [Recycling 1 & 3] | 191 | 158 |

use the terminology CS to refer to a combination of R-strategies implemented jointly in practice (illustrated in Table 4).

Literature proposes multiple assessment approaches⁴ that evaluate

⁴ Alternatively labeled as methods, frameworks, metrics, or indicators.

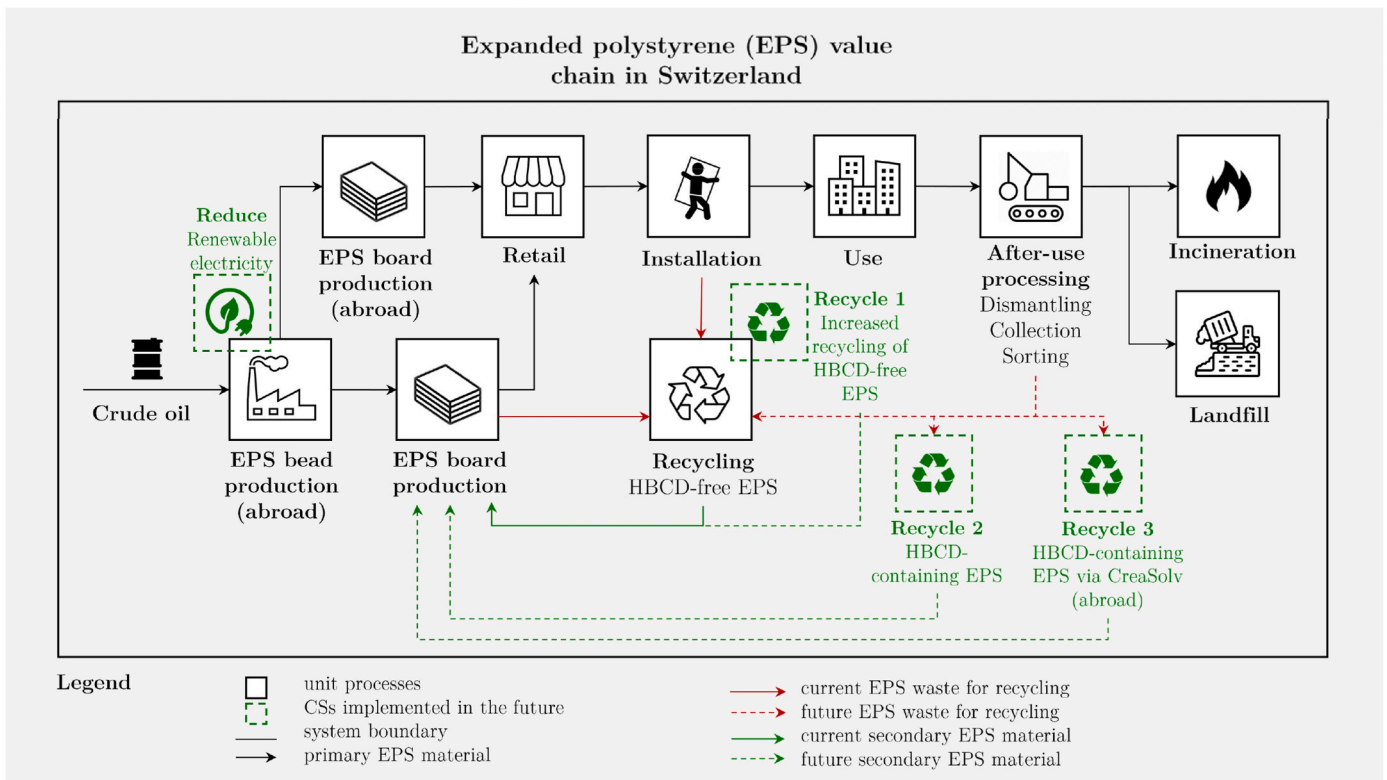


Fig. 3. Schematic representation of the expanded polystyrene (EPS) value chain in Switzerland. Current unit processes are shown in white boxes; circular processes that can potentially be implemented in the future are shown in dotted green boxes; **Reduce**: Lowering environmental impacts in EPS bead production through increased renewable electricity use (Potting et al., 2017). **Recycling 1**: Enhanced mechanical recycling of HBCD-free (clean) EPS waste. **Recycling 2**: Mechanical recycling of HBCD-containing (contaminated) EPS waste in Switzerland. **Recycling 3**: Solvent-based recycling of contaminated EPS waste using CreaSolv technology in Terneuzen, Netherlands. Arrows indicate material flows. All unit processes are located in Switzerland unless “abroad” is specified.

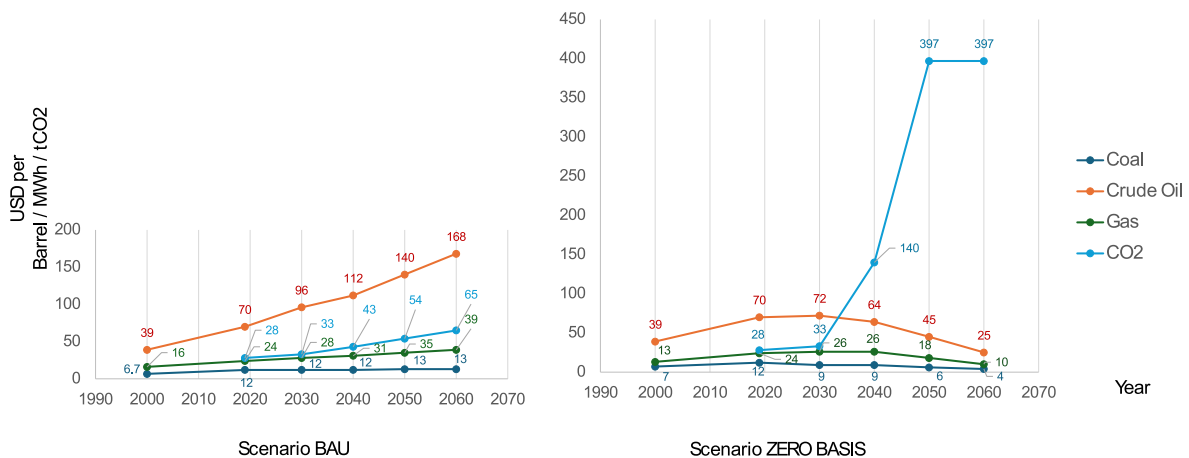


Fig. 4. Price and policy (P&P) scenarios. Scenarios for price developments of CO2 and primary energy sources, based on Perspectives 2050+ (SFOE, 2021, p.47): Business-as-usual (BAU, left), and Zero Basis (right) scenario.

