MEMBRANE TECHNOLOGY

Engineering, design, and optimization of membrane processes for industry and research.

Circular Economy

Turning Losses into Business with Membrane Technology

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Abstract

The transition toward a circular economy requires new conceptual frameworks for understanding how waste can be transformed into valuable resources. This article introduces the concept of a value gradient as a driving force for waste-to-resource transformations, drawing an analogy to thermodynamic systems. The feasibility of such transformations is shown to depend on whether the value differential exceeds associated transformation and transport costs. Membrane technologies are positioned as key enablers that amplify and realize these value gradients by facilitating selective separation and conditioning processes. The framework is illustrated through a case study in wastewater treatment, demonstrating how membrane systems can unlock latent value in material streams. The proposed model provides a unifying perspective linking economic feasibility, material flows, and process technologies in circular economy systems.

Value Gradients as Driving Forces

The transition toward a circular economy requires a fundamental reconsideration of how materials are classified, processed, and valued. Conventionally, waste is understood as a residual output that represents a loss at the point of generation. However, this perspective obscures the possibility that such outputs may retain latent value, which can be realized through appropriate transformation and reuse processes. This article argues that waste, while initially constituting a loss, can be reconfigured as economic value when viewed within a broader system of material flows.

From a material perspective, the designation of a substance as waste is not absolute but relational. What is classified as waste by one actor may serve as a valuable input for another, depending on technological capabilities, process requirements, and economic context. This relational nature of value highlights that waste is not an intrinsic property of materials, but rather a function of system boundaries and actor-specific constraints.

The feasibility of transforming waste into valuable resources is governed by an economic condition: the value generated through reuse must exceed the costs associated with transformation and transport. This condition can be conceptualized as a *value gradient*, defined as the difference between the value of a material in its current state and its potential value in a subsequent application. This value gradient constitutes a margin that acts as the driving force for transformation processes.

Drawing on an analogy to thermodynamics, this margin can be interpreted as equivalent to a free energy difference that determines whether a reaction can proceed. Just as chemical reactions occur spontaneously only when a sufficient driving force is present, waste-to-resource transformations require a value gradient that exceeds the economic barriers associated with processing and logistics. In this framework, transformation costs resemble activation energy barriers, while the value gradient provides the necessary impetus for system change.

Within this conceptualization, membrane technologies play a critical enabling role. By providing selective separation and concentration capabilities, membranes function as interfaces that regulate material flows and facilitate the realization of value gradients. They enhance the recoverability of resources, reduce processing costs, and enable the conditioning of materials to meet product specifications. In doing so, membrane technologies effectively lower the barriers to transformation and expand the range of economically feasible reuse pathways.

This perspective positions membrane technologies not merely as technical solutions, but as key instruments in activating latent value within material systems. By enabling more efficient and targeted transformations, they contribute to the reconfiguration of waste streams into resource flows, thereby supporting the broader objectives of circular economy systems.

Conceptual Model: Value Gradient Framework

Value Gradient Definition

The transformation of waste into valuable resources can be formalized through a value gradient:

$$\Delta V = V_B - V_A \tag{1}$$

where:

- V_A is the value of the material in its initial state (waste),
- V_B is the value in its subsequent state (resource),
- ΔV represents the value gradient (margin).

Economic Feasibility Condition

A transformation is economically feasible only if the value gradient exceeds the associated costs:

$$\Delta V > C_{\text{trans}} + C_{\text{transport}} \tag{2}$$

where:

- C_{trans} denotes transformation (processing) costs,
- $C_{\text{transport}}$ denotes transportation costs.

This inequality defines the condition under which waste-to-resource transitions can occur.

Thermodynamic Analogy

The proposed framework can be interpreted through an analogy to thermodynamic systems. Table 1 summarizes the correspondence.

Economic System	**Thermodynamic System**
Value gradient (ΔV)	Free energy difference (ΔG)
Transformation process	Chemical reaction
Costs / barriers	Activation energy
Membrane technologies	Selective interfaces / catalysts

Table 1. Conceptual analogy between economic and thermodynamic systems

In this analogy, transformations occur only when sufficient driving force is available. The value gradient plays the role of free energy difference, determining whether a process is feasible.

