Energy Proceedings
Vol 67, 2026

ISSN 2004-2965

A Material–Energy–Behavior Tri-loop Design Study for Waste and Energy Management Toward Integrated Circular Economy Systems

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ABSTRACT

The global promotion of decarbonization and the circular economy (CE) calls for a new perspective on waste reduction and energy management in an integrated way. Single-use plastics, especially beverage containers, remain a major contributor to resource inefficiencies and environmental impacts, and life cycle assessment (LCA) and material flow analysis (MFA) studies have quantified their environmental impact (Busch et al., 2021; Chairat et al., 2023; Liang et al., 2023). On the other hand, policies such as the EU's Single-Use Plastics Directive and the Deposit Return Scheme (DRS) have achieved some results (European Commission, 2020; OECD, 2022), political conflicts and difficulties in institutional adjustment have become apparent in the social implementation stage (UK Government, 2024; BBC, 2024). Additionally, IoT-based technologies such as smart collection devices and refill vending machines enhance resource circulation while increasing overall facility electricity consumption, creating energy management challenges (Islam et al., 2021; Ruan et al., 2022). Recent research has shown the effectiveness of integrating CE with energy efficiency measures (Seljak et al., 2023), but there is a lack of design frameworks that link device-level power loads and consumer behavior. In this study, we propose the "Material–Energy–Behavior Tri-loop Framework" to fill this research gap. This framework simultaneously deals with the three elements of (1) material loop, (2) energy management, and (3) behavior loop, and integrates usage data and energy data through IT and IoT platforms. This will redefine waste reduction from a "resource problem" to a "system design issue that connects energy and action" and provide new design guidelines for researchers and policymakers.

Keywords: circular economy, plastic reduction, energy management, deposit return scheme (DRS), demand response (DR), behavior change

NONMENCLATURE

BEMS	Building Energy Management System, a digital platform to monitor and optimize energy use in buildings.
BYO	Bring Your Own, here referring to consumer behavior of bringing personal reusable containers (e.g., bottles, cups).
CE	Circular Economy, an economic model aimed at minimizing waste and maximizing resource efficiency through reuse, recycling, and sustainable design.
DR	Demand Response, an energy management approach that adjusts electricity consumption in response to supply conditions, often for grid balancing.
DRS	Deposit Return Scheme, a policy mechanism where consumers pay a deposit on beverage containers and receive a refund upon returning them.
GHG	Greenhouse Gas, including CO_2 and other emissions contributing to climate change.
LCA	CO_2 – Carbon dioxide, a primary greenhouse gas emitted from fossil fuel combustion and waste processing.
MFA	Material Flow Analysis, a systematic assessment of flows and stocks of materials within a system defined in space and time.
RVM	Reverse Vending Machine, a smart device that accepts empty beverage containers and returns a deposit or reward.
Tri-loop Framework	A conceptual design linking three loops: Material (resource circulation), Energy (management and efficiency), and Behavior (consumer incentives and change

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This is a paper for the 17th International Conference on Applied Energy (ICAE2025), December 8-12, 2025, Bangkok, Thailand.

1. INTRODUCTION

Waste reduction and circular economy (CE) have their own measures and are being promoted as policies in each country. For example, the EU's Single-Use Plastics Directive mandates the reduction of single-use plastics, including beverage containers, and mechanisms such as the Extended Producer Responsibility Scheme (EPR) and the Deposit Return Scheme (DRS) have been introduced (European Commission, 2020; OECD, 2022). While these measures have achieved certain results in resource circulation, political conflicts and difficulties in institutional adjustment have become apparent in the implementation process (UK Government, 2024; BBC, 2024).

In addition, life cycle assessment (LCA) and material flow analysis (MFA) studies have quantified the environmental impact of single-use plastics in detail and demonstrated the effectiveness of reuse systems (Busch et al., 2021; Chairat et al., 2023; Liang et al., 2023). However, it has been pointed out that not only technical support but also a digital infrastructure that supports user behavior is essential when actually promoting social implementation (White et al., 2020; Duffy et al., 2021). In particular, IoT-based applications such as smart collection devices and refill vending machines are effective means of enhancing resource circulation while increasing overall facility electricity consumption and creating new energy management challenges (Islam et al., 2021; Ruan et al., 2022).

In this way, waste reduction and CE measures have developed respectively, but in the phase of social implementation, IT and IoT infrastructure and energy consumption are inevitably linked, and conventional system design and evaluation research alone are not enough. Seljak et al. (2023) argued for the integration of the two at the macro level, showing a positive correlation between improving the Circular Economic Index (CE index) and implementing energy efficiency measures. However, most of the existing studies are biased towards the institutional and policy levels, and there is a lack of frameworks for integrating device-level power loads and user behavior (Kirchherr et al., 2017; Ghisellini et al., 2016).

The Material - Energy - Behavior Tri-loop Framework proposed in this study fills this gap. In other words, by simultaneously dealing with the three elements of (1) material loop, (2) energy management, and (3) behavior loop, and integrating the usage data and energy data obtained through IoT applications, this study aims to create a design model that connects waste reduction, circular economy, and energy efficiency, and reduce plastics. By redefining the "resource problem" to "system design issues that connect energy and action," to present a path to promote sustainable social implementation.

On the other hand, macro-level policy research emphasizes the need for integrated design of circular economy (CE) and energy systems. Seljak et al. [8] showed a correlation between improving the circular economy index (CE index) and the introduction of energy efficiency measures through analysis using national data, and revealed that the integration of the two may achieve both resource efficiency and environmental improvement at the same time. This suggests that resource circulation and energy management should not be treated as separate domains, tough rather require an integrated design framework.