CSs from an environmental, economic, and/or social dimension in order to compare alternatives to each other. It is widely acknowledged that ideally CSs are assessed by using multi-criteria (Ahmed et al., 2022) combining social, environmental and economic aspects as well as multiple levels including micro, meso and macro levels (dos Santos Gonçalves and Campos, 2022; Ferrante et al., 2025) where micro refers to individual products or components, meso to industrial value chains or organizational networks, and macro to entire economic systems such as national or regional economies. A review by Calzolari et al. (2022) finds that practitioners often assess and communicate about the

environmental impact of CSs, while academics seem to focus more and more on the economic aspects. Prominent circularity indicators such as the standard MCI (Material Circularity Indicator) by the Ellen MacArthur Foundation and the building-specific BCI (Building Circularity Indicator) and PBCI (Predictive Building Circularity Indicator) (Cottafava and Ritzen, 2021) reveal if material circulates, but not if it is economically viable to circulate it, while the economic version of the MCI (Jiang et al., 2022) and the built-environment specific PBSCI (Predictive Building Systemic Circularity Indicator) (Antwi-Afari et al., 2022) integrate cost-models. However, these indicators have initially

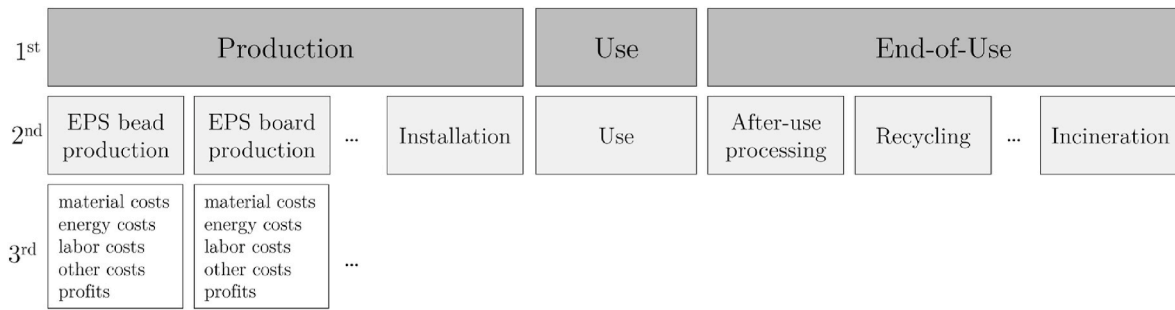


Fig. 5. Three levels of cost categories of expanded polystyrene (EPS) value chain in Switzerland considered in the assessment (adapted from Hunkeler et al. (2008) and ISO 14051).

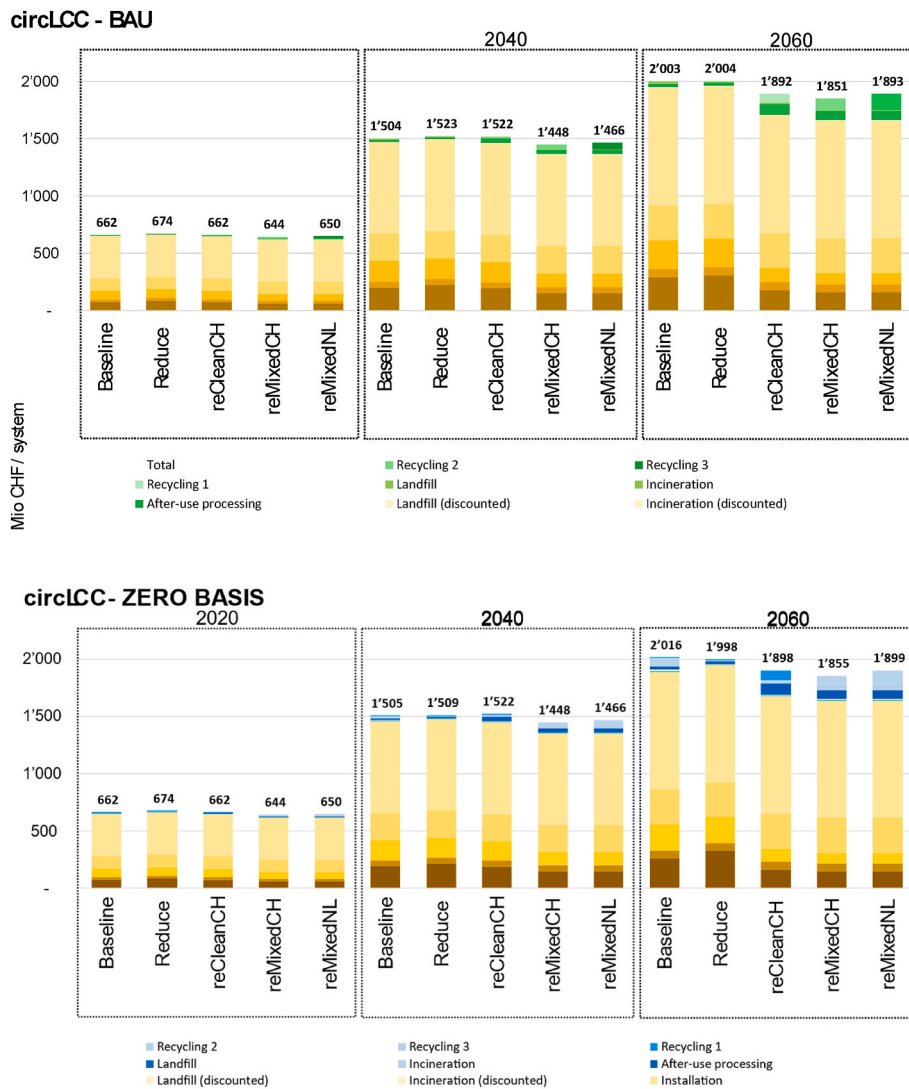


Fig. 6. Circular Life-Cycle Costing (circLCCs) for the baseline and circular strategies (CSs) under the business-as-usual (BAU) and ZERO BASIS scenarios. In Mio CHF for the overall system. The system encompasses the total amount of expanded polystyrene (EPS) boards installed and deconstructed in Switzerland in one year. It highlights that the considered policy and price (P&P) scenario ZERO BASIS has little impact on the overall costs neither the cost distribution along the value chain compared to the P&P scenario BAU.

been developed for the product (micro) level. Sometimes they are used in an aggregated form on a meso level though. With respect to building-specific circular economy indicators, Li et al. (2025) provide a comprehensive review of 66 indicators spanning micro-, meso-, and macro-level applications, encompassing environmental, economic, and systemic dimensions rather than focusing exclusively on economic

aspects. Thus, Chennak et al. (2024) point out that the transition towards a CE is also an economic issue and suggest to analyze costs and benefits along the value chain and on a regional level.



Fig. 7. Comparative Circular Economy Indicator (CCEi). CCEi Values for circular strategies (CSs) under the business-as-usual (BAU) and ZERO BASIS scenario, in %. The baseline is not included as the other CSs are in comparison to the baseline and the baseline would be at 0% for all calculated options.

2.2. Shortcomings of existing economic and value-chain level CE indicators

In a recent review study Kulakovskaya et al. (2022b) provided an overview of the state of research on economic value-chain level CE indicators. They conclude that existing indicators that focus on economic aspects hardly address the temporality, often neglect end-of-use (EOU) impact of the current system, and are rarely on a value chain level. In contrast, environmentally focused frameworks highlight the importance of explicitly integrating EOU and temporal dynamics (e.g., Jansen et al., 2020; or Pauliuk, 2018, emphasizing material residence time in the technosphere). However, economic assessment methods have largely failed to incorporate these dimensions and could draw more systematically from environmental assessment approaches. As a result, economic impacts are typically evaluated for static time horizons, without forward-looking scenarios that capture future system evolution (e.g., Kambanou and Sakao, 2020; Laso et al., 2018; Chen et al., 2020). Kulakovskaya et al. (2022b) in specific argue that temporality is crucial as the material mass balances for some products⁵ may change substantially over time, thus revealing potential for CSs’ implementation. Second, current EOU impacts, i.e., economic impacts of the products currently in use, occurring at the EOU phase, are often neglected. Furthermore, standard Life Cycle Costing (LCC) – often used in circularity assessments - tends to focus on discounted future costs (Seuring and Goldbach, 2002; Kneifel and Webb, 2020), neglecting the immediate value of current waste streams available for recirculation. Finally, the literature reveals a significant gap at the meso (value-chain) level (Kulakovskaya et al., 2022b; Banaite, 2016; Saidani et al., 2019; Vinante et al., 2021; Sassanelli et al., 2019); while essential for effective policy and implementation, this scale is rarely assessed compared to micro or macro levels (Kulakovskaya et al., 2022b; Leising et al., 2018; Saidani

⁵ We use the term “product” to refer to materials, services, and physical products.

et al., 2017; Kambanou and Sakao, 2020).