Role of Membrane Technologies

Membrane technologies influence the system in three principal ways:

1. **Increasing output value (V_B):** By improving purity and concentration, membranes enhance the economic value of recovered materials.
2. **Reducing transformation costs (C_{trans}):** Membrane processes are often more energy-efficient

than conventional separation methods.

3. **Enabling transformation pathways:** Selective separation allows previously inaccessible or uneconomical resource recovery routes.

Through these mechanisms, membrane technologies effectively amplify the value gradient and facilitate its realization.

The concept of a value gradient provides a unifying framework for understanding these waste-to-resource transformations within a circular economy. By interpreting economic feasibility as a function of a driving force analogous to thermodynamic systems, this approach offers a structured way to analyze when and how value can be recovered from waste streams. In this sense, reuse processes can be understood as transformations that occur when sufficient value gradients exist to overcome associated costs and barriers.

Material Cycles in Nature

An example of circular economy principles can be observed in a *tree over its annual cycle*.

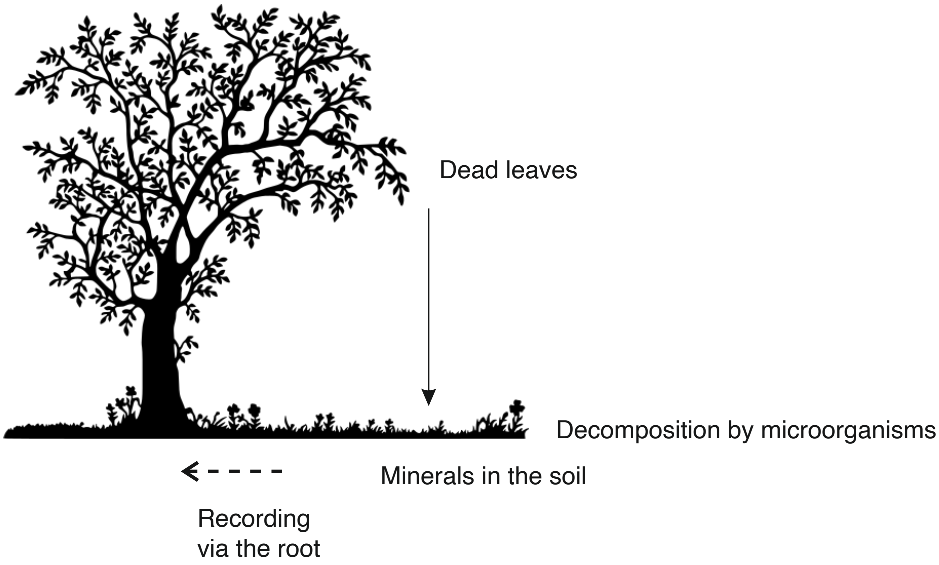

Figure 1. Decomposition and mineral recycling in the annual cycle of a tree as an example of circular economy principles.

Fallen leaves decompose through the action of microorganisms, releasing minerals into the soil. These nutrients are taken up again by the roots and enable the growth of new leaves.

This example illustrates a natural material cycle without considering economic aspects. A similar principle can be applied to industrial systems.

Material Cycles in the Economy

In an economic system where products are manufactured and consumed, material cycles inevitably arise. Raw materials are processed into products and delivered to consumers. After use, these products are disposed of, recycled, or reused.

Unlike natural cycles, economic cycles are often not fully closed: resources are lost, and waste cannot always be reintegrated. Circular economy approaches aim to move closer to natural systems by extending material use and minimizing waste.

What is waste for one actor can be a valuable resource for another. Realizing this potential often requires organizing material flows beyond individual companies — and sometimes across regions or national borders.

The central challenge is economic viability: for circular systems to be implemented and sustained, they must be economically attractive to all involved.

Circular Economy

Definition

The circular economy describes an economic and production system that aims to close material loops and minimize the use of primary resources.

→ Circular Economy (Wikipedia)

It is based on the targeted recovery and reuse of raw materials.

Economic Challenge

Companies act based on cost and benefit. If recycling or recovering materials is more expensive than using new raw materials, there is no incentive to close loops. Economic conditions, technological capabilities, and regulatory frameworks therefore play a decisive role.