2.3. The economic calculation method of life-cycle-costing

Among different economic assessment methods, LCC has increasingly been employed as a methodological tool within circular economy research, often referred to as circular life-cycle costing (cLCC), to quantify and assess economic performance throughout a product’s entire lifecycle. Unlike standard LCC, cLCC emphasizes resource efficiency, reuse, and recycling while accounting for circular strategies (CSs) such as remanufacturing, refurbishment, and material recovery (Kambanou and Sakao, 2020; Malabi Eberhardt et al., 2020). Advanced approaches also incorporate temporal dynamics to evaluate how costs evolve over time, reflecting changes in material flows, technological developments, and market conditions (Laso et al., 2018). However, most existing studies focus predominantly on the micro level, analyzing economic performances of individual products, components, or buildings (Rodrigues and Freire, 2017; Marzouk and El-Korany, 2020; Jansen et al., 2020; Braakman et al., 2021). For instance, Jansen et al. (2020) developed a cLCC model specifically tailored for building components, incorporating multiple usage cycles and end-of-life strategies. Similarly, Kambanou and Sakao (2020) provided practical guidance for businesses to choose economically viable circular measures, emphasizing profitability alongside material circularity. At the meso level, a smaller yet growing body of research has emerged, addressing industrial and municipal value chains within specific sectors such as construction and waste management (Bradley et al., 2018; AlJaber et al., 2023; Zhang et al., 2024). Bradley et al. (2018), for example, introduced a total life cycle cost model (TLCCM) aimed at assessing economic impacts of resource recovery within industrial chains. Zhang et al. (2024) further explored meso-level applications through evaluating the economic feasibility of circular practices in municipal waste management systems, whereas AlJaber et al. (2023) and Giorgi et al. (2023) examined the integration of Building Information Modeling (BIM) with LCC to foster circularity in construction. Despite these advancements, existing

meso-level studies often emphasize sector-specific methodologies or lack broader applicability to national contexts. At the macro level, comprehensive analyses encompassing entire economies remain notably scarce, typically limited to theoretical overviews without extensive methodological adaptation to CE specifics (Kerdlap and Cornago, 2021). Consequently, a distinct research gap exists concerning the application of LCC methodologies explicitly designed for circular industrial value chains, particularly at the meso level, within focused national contexts, highlighting an under-researched area warranting further exploration.

3. Method development

To address this gap and answer the research question of “How can circular strategies systematically be compared on an industrial value chain level, and thereby support policymakers in designing cost-effective interventions for their broader diffusion?”, we proceeded in two steps. First, we develop the CEACE process (this Section) and, second, apply it to the case of EPS insulation material in Switzerland and Swiss P&P scenarios to test it (Section 4).

To develop the CEACE process we identified methodological shortcomings of current methods used, i.e. eLCC. Based on this evaluation, we suggest a solution to overcome selected shortcomings, namely by employing a meso-level (value chain level) approach, incorporating temporal aspects along the lifespan of a circular product, as well as costs at the EOU. And finally we design a process around the developed method for policy making by introducing P&P scenarios to the process (referred to as CEACE process).

3.1. CEACE process for policy making

We explain the CEACE process⁶ (Fig. 1) along its four steps 1) scope definition, 2) calculation of our interpretation of cLCC, short cirLCC, for the baseline (status quo) and different alternative CSs, as well as different P&P scenarios 3) the comparison between the baseline, different CSs⁷ and for different P&P scenarios in a single value indicator, labeled as Comparative Circular Economy Indicator (CCEi), and 4) the interpretation of the results. The process is applied for a defined period of time at the meso, value-chain level. The calculation method behind the CEACE process has previously been published in a preprint (Kulakovskaya et al., 2022a).

3.1.1. Step 1 - scope definition

The CEACE process starts by defining the scope.⁸ First, choosing a product and its value chain where policy intervention is planned – including a system boundary, a time period for observation based on the lifespan of the product, and system boundaries. Hereby the system should be expanded to account for the EOU impacts. Second, choosing alternative CSs (such as reduce, rethink, or reuse) within this value chain that shall be compared, for example based on existing life cycle assessments (LCA) environmentally-friendly CSs can be identified and chosen. Third, choosing different policy interventions that have financial implications on (some of) the chosen value chains. To this end, either concrete, future policy measures such as for example future subsidies, new taxes, or recycling tariffs or future price developments of materials,

⁶ A previous version of parts of the CEACE process has been published as a non peer-reviewed pre-print under https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4272446.

⁷ The baseline describes a current system that is usually linear or minimally circular in most value chains, while the alternatives describe more circular equivalents—i.e. one where more CSs are implemented. Comparing different CSs will enable to determine the CSs that are economically viable.

⁸ This step is analog as in LCA and LCC methods (Hunkeler et al., 2008), and outlines the specific scope of the selected value chain using Material Flow Analysis (MFA).

energy or disposal fees – among others - can be considered. Such future policy measures or price developments may be sourced from forthcoming, planned or envisioned regulations, and price development forecasts, and may be combined into P&P scenarios entailing one or more future policy measures.

3.1.2. Step 2 - calculation of cirLCCs

Our process is based on MFA and LCC/eLCC that are suitable methods for assessments along entire value-chains (Brunner and Rechberger, 2016; Allesch and Brunner, 2015). MFA is widely applied in CE studies (e.g., Wiprächtiger et al., 2020; Virtanen et al., 2019; Meglin et al., 2022). It analyzes material stocks and flows across regions, national economies, or along specific value chains, making it suitable for the purpose of calculating cirLCC (Brunner and Rechberger, 2016; Allesch and Brunner, 2015).

LCC, while lacking a uniform definition (Woodward, 1997; Seuring and Goldbach, 2002), generally aggregates costs across a product's life cycle (Woodward, 1997; Hunkeler et al., 2008). LCC often discounts future EOU costs to their present value but neglects the economic significance of current EOU impacts, such as the value of reusable waste materials costs (Jansen et al., 2020; Fregonara et al., 2017; Li et al., 2019). Additionally, LCC tends to focus on individual products, making it less effective in evaluating open-loop circular strategies (CSs) that involve multiple value chains and span over medium (5–30 years) to long-term (30–50 years) lifespans (Börjeson et al., 2006). LCC's environmental extension – eLCC - supports life-cycle thinking (Pauliuk, 2018), considers multiple actors, can include environmental damage if this damage is monetized, and can be integrated with LCA for holistic assessments. However, it does not yet fully address the complexity of CE systems, i.e., does neither consider temporality and the current EOU costs at a value-chain level (Kulakovskaya et al., 2023). Therefore, we suggest an alternated e/LCC, and label it as cirLCC, it integrates the temporality and current EOU costs.

To do so, cirLCC starts by defining cost categories (e.g., material, energy, labor; ISO 14051). Cost categories should align with the scope and be adjusted as needed during data collection (iterative approach). Economic data must be gathered for each unit process and the baseline as well as all CSs. It is assigned to material flows and specific cost. The nomenclature used is summarized in Table 2.

To include current EOU impacts, cirLCC is calculated using system expansion by combining costs of newly produced products C_{NP} with costs of currently disposed products C_D (Equation (4.1)). This approach captures the economic value at the EOU phase and accounts for costs across past, current, and future time periods.

$$cirLCC = C_{NP} + C_D \quad (\text{Equation 4.1})$$

cirLCC follows the e/LCC methodology where costs for each MFA unit process c are multiplied by quantities q . C_{NP} includes costs for production (C_{prod}), use (C_{use}), and EOU (C_{EOU}) phases (Equation (4.2)).

$$C_{NP} = C_{prod} + C_{use} + C_{EOU} \quad (\text{Equation 4.2})$$

The production phase includes unit processes i that happen before the use phase, such as raw-material processing, product manufacture, or retail. Production is assumed to last less than a year and therefore C_{prod} is not discounted (Equation (4.3)).

$$C_{prod} = \sum_{i=1}^{n_i} C_i q_i \quad (\text{Equation 4.3})$$

However, other constitutes of C_{NP} are adjusted for inflation.

The use phase covers unit processes j between production and EOU, including utilization or refurbishment, lasting up to the product's functional lifetime (LT). C_{use} are discounted using a discount factor d and rate r (Equation (4.4)).

$$C_{use} = \sum_{t=1}^{LT} \sum_{j=1}^{n_j} d_t \cdot c_{j,t} \cdot q_{j,t} \quad (\text{Equation 4.4})$$

$$dt = 11 + rt$$

The EOU phase includes unit processes k like disposal, sorting, recycling, and EOL activities (e.g., incineration, landfilling). As it is assumed to last less than a year, C_{EOU} is discounted at $t = LT + 1$ (Equation (4.5)).

$$C_{EOU} = d_{LT+1} \cdot \sum_{k=1}^{n_k} c_{k,LT+1} \cdot q_{k,LT+1} \quad (\text{Equation 4.5})$$

$$d_{LT+1} = \frac{1}{(1+r)^{LT+1}}$$

Discounting is crucial for products with medium or long lifetimes (e.g., furniture, insulation) to avoid overestimating EOU costs, while it is irrelevant for short-lived products (e.g., packaging) as costs occur within the same year. C_D represents the life-cycle costs of products currently disposed ($t = t_0$) calculated as real costs c_k multiplied by quantities q_k in the EOU-phase unit processes (Equation (4.6)). Costs from prior phases (production, use) are excluded, as they occurred before t_0 . Unlike C_{NP} , C_D is not discounted unless the EOU phase lasts over a year. C_D is scaled by α (alpha) and adjusted using a revers discount factor $1 - d_{LT+1}$ to prevent overestimating EOU costs when summing C_{NP} and C_D . The mass ratio parameter α we define, by drawing upon the substitution framework by Vadenbo et al. (2017), as the share of disposed material coming out of a system S at time t in relation to the material coming into the same system at the same point in time—for example, the amount of old insulation currently being deconstructed in relation to new insulation currently being installed in a given system. If less insulation is being installed than deconstructed, then $\alpha < 1$. If the amounts of insulation installed and deconstructed are identical, then $\alpha = 1$.

$$C_D = \alpha(1 - d_{LT+1}) \cdot \sum_{k=1}^{n_k} c_{k,LT+1} \cdot q_{k,LT+1} \quad (\text{Equation 4.6})$$

Fig. 2 summarizes the cost terms and their respective time periods in the calculation of circLCC, while Equation (A.1) in Appendix A presents a full cost expression.

3.1.3. Step 3 - Comparative Circular Economy Indicator (CCEi) - comparison between status quo and different CSs

Polymakers might be interested in identifying CE-related economic hotspots in different (circular) value chains as they hint at spots where circular value chains do not happen due to cost restraints. At the same time industry players as part of circular value chains might benefit from this knowledge too in their quest for building the inter-organizational collaboration necessary for CE. Because such collaborations might be the more feasible, the more value chain players benefit from the new, circular value chain. For these reasons, the CEACE process seeks to compare CSs with a status quo, i.e., business-as-usual (BAU) scenario, enabling informed policy decisions for supporting CSs in a chosen value chain.

In this third step, circLCC are therefore translated into single value indicator, the Comparative Circular Economy Indicator $CCEi$. While circLCCs are useful for revealing how costs can change in absolute terms across life-cycle phases and unit processes, $CCEi$ aggregates the costs of each CSs into a single value, enabling easy comparison of multiple CSs and insights on the economic attractiveness of implementing different CSs at the value-chain level. The indicator compares the baseline costs $circLCC_{baseline}$ with the CSs costs $circLCC_{CS}$ in relative terms⁹ (Eq. (4.7))

and B-2 in Appendix A), i.e. it adjusts for the absolute cost values and normalizes them across CSs, simplifying their comparison, which enables policy makers and industry players a quick overview.

$$CCEi = \frac{CC_{baseline} - CC_{CS}}{CC_{baseline}} = \frac{(C_{baseline,NP} + C_{baseline,D}) - (C_{CS,NP} + C_{CS,D})}{(C_{baseline,NP} + C_{baseline,D})} \quad (\text{Equation 4.7})$$

Negative $CCEi$ values indicate CSs that are, when considering the entire value chain, less financially attractive than the status quo, with greater negativity signifying lower attractiveness. Conversely, positive $CCEi$ values represent CSs that are overall more financially attractive than the status quo, with higher values reflecting greater financial appeal. For an expanded version of Equation (4.7) see Equation (A.2) in Appendix A.

3.1.4. Step 4 - interpretation of results for policy making

While step 1 of the CEACE process defines the scope, step 2 leads to circLCCs that show the distribution of costs along the value chain, for different CSs, and in step 3 these CSs are relatively compared in the $CCEi$ to the status quo, in the fourth and final step, the effect of selected policy measures that influence costs is elicited through the application of P&P scenarios. Introduced into the calculation of circLCC and $CCEi$, these P&P scenarios yield to new values, which then can be compared to the business as usual scenario.

Each step of the CEACE process helps answering different questions. Where step 1, helps to set a focus on a specific value chain, some – ideally based on the environmental performance - selected CS, and P&P scenarios, step 2 answers the following question: Which steps in the (circular) value chain cost most, and how does the chosen P&P scenario influence this cost distribution? Second, $CCEi$ offers an overall comparison at one sight and might answer questions such as: Which CS is compared to the status quo financially most attractive in the future (overall), and how does the chosen P&P scenario influence this? Both steps are crucial for policy makers and industry players alike and should be interpreted in a final step together by gauging the effects of different policy interventions against each other. This can minimize unintended financial side effects. Table 3 summarizes the steps and the associated questions that might guide the interpretation of circLCCs and $CCEi$.