Closing loops becomes particularly challenging when it extends beyond individual companies. Multiple stakeholders along the value chain must cooperate to return materials to production. This can span entire regions or even countries. Differences in regulation, transport costs, and logistical complexity make implementation difficult.

To make such cross-system loops economically viable, innovative business models, cooperation, and appropriate policy incentives are required. The goal is to align environmental benefits with economic value — making circular systems not only possible but profitable.

The driving force behind economically viable circular systems is the margin — the profit generated by transforming waste into a marketable product.

Value Creation

Definition

Value creation refers to the process by which a material or product gains economic value through multiple processing steps. In the context of the circular economy, this specifically means transforming waste into a usable raw material or marketable product.

Value is created through activities such as collection, sorting, processing, upgrading, and reuse. The key is that these processes generate higher utility or market value than the original state.

In circular systems, value creation includes all activities that keep materials in use for as long as possible while maximizing their economic and environmental benefit.

A key requirement is the development of suitable processes that enable materials to be efficiently collected, processed, and reintegrated into production. These processes require technical expertise, infrastructure, and careful coordination across the entire value chain.

> The central challenge is to make these processes economically viable. Only if converting waste into new products is profitable will companies invest and commit to circular models in the long term. Key factors include process costs, market prices for secondary raw materials, economies

of scale, and regulatory conditions.

Waste and Value

It repeatedly becomes clear that the waste of one actor is often the raw material of another. Waste is therefore less a material issue and more a *systemic problem*. This is particularly true for by-products and residual streams in the agro-industrial sector, where waste streams can often serve as inputs for new processes or products.

From a conceptual perspective, waste in the agro-industry is not primarily a material issue but an economic construct. Nearly every material stream can be technically converted into usable molecules — with membrane technology playing a key role.

Systemic Problem	A systemic problem is not caused by individual elements, but arises from the structures, interactions, and constraints of an entire system.
Systemic Solution	A systemic solution in the food industry connects production, processing, logistics, and utilization in such a way that by-products and residual streams are treated as resources and economically integrated into new processes across the entire value chain.

Value Creation Margin

From an economic perspective, closing a loop becomes attractive when there is a sufficiently large gap between the price a buyer is willing to pay for the processed material and the cost of providing, collecting, and processing that material at its source.

This gap is referred to as value creation. It represents the difference between the achievable market price and the associated costs. Only if this margin is sufficiently large does circular processing become economically viable.

Membrane technology plays a central role by transforming waste streams in a way that increases this margin. Selective separation and processing enable the recovery of valuable components and their conversion into higher-value products, increasing revenue while reducing process costs.

Market Value and Value Creation

To evaluate value creation potential, two key questions must be answered:

a) What is the market value of a material at a defined quality?
b) What technologies are required to reliably achieve this quality?

Market value is not determined solely by purity or functionality, but also by perceived utility from the perspective of potential users.

The market value of the final product defines the upper limit of value creation.

Value is created by transforming a material in a way that increases its market value.

Whether value creation is realized depends on whether processing costs are lower than the achievable market value.