4. Application of the CEACE process

This chapter exemplifies the CEACE process on the example of the Swiss EPS insulation value chain and a Swiss P&P scenario. Before describing the application of the process, the following chapter provides an overview of the case.

4.1. EPS insulation material in Switzerland – case description

The case of the EPS insulation industry in Switzerland has been chosen due to its environmental relevance. As by 2035, insulation materials will be responsible for most of the environmental impacts of the building stock in Switzerland (Heeren and Hellweg, 2019), while EPS represents one of the most emission-intensive insulation materials (Wiprächtiger et al., 2020) and leads the Swiss insulation market by volume¹⁰. Moreover, the amount of EPS waste is expected to increase considerably in the future, while the recycling capacity in Switzerland remains limited (Wiprächtiger et al., 2020; Heeren and Hellweg, 2019).

¹⁰ EPS belongs to the group of oil-based insulation materials that constitute the largest share (57%) of the total insulation market in Switzerland by volume. The rest of the market is represented by mineral-based insulation (stone wool and glass wool) comprising 36% and bio-based insulation (wood fiberboard, cellulose, hemp) comprising 7% of the market by volume (Jakob and Rubli, 2016; secondary data provided by industry, 2021; interviews with industry representatives during 2020-2022).

⁹ The method of relative scenario comparison is commonly used in environmental assessments. Compare for example the retained environmental value (REV) (Haupt and Hellweg, 2019).

Different CSs can both minimize waste and reduce the negative environmental impacts of EPS at the same time (Wiprächtiger et al., 2020) - however, their economic feasibility is unclear. Lastly, due to EPS' long life-time (LT) of around 50 years (Lazzarin et al., 2008; Schleier et al., 2022) and the large and growing material volumes of EPS waste (Wiprächtiger et al., 2020), this case is ideal for demonstrating how CEACE captures the temporality and the economic value of waste materials at the EOU phase. In addition, Swiss policy increasingly aims at supporting circular economy (CE) principles in construction through both regulation and voluntary standards (BöB, 2021; EnG, 2016/2025; USG, 2022; KIG, 2023; Minergie, 2023; SNBS, 2022; SIA, 2020). The Swiss Energy Act (EnG, 2016/2025) and the draft MuKE 2025 (not in force yet, EnDK, 2025) promote energy efficiency and sustainable resource use (EnG, 2016/2025), while the Environmental Protection Act (Art. 35j in USG (2022)) and the Federal Act on Public Procurement (BöB, 2021 Art. 29) require life-cycle considerations and the use of secondary materials (USG, 2022; BöB, 2021). However, most of these regulations do (a) not contain specific targets, and (b) limit their scope to environmental aspects, omitting economic considerations. In parallel, labels like Minergie ECO, SNBS Hochbau, and SIA 2040 integrate CE criteria into building assessment frameworks (Minergie, 2023; SNBS, 2022; SIA, 2020), and sectoral initiatives, such as the inter-organizational Charta Kreislauforientiertes Bauen (CBCharta, n.d.) raise awareness for the topic in the construction sector. Given the current uncertainty surrounding both existing and forthcoming regulations, this case is particularly well-positioned to inform ongoing policy development in Switzerland.

4.1.1. Data collection

To apply the developed CEACE process to the case of EPS insulation material in Switzerland, the following three data collection steps have been applied: First, to set the scope, particularly to identify the baseline and alternative CSs¹¹ in the Swiss EPS insulation value chain, eight qualitative, confidential, semi-structured interviews with Swiss EPS insulation industry stakeholders were conducted between 2020 and 2022 (a full list of interviewees, the interview guide and the respective follow-up email is provided in Appendix C). Second, MFAs were conducted for the baseline and the alternative CSs for 2020, 2040, and 2060. They relied on data from Wiprächtiger et al. (2020) for EPS material flows in 2015, 2035, and 2055, extrapolated to the target years and supplemented with clean EPS flow data (secondary data provided by industry, 2021). An MFA map is provided in Fig. B in Appendix B. And finally, third, to access cost data, absolute costs (CHF/t) and relative costs (% of total output) were collected from public price lists, industry reports, company income statements, interviews, and expert communications. Missing data were estimated relying on product prices, or by summing up production costs such as energy, materials, and other costs to arrive at a realistic product price, then assigning them to material flows for the baseline, each CSs and time period. As most of the collected cost data is sensitive to the involved companies, it is not shared in an open data repository.

4.2. CEACE process applied to EPS insulation in Switzerland

This section exemplifies how the CEACE process can be used to evaluate different P&P scenarios in terms of their cost-effectiveness. The chosen case is EPS insulation in the Swiss construction sector in 2020.

¹¹ The baseline describes a current system that is usually linear or minimally circular in most value chains, while the alternatives describe more circular equivalents—i.e. one where more CSs are implemented. Comparing different CSs will enable to determine the CSs that are economically viable.

4.2.1. Step 1 - scope definition (value chain, CSs, and P&P scenarios)

4.2.1.1. Value chain of EPS boards in Switzerland. The chosen system is the total of EPS boards installed and deconstructed annually in Switzerland, including system expansion by considering material entering and exiting the system. The analysis of economic impacts focuses on the years 2020, 2040, and 2060, as these correspond to available Swiss P&P scenarios. Such long time horizons are required in order to account for EPS's 50-year lifetime (Lazzarin et al., 2008; Schleier et al., 2022).

4.2.1.2. CSs for EPS boards in Switzerland. The baseline reflects the current EPS value chain, which is complex, fragmented, and project-dependent (Kahlert et al., 2022). Processes include EPS bead and board production, retail, use, dismantling, collection, sorting, recycling, incineration, and landfill (secondary data provided by industry, 2021; interviews with industry representatives during 2020-2022). Circularity in 2020 is low (3%) and limited to recycling HBCD-free EPS byproducts from production and installation (secondary data provided by industry, 2021). Post-use EPS waste is incinerated due to hazardous HBCD content, as Swiss recycling capacities cannot detoxify it and because it is currently by far the most cost-effective option.

CSs were identified based on interviews with industry representatives between 2020 and 2022, and through explorative CSs building (Börjeson et al., 2006), considering parameters such as collection rate, recycling efficiency, energy inputs, profit margins, and labor costs. This analysis revealed four potential future circular processes¹² (Fig. 3) that were then combined into four CSs that might combine some of these circular processes and that reflect plausible industry developments (Wiprächtiger et al., 2020; Heeren and Hellweg, 2019; secondary data provided by industry, 2021; interviews with industry representatives during 2020-2022) (see Table 4).

An environmental analysis of the different CSs by Kulakovskaya et al. (2023) indicates that from an environmental perspective reMixedCH and reMixedNL are more favorable than reCleanCH, and the baseline CS.

4.2.1.3. Policy and price (P&P) scenarios. P&P scenarios had been chosen based on information published by the Swiss Federal Office of Energy (SFOE) in their publication "Energieperspektiven Schweiz 2050+" (SFOE, 2021). The document outlines different energy scenarios in terms of CO₂ prices, and prices for primary energy sources such as coal, raw oil, and gas. The business-as-usual scenario (BAU) describing price developments under enforced, current energy and climate regulations and foreseeable technological advancements (scenario WWB in SFOE, 2021). As second, alternative scenario we employed the ZERO BASIS scenario, that was developed by the SFOE with the ambition for Switzerland to become a net-zero CO₂ emitter by 2050. In this scenario prices are substantially different over time, either due to market developments or because of policy intervention (SFOE, 2021). As an intermediary result, the SFOE (2021) published price developments for CO₂, Coal, crude oil, and gas for both scenarios (Fig. 4), which we take as input into our cirLCC calculation to develop scenarios.