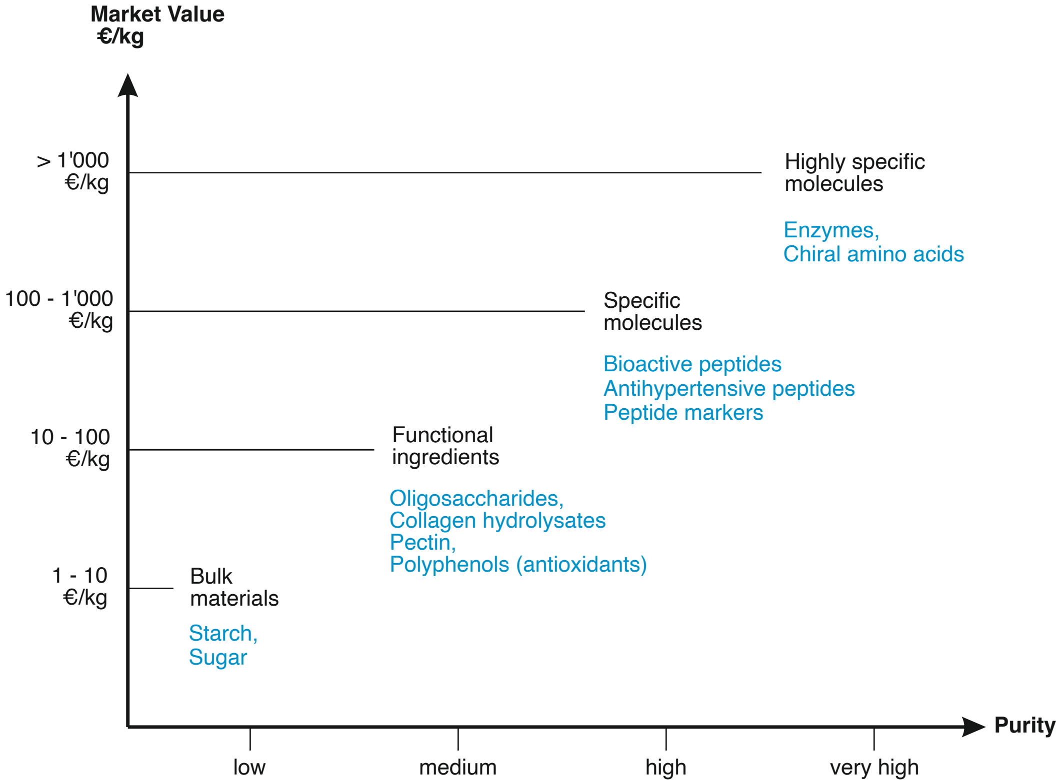

Figure 2. Relationship between purification level and market value. Downstream processing enables the conversion of complex waste and side streams into higher-value, marketable fractions.

1. The economic value of a material is primarily determined by its function and quality, not by its quantity.
2. High-value target compounds can economically compensate for lower technological maturity.
3. Membrane-based separation processes enable the transformation of low-value bulk streams into high-value specialty products.
4. Economically viable circular systems require a value-based rather than purely volume-based perspective on material streams.

Technology Readiness

For practical implementation, it is not only the choice of the appropriate technology that matters, but also the technological maturity (*Technology Readiness Level*) of the process.

The Technology Readiness Level (TRL) is a standardized measure used to assess the maturity of a technology. It describes how close a concept is to industrial application — independent of how innovative or economically attractive it may be.

Table 2. Technology Readiness Level (TRL) Scale

TRL	Description	Process and Membrane Context
TRL 1	Basic principle observed	Physical or chemical separation mechanisms are identified and described theoretically.
TRL 2	Technology concept formulated	A membrane or separation process is conceptually outlined without experimental validation.
TRL 3	Experimental proof of concept	Feasibility is demonstrated at lab scale using model solutions.
TRL 4	Laboratory validation	The process is tested with real or representative streams at lab scale.
TRL 5	Validation in relevant environment	Operation with complex matrices under representative process conditions.
TRL 6	Pilot-scale demonstration	A continuously operated pilot plant is tested with real streams.
TRL 7	Demonstration in industrial environment	The process is implemented at an industrial partner under real operating conditions.
TRL 8	System fully qualified	Plant and process are technically validated and approved for industrial operation.
TRL 9	Industrially established	The process is in routine operation and commercially deployed.

Source: European Commission (2014): Technology Readiness Levels (TRL). HORIZON 2020 Work Programme.

The Technology Readiness Level (TRL) has become an international standard for assessing the maturity of innovations. Originally developed by NASA, it is now widely used in applied research, funding programs, and industrial development projects, including in Europe and Germany.

The widespread adoption of the TRL framework is driven by several factors. First, it provides a simple and clearly structured scale that divides technological development into understandable stages. Second, it enables standardized communication between stakeholders such as research institutions, industrial partners, and funding bodies. Third, it creates transparency regarding the maturity of a technology and supports decision-making related to investment, collaboration, and further development.

As a result, TRL has become a de facto reference framework, particularly at the interface between research, development, and industrial application.

Increasing the Probability of Success

Looking at innovation projects along the Technology Readiness Levels (TRL 1–9), it becomes clear that many projects stall in the transition from TRL 3 to TRL 5. While technical feasibility is often successfully demonstrated at lab scale (TRL 3–4), further development frequently fails when moving toward realistic process conditions and pilot-scale implementation.