4.2.2. Step 2 - cirLCC for EPS insulation in Switzerland

cirLCCs were estimated using three cost-category levels adapted from Hunkeler et al. (2008) and ISO 14051, including costs only if they can be monetized. The categories and are depicted in Fig. 5.

Further the single variables were defined as follows; C_{NP} represents costs of EPS boards installed in one year, and C_D the costs of boards deconstructed in one year (in million CHF) in Switzerland. EOU costs of

¹² Other treatments, such as pyrolysis and co-combustion in cement clinker plants (Recover), are excluded as they are not common or anticipated in Switzerland (Schleier et al., 2022; secondary data provided by industry, 2021; interviews with industry representatives during 2020-2022).

C_{NP} were discounted ($r = 3\%$, $LT = 50$ years), while C_D required no discounting due to a short EOU phase (data collected in interviews with industry representatives during 2020-2022).

Results (see Fig. 6) show total circLCCs for all scenarios rise over time due to increased material installation and deconstruction. Although, the three recycling scenarios show consistently lower circLCCs compared to the baseline and reduce scenarios, the differences remain rather small. EOU costs rise faster than production costs, quadrupling by 2040 and increasing eightfold by 2060, compared to a twofold and threefold rise for production costs. This results from a higher deconstruction-to-installation ratio (α) and potential labor cost increases from selective dismantling. Use-phase costs remain zero, indicating no additional costs during EPS use.

At the unit process level, installation is the most cost-intensive, followed by retail, EPS bead, and EPS board production. After-use processing and recycling costs are substantial and increase over time due to higher mass ratios and labor costs. Incineration and landfill costs remain negligible due to small material volumes and discounting. Across CSs, EPS bead and board production costs vary significantly. EPS bead production costs generally decrease except in the Reduce CS, which shows higher costs due to rising electricity prices, especially under the ZERO BASIS scenario (+14% in 2040 and +10% in 2060 under BAU; +23% in 2040 and +50% in 2060 under ZERO BASIS). EPS board production costs decrease in all CSs compared to the baseline, with significant reductions (−48% in 2040 and −150% in 2060 on average) when recycling is integrated into production. If recycling costs are allocated to EPS production, costs remain lower than the baseline.

The ZERO BASIS scenario, based on trends like energy efficiency and electrification (SFOE, 2021), yields circLCC slightly lower than BAU (−1.6% in 2040, −4.1% in 2060). Results for CSs under ZERO BASIS are economically similar to BAU but slightly more favorable at the value-chain level.

EOU impacts (Fig. 6) account for 10–14% of total circLCC by 2060 in most CSs, emphasizing the economic significance of expanding the system to include currently disposed products, particularly for long-lifespan items.

4.2.3. Step 3 - CEEi for EPS insulation in CH

The results of the circLCC assessment were translated into CEEi by summing up the first-level costs of each CSs and conducting a relative comparison. In contrast to the total circLCCs, the indicator results (Fig. 7) display more substantial differences between the scenarios and across CSs at the value-chain level.

Under BAU, CSs generally show higher indicator values than under ZERO BASIS, with differences increasing over time due to rising electricity prices under ZERO BASIS. Most recycling CSs are less costly than the baseline, except for reCleanCH, which shows negative values in 2040 due to limited clean EPS availability and higher labor costs from increased collection rates. By 2060, reCleanCH becomes economically viable as clean EPS availability increases. The CSs reCleanCH, reMixedCH, and reMixedNL are the most beneficial, with reMixedCH consistently the most attractive across time periods and scenarios. The Reduce CS shows negative values except for ZERO BASIS in 2060 where it is slightly positive. The negative values result from the fact that electricity prices exceed those of coal and natural gas in both scenarios (SFOE, 2021, compare Fig. 4).

4.2.4. Step 4 - interpretation of results for policy making in the context of EPS insulation in Switzerland

The final step of the CEACE process draws implications for policy making. The assessment of the Swiss EPS value chain using CEACE sheds light on the magnitude and location of costs across the value chain as well as the economic attractiveness of implementing different CSs.

Answering the first guiding question for the interpretation (compare Table 3): Which steps in the (circular) value chain cost most? And how does the chosen P&P scenario influence this? We find that while

installation remains the biggest cost point at the life-cycle phase level, EOU costs increase the most over time, highlighting the need to expand and optimize after-use and recycling processes. Greater material output from the system enhances its reuse potential, yielding economic benefits for value-chain players and reducing demand for virgin resources, as shown for EPS-based insulation materials (Schleier et al., 2022). Fully reusing current and future EPS waste streams will require expanding recycling capacity in Switzerland (Wiprächtinger et al., 2020; and interviews with industry representatives during 2020-2022). Improved deconstruction-site waste collection and reverse-building practices are also needed to minimize incineration and landfilling. Further, our analysis shows that at the unit-process level, EPS bead producers could benefit from recycling but may face losses when switching to electrically heated steam cracker furnaces, underscoring the importance of accelerating the renewable energy transition (Markard, 2018). EPS board manufacturers gain significantly from recycling, as CS scenarios reduce absolute costs compared to the baseline. With a 100% substitution rate, virgin materials can be replaced with secondary resources. Recycling companies and service providers for waste collection and separation can also profit if secondary EPS material prices remain competitive.

Moving to the guiding question 2 (compare Table 3): Which CS is compared to the baseline financially most attractive in the future? And how does the chosen P&P scenario influence this? The single-score indicator CEEi results (Fig. 7) reveal changes in the economic viability of CSs over time under BAU and ZERO BASIS scenarios (SFOE, 2021). ZERO BASIS shows lower values, highlighting the negative financial impact of rising energy prices on CS implementation, which crude oil price reductions may not offset. Accelerating renewable energy adoption and phasing out established technologies (Markard, 2018) could reduce electricity costs, supporting CSs. Recycling in Switzerland is shown to be more profitable due to lower transport costs, with “mixed” recycling—processing EPS-free and EPS-containing waste together—being the most cost-effective option.

And finally concluding (compare Table 3): What can be concluded based on 1 and 2 for different P&P scenarios? Do they influence the circLCCs and the CEEi for desirable CS? What could potentially be different financial leverage points in case the influence is not as initially intended? One conclusion might be that the under ZERO BASIS planned policy interventions might not be sufficient to shift the Swiss EPS industry to more circularity, as it is financially not attractive. And we therefore suggest to consider additional financial leverage points for innovation in form of promotion of circular innovations, and the EOU phase in form of an increase in fees for incineration and landfill or a recycling obligation as suggested in a recent study by Wiprächtinger et al. (2025). However, CEEi also indicates, that the differences between BAU and ZERO BASIS, are minor for most CSs, one small exception being the CS reduce, where the cost along the value chain might substantially be reduced compared to the baseline CS.

At the same time, in industry, EPS bead producers could seek additional funding to economically support the shift to electrically heated steam cracker furnaces, while both bead producers and recyclers could focus on expanding domestic EPS recycling capacities.