The main challenge is less technical feasibility and more economic and systemic complexity. Real process streams are variable, contain impurities, and lead to effects such as fouling or unexpected interactions. At the same time, requirements for process stability, integration into existing infrastructure, and capital and operating costs increase. In addition, the value creation margin is often unclear in early stages, making investment decisions difficult.

To increase the probability of success, it is essential to work systematically under realistic conditions as early as TRL 4. The use of small, computer-controlled experimental systems allows efficient variation of process parameters, early identification of critical effects, and generation of reliable data for techno-economic evaluation. At the same time, economic aspects — particularly cost structures, market prices, and scaling effects — must be considered from the beginning.

An integrated approach that closely links technical development with economic evaluation significantly increases the likelihood that projects successfully transition from laboratory scale to industrial application.

Membrane Technology as a Key Enabler

When proposing the recovery of valuable compounds and water from process streams, you will inevitably encounter recurring objections from production managers. Although these concerns reflect real operational constraints, they often underestimate the value embedded in these streams. A rigorous technical assessment—particularly when applying membrane-based separation processes—demonstrates that substantial material and economic potential can be unlocked in a systematic and economically viable manner.

Typical practical objections include:

Typical Objection	**Assessment / Response**
It is not economically viable.	Economic viability depends on the value creation margin. Appropriate separation technologies increase concentrations and enhance recoverable value.
Our volumes and concentrations are too low.	Even dilute streams can be utilized through selective concentration, particularly for high-value components.
This is too complex for our operations.	Modular and automated systems enable integration with minimal disruption to existing processes.
We do not want additional operational risk.	Pilot studies and TRL-4 validation allow risks to be identified and mitigated under realistic conditions.
We lack space and resources.	Compact, containerized systems reduce spatial requirements and require limited personnel.
This is not our core business.	Partnerships or service-based models enable value recovery without full in-house capabilities.

Table 3. Typical objections and responses regarding the use of process water as a source of value

While these objections reflect practical experience, they do not necessarily preclude implementation. In many cases, they can be systematically addressed through appropriate technical solutions and economically robust process concepts.

Critical Step: TRL 4

If you aim to translate technical potential into implementation, demonstration at TRL 4 is a decisive step. At this stage, the question is no longer whether a concept works in principle, but whether it performs reliably under real process conditions. For decision-makers, theoretical feasibility is insufficient; what matters is verifiable performance using actual process streams. Validation at TRL 4 allows you to directly assess both the technical potential and the practical limitations, thereby significantly reducing uncertainty regarding feasibility and economic relevance.

TRL 4 marks the transition from conceptual development to application-oriented validation. To address this step effectively, small, computer-controlled membrane systems are particularly valuable. They enable you to investigate real process streams at laboratory scale without the complexity, cost, and risk associated with large pilot installations.

Thanks to their high degree of automation and precise controllability, these systems allow you to systematically vary process parameters and directly observe their impact on separation performance, fouling behavior, and energy efficiency. In addition, they support parallel experimentation, making it possible to efficiently compare operating conditions, membrane materials, and process configurations.

A key advantage lies in the scalability of the generated data. Miniaturized systems provide reproducible and quantitatively robust results that form a reliable basis for scaling up to pilot systems (TRL 5–6). This enables early techno-economic assessment and reduces development risk before significant investments are made.

In practical terms, computer-controlled mini membrane systems allow you to validate separation processes quickly, flexibly, and cost-effectively at TRL 4. They are therefore essential tools for turning theoretical potential into technically proven and economically viable solutions.

Mini Membrane Cells

By-Products and Waste Streams in the Food Industry

There is a growing number of processes that enable the recovery of specific, valuable molecules from by-products and waste streams.

These examples illustrate that nearly every process stream contains recoverable value — if the right separation strategy is applied. All products listed below can be produced using small-scale systems.