To sum it up, the application of the CEACE process to the Swiss EPS insulation value chain indicates that EOU costs drastically increase over time across all scenarios, highlighting the need to expand and optimize recycling and after-use infrastructures. Among the circular strategies assessed, domestic EPS recycling—particularly mixed recycling—emerges as the most economically attractive option, benefiting board manufacturers, recyclers, and waste service providers, while EPS bead producers may face transitional cost disadvantages when shifting toward low-carbon production technologies. Scenario analysis further shows that differences between business-as-usual and ZERO BASIS remain modest for most strategies, suggesting that current policy signals alone are unlikely to induce a systemic transition toward circularity. These findings imply that additional, well-targeted policy instruments may be required to effectively support the diffusion of economically

viable circular strategies along the EPS value chain, which we discuss in the following section.

5. Discussion – implications for policy making

While Section 3 introduced the CEACE process as a tool for assessing the costs of different CSs in a value chain under different P&P scenarios, section 4 demonstrated its applicability to a real case. In the remainder, we discuss implications for policy making.

Policymakers currently face three interrelated challenges: (1) societal pressure to implement effective policies for sustainable development, (2) fiscal constraints that require the prudent use of public funds, and (3) industry demands to minimize regulatory intervention. In the context of promoting circular value chains, the first challenge can be addressed by integrating environmental and social life-cycle assessments (sLCAs), which help identify circular strategies (CSs) that align with broader sustainability goals (Haupt et al., 2018; Hosseinijou et al., 2014; Kulakovskaya et al., 2023). However, addressing the second and third challenges requires additional tools. When multiple CSs demonstrate comparable sustainability performance, a key policy question emerges: Which strategies can be implemented with the lowest financial investment by governments; through mechanisms such as standards (see e.g., Morris et al., 2024), subsidies, taxes, or other policy instruments (Chennak et al., 2024)? The CEACE process contributes to answering this question by providing insight into the cost structures and distribution of economic impacts along circular value chains under different P&P scenarios. This enables the selection of policy interventions that are both cost-effective and minimally intrusive—meeting sustainability targets while responding to industry's preference for limited regulation.

The CEACE process provides targeted support for policymakers seeking to assess the financial implications of circular strategies (CSs) at the value-chain level. Unlike most conventional approaches, CEACE explicitly incorporates both temporal dynamics and current end-of-use (EOU) impacts—factors that are frequently overlooked in existing assessment methods. By quantifying costs (referred to as circular life-cycle costs, circLCC) in absolute terms and disaggregating them over time and across actors within the value chain under varying P&P scenarios, CEACE enables the identification of economic “winners” and “losers” resulting from CS implementation. This information can guide policymakers in designing incentives that strengthen underperforming segments or foster collaboration across organizational boundaries—collaboration that is widely recognized as essential for advancing the circular economy (Korhonen et al., 2018).

Furthermore, because the circLCC indicator reflects costs along an entire life-cycle, it inherently assumes that stakeholders—particularly in sectors characterized by long product lifespans, such as construction—adopt a long-term investment perspective when engaging in circular practices. Emerging research suggests that family-owned businesses, which are more likely to prioritize long-term value creation, often act as early adopters and innovators in the transition to circularity (Blum, N.U., Meili, R., Schell, S., & Stucki, T. unpublished results).

An additional contribution of the CEACE process lies in its ability to assess how policy interventions alter the distribution of costs along a (circular) value chain. By providing transparency on the financial effects of specific P&P scenarios along the value chain for producers, users, and end-of-life companies, CEACE helps identify potential unintended consequences—such as the promotion of CSs that are economically viable but environmentally suboptimal. To support decision-making further, CEACE introduces a single-score indicator, the Circular Cost Effectiveness Index (CCEi), which highlights the most and least beneficial CSs over time and across varying policy contexts. This enables policymakers to draw overarching conclusions about the financially most desirable

pathways for circular transition.

At the same time, as demonstrated in our case study on expanded polystyrene (EPS) insulation in Switzerland under government-developed energy price scenarios, CEACE can reveal when anticipated policy measures or market developments have minimal impact on the cost structure of desirable CSs. In such instances, it is unlikely that financial incentives alone will drive behavioural change among actors in the value chain. This insight underscores the importance of considering supplementary measures, including additional financial instruments or non-financial incentives. These may involve voluntary sectoral commitments by industry pioneers (e.g., the Charta Circular Building in the Swiss construction sector (CBCharta, n.d.)), shifts in consumer preferences (as observed in European responses to plastic packaging (European Commission, 2018)), or public-private agreements facilitated by policymakers (such as the PET recycling initiative in Switzerland).

In conclusion, the transformation of value chains toward circularity may require a combination of financial and non-financial incentives. The CEACE process offers policymakers evidence-based insights into long-term, life-cycle cost-effective options, while also identifying strategic leverage points for targeted interventions that support the adoption of environmentally desirable CSs.

6. Conclusion & outlook

6.1. Conclusion

This study introduced the CEACE process as a tool for assessing the economic feasibility of circular strategies (CSs) across industrial value chains. By incorporating temporal dynamics and end-of-use (EOU) impacts, as well as by comparing different CSs, CEACE enables policymakers to identify cost-effective and environmentally desirable CSs, while also revealing how costs are distributed among value chain actors. This might reveal unforeseen effects, such as financial policies without the intended effect or a value chain player bearing the highest economic burden of shifting from one CS to another. Such findings on a national, value chain level will support policy making.

Applied to the Swiss EPS insulation sector, CEACE demonstrated its utility in pinpointing where policy support may be needed and where it may be ineffective—thus aiding the design of more targeted and efficient interventions. The process also highlights potential economic “winners” and “losers,” offering insights for fostering collaboration, employing a long-term perspective, and minimizing resistance to circular transitions.

6.2. Limitations & future research

The limitations of the CEACE process and this study might highlight avenues for future research. First, while CEACE is designed to assess multiple CSs, its application is often constrained by limited availability of high-quality data. Enhancing collaboration with industry stakeholders and improving corporate reporting transparency could address these data challenges inherent in MFA- and LCC-based studies (Marzouk et al., 2018; Laner et al., 2014). Second, CEACE does not consider the complexity of multiple cycles (Corona et al., 2019), as it excludes the impacts of materials undergoing multiple recirculation cycles before reaching their EOL. Future work could address this by differentiating between intermediate disposal (e.g., reuse or recycling) and final disposal (e.g., incineration or landfilling), as outlined by Jansen et al. (2020), distinguishing EOU from EOL phases. Third, while the EPS case effectively demonstrated CEACE's features, further research in other industries is needed to validate the process and uncover industry-specific insights.

CRedit authorship contribution statement

Nicola U. Blum: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Anna Kulakovskaya:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Christof Knoeri:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

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Appendix A

Equations A. Expanded equations for Circular Life-Cycle Costing (circLCC) and Comparative Circular Economy Indicator (CEEi).

$$circLCC = C_{NP} + C_D = C_{prod} + C_{use} + C_{EOU} + C_D = \sum_{i=1}^n c_i q_i + \sum_{t=1}^{LT} \sum_{j=1}^n d_t \cdot c_{j,t} \cdot q_{j,t} + d_{LT+1} \cdot \sum_{k=1}^n c_{k,LT+1} \cdot q_{k,LT+1} + \alpha(1 - d_{LT+1}) \cdot \sum_{k=1}^n c_{k,LT+1} \cdot q_{k,LT+1}$$

(Equation A.1)

$$CEEi = \frac{circLCC_{baseline} - circLCC_{CS}}{circLCC_{baseline}} = \frac{(C_{baseline,NP} + C_{baseline,D}) - (C_{CS,NP} + C_{CS,D})}{(C_{baseline,NP} + C_{baseline,D})}$$

(Equation A.2)

Appendix B

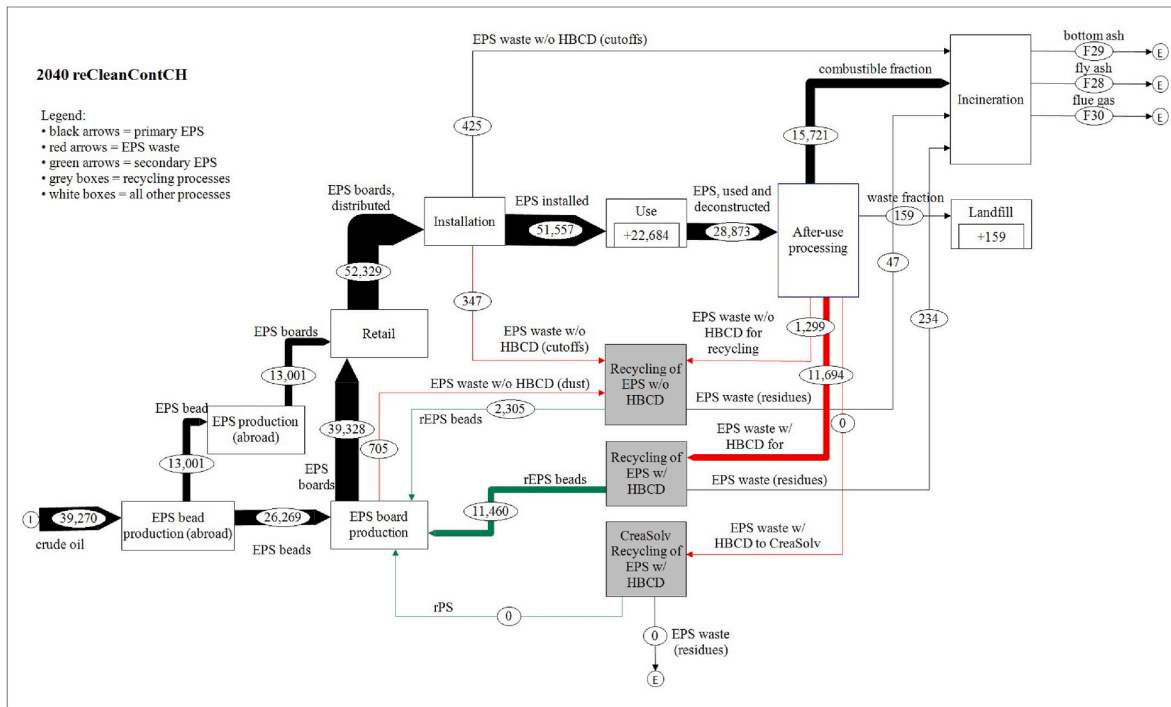


Fig. B. Material flow analysis (MFA) for 2040 reCleanCH scenario. This scenario is defined as follows: HBCD-free (clean) and HBCD-containing (hazardous) EPS waste are in two separate waste streams; only HBCD-free EPS waste is recycled in Switzerland. The recycling process is fully integrated into EPS board production. For other circular scenarios (CSs) see Table 4.

Appendix C

Information on Interviews

Eight qualitative semi-structured interviews, lasting 45–60 min each, were conducted with the key stakeholders in the Swiss EPS industry in German and English between February 2020 and June 2022.

Table C
Organizations interviewed (with the position of the interviewed person and a business/field of operation)

| Nr. | Company/Field of operation | Country | Interviewee |
|-----|-----------------------------------------|---------|-------------------------------|
| 1 | EPS beads producer | DE | Senior Innovation Manager |
| 2 | EPS Production and Recycling Company | CH | Director Business Development |
| 3 | EPS Production and Recycling Company | CH | CEO |
| 4 | Construction Company | CH | Innovation Manager |
| 5 | Deconstruction & Recycling Company | CH | Division Head Development |
| 6 | Recycling & Waste Incineration Company | CH | Head of Production |
| 7 | Recycling company | CH | CEO |
| 8 | Construction Material Database Provider | CH | CEO |

Interview guide (semi-structured interview)

1. **General Introduction by the interviewers:** TACLE project description, incl. its goal (assessing various circular strategies in economic terms), case study (insulation industry in Switzerland), and potential contribution of the interviewee to our project (how we expect they can contribute to research).
2. **Introduction of the interviewee:** Please introduce yourself, your organization, and your field of expertise.
3. Value Chain:
 - 3.1. In your view, who are the key players in the EPS industry value chain?
 - 3.2. What role does your organization play within this value chain?
 - 3.3. How would you describe the current level of collaboration across this industry value chain?
4. Link to Circular Economy:
 - 4.1. How do you understand Circular Economy (CE)?
 - 4.2. If and how do you currently implement it?
 - 4.3. How do you think CE can be implemented in your organization in the future?
5. Cost data:
 - 5.1. What cost categories in your organization are linked to CE activities? For example, consider energy, material, labor, transport costs, and any other relevant cost areas.
 - 5.2. Would you be willing to share this cost data, assuming an NDA is in place?
 - 5.2.1. If yes → we will send a follow-up email (see below), specifying data requirements.
 - 5.2.2. If no → could you link to another person who could share more information regarding costs?

In addition, to the semi-structured interviews as outlined above, a follow-up email was sent to the participants to collect data on shares of costs for specific unit processes.

Example of a follow-up email

“Dear X, Thank you again for the engaging conversation today. I wanted to follow up by outlining our project's objective, the data we're seeking, and how [organization name] could benefit from this collaboration.

Project Overview.

We're developing an economic Circular Economy indicator that evaluates different circular strategies—such as reuse, recycling, and remanufacturing—in economic terms across value chains. While the indicator is applicable across industries, we're currently focusing on the EPS insulation sector due to its strong potential for implementing circular strategies.

Data Requirements.

To apply this indicator, we need cost distribution data for specific unit processes. Specifically, we're looking for the relative breakdown of costs across key categories. Here's an illustrative example:

For an annual total cost to install X amount of EPS on a facade in Switzerland.

- Material costs: 25%
- Energy costs: 40%
- Labor costs: 20%
- Transport: 10%
- Other significant costs: 5%

We need these relative values, which can be provided as ranges (e.g., material costs represent approximately 30-40% of total annual cost). Could you provide this data, or connect me with someone who has access to it? Alternatively, I'd be happy to speak with colleagues working on sustainability or circular economy initiatives at your organization who are responsible for finances. I'm prepared to sign an NDA if required.

Benefits to [organization name]

Sharing this data would contribute to important research advancing the Circular Economy field while providing [organization name] with valuable insights into the economic viability of different circular strategies. For instance, our indicator could quantify the cost savings [organization name] and the broader EPS insulation industry could achieve through increased chemical EPS recycling.

I hope this clarifies our request. Please do not hesitate to reach out if you'd like additional details or have any questions.

Thank you again for your time!

Best regards,

[Co-Author]

Data availability

The data that has been used is confidential.

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