Table 4. Examples of upgrading by-products and residual streams in the food and agro-industrial sector

Source / By-Product	Target Product	Description / Application
Whey permeate	Oligosaccharides	Whey permeate contains, in addition to lactose, bioactive oligosaccharides that can be used in infant nutrition or functional foods.
Whey and dairy wastewater	Whey proteins / peptides	Valuable protein fractions can be concentrated and used for sports nutrition, functional foods, or specialty formulations.
Fish by-products	Bioactive peptides	Enzymatic hydrolysis followed by fractionation enables the recovery of antioxidant or antihypertensive peptides.
Fish processing wastewater	Collagen / gelatin fragments	Dissolved protein fractions can be recovered and used in food, cosmetics, or biomaterials.
Tomato skins and pepper residues	Carotenoids (e.g., lycopene, capsanthin)	High-value colorants used in food, cosmetics, and nutraceutical applications.
Citrus peels	Pectin	Pectin is a valuable raw material for gelling and stabilizing agents in the food industry.
Apple pomace	Polyphenols / dietary fiber	Polyphenols serve as functional ingredients, while fiber can be used in baked goods or dietary supplements.
Grape pomace	Polyphenols / anthocyanins	Phenolic compounds with antioxidant properties and high potential for food and cosmetic applications.
Berry pomace	Anthocyanins / flavor extracts	Color and flavor compounds can be recovered and marketed as natural ingredients.
Crustacean shells	Chitin and chitosan oligomers	Short-chain oligomers with pharmaceutical and technological relevance require precise processing.
Biotechnological process wastewater	Enzymes	Low-concentration but highly active enzymes can be recovered using technically advanced yet economically attractive processes.
Fermentation broths	Organic acids	Lactic acid, citric acid, or succinic acid can be concentrated and purified.

Source / By-Product	Target Product	Description / Application
Molasses from sugar production	Amino acids / organic acids	By-products can be converted into high-value platform chemicals through fermentation and separation processes.
Brewer’s spent grain	Proteins / dietary fiber	Used as functional food ingredients, in meat alternatives, or in animal feed.
Brewery wastewater	Yeast derivatives / mannoproteins	Cellular components and soluble fractions can be used as additives or feed ingredients.
Potato processing by-products	Proteins (e.g., patatin)	High-quality plant proteins for food, feed, or specialty applications.
Potato fruit water	Amino acids / mineral fractions	Dissolved components can be concentrated and used in feed or as fermentation substrates.
Fruit juice by-products	Polyphenols	Antioxidant compounds with high market value for dietary supplements or functional beverages.
Fruit juice side streams	Flavor compounds	Volatile and dissolved aroma compounds can be recovered and reused in new products.
Vegetable oil extraction by-products	Phospholipids (lecithin)	Lecithin is widely used as an emulsifier in food and pharmaceutical applications.
Oilseed press cake	Protein isolates	Sunflower, rapeseed, or soybean residues contain valuable protein fractions.
Soy processing by-products	Isoflavones / proteins	Valuable secondary plant compounds and proteins for specialty products.
Rice processing by-products	Rice proteins / starch fractions	Fractionated components for gluten-free foods and specialty applications.
Corn processing by-products	Xylooligosaccharides / proteins	Residual streams can be converted into prebiotics or feed components.
Coffee production by-products	Caffeine / polyphenols	Caffeine and antioxidant compounds are valuable for food, beverages, and cosmetics.
Cocoa shells	Polyphenols / dietary fiber	Contain valuable compounds for functional foods or extracts.
Mushroom production by-products	Beta-glucans / proteins	Cell wall components and soluble fractions with potential for immunonutrition and functional foods.
Algae biomass	Pigments / proteins / omega-3-rich fractions	High potential for valuable ingredients with specialized applications.
Slaughterhouse by-products	Collagen / peptides	Protein-rich residues can be processed into gelatin, collagen hydrolysates, or technical products.

Source / By-Product	Target Product	Description / Application
Poultry by-products	Fats / protein hydrolysates	Can be processed into feed components or specialty fats.
Eggshells	Calcium compounds / membrane proteins	Mineral and organic fractions can be separated and reused.
Vegetable washing water	Sugars / organic acids / flavor compounds	Dilute but valuable compounds can be concentrated and reused.
Canning industry by-products	Salt and seasoning solutions	Process solutions contain dissolved compounds that can be recovered or reused internally.
Dairy process water	Lactose / minerals	Dilute streams contain valuable components suitable for feed, fermentation, or technical applications.