However, much of the existing research has focused on the institutional and policy levels, and the integrated examination of factors such as actual energy consumption at the device level, changes in consumer behavior, and promotion of participation through environmental scores and incentives has not been sufficiently advanced. In order to fill this research gap, this study proposes the "Material–Energy–Behavior Tri-loop Framework". This framework aims to bridge the gap between micro-level empirical data and macro-level institutional design by enabling design studies that simultaneously consider three aspects at the same time: (1) material loop, (2) energy management, and (3) behavior loop.

2. LITERATURE REVIEW

2.1 Policy and Institutional Design (Revised with Case Studies)

Globally, policies such as the EU Single-Use Plastics Directive, Extended Producer Responsibility (EPR), and Deposit Return Schemes (DRS) have been implemented to reduce single-use plastics (European Commission, 2020; OECD, 2022). Among these, DRS systems in Germany and Nordic countries have achieved return rates of about 98 **%**, often cited as successful examples of institutional design that effectively links economic incentives with behavioral change (TOMRA, 2020).

In contrast, the United Kingdom has postponed its DRS implementation until 2027, revealing the challenges of political negotiation and industry consensus (UK Government, 2024; BBC, 2024).

Meanwhile, Japan has maintained one of the highest plastic recycling rates globally - over 90% for PET bottles (MOEJ, 2023), supported by strong local collection systems and industry collaboration through the Japan Containers and Packaging Recycling Association. However, much of this “recycling” still depends on thermal recovery and downcycling, highlighting the need for more circular material flows and behavioral engagement beyond collection.

Institutional success therefore requires not only regulation but also integration between material systems, energy management, and consumer participation. To illustrate this connection, several practical initiatives demonstrate how policies are translated into action through technology and design.

2.1.1 Case Studies of Digital and Behavioral Recycling Initiatives

While national frameworks provide the foundation, multiple field-level case studies show how digital services, IoT systems, and behavioral incentives interact within the material–energy–behavior nexus. These examples clarify both the effectiveness and the systemic limitations of current approaches.

(1) App-Based Bottle Initiative (Japan)

The initiative named Fills represents a app-based behavioral intervention designed to promote reusable bottle use without requiring any additional energy input.

Users log their beverage purchases or refills through the mobile application, which assigns environmental scores and visualizes their cumulative CO_2 savings. During short-term pilots conducted in office and retail environments, reusable bottle usage increased by approximately 70% compared with baseline levels, indicating a strong Behavior-Material coupling**.** Because the system operates solely through digital engagement without any IoT hardware or powered collection device, the energy loop remains neutral, effectively achieving behavioral change with minimal environmental overhead.

This case thus demonstrates how a non-energy-dependent digital service can complement physical circularity mechanisms by leveraging motivational feedback and environmental scoring.

(2) Water3 Smart Refill Dispenser (Australia)

The Water3 system provides vending-style refill stations. It eliminates single-use PET bottles by encouraging consumers to refill personal bottles directly. While this system achieves high material efficiency and minimizes grid dependence, refrigeration and payment modules require 220 W of continuous load. The user participation remains limited to environmentally conscious early adopters due to required app registration and payment setup.

(3) Reusable Cup Services (UK)

Services such as CupClub (UK) introduce a subscription-based return model for reusable cups in offices and cafés. These systems achieve **40–60% reuse rates**, yet the collection, washing, and redistribution logistics consume significant energy and water. Life Cycle Assessments indicate that a net CO_2 reduction appears only after 15–20 reuse cycles, suggesting a gap between behavioral success and overall energy efficiency (Verbeek et al., 2021).

(4) Reuse Cup Vending Machines (South Korea, 2023)

Emerging refill vending machines that dispense reusable cups or bottles represent a hybrid model integrating digital tracking, material recovery, and energy use. These units typically consume around 200W during operation and are not yet connected to building energy management systems (BEMS). They highlight both the potential for comprehensive integration and the remaining challenges in aligning operational energy loads with behavioral benefits.

2.2 Environmental Impact Assessment through LCA/MFA

Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) studies on beverage containers have systematically quantified environmental impacts, including comparisons between virgin PET and recycled PET, and the emission reduction effects of reusable containers depending on the number of reuses (Busch et al., 2021; Chairat et al., 2023; Liang et al., 2023). Verbeek et al. (2021) compared CO_2 emissions between reusable and single-use containers, demonstrating the advantages of circular scenarios. However, these studies focus on quantifying environmental impacts and show limited connection to energy management.

2.3 Smart Collection Devices and Reuse Services

IoT- and RFID-enabled smart collection devices and cloud-based reuse services can enhance user convenience and promote circularity (Islam et al., 2021). CupClub (2021) and SmaGo (2020) demonstrated city-scale reuse collection, while LALA Loop (2022) piloted reusable cup circulation in Japan. Nevertheless, challenges remain regarding energy loads and long-term social adoption

2.4 Energy Management

Research on demand response (DR) and Building Energy Management Systems (BEMS) has highlighted the potential of leveraging flexible loads (Siano, 2014; Li et al., 2021). Studies on vending machines and commercial appliances as DR resources (Ruan et al., 2022; Ahmed et al., 2023) suggest that beverage-related equipment could serve as new energy assets. However, discussions rarely integrate these perspectives with resource circulation equipment such as collection machines and refill vending systems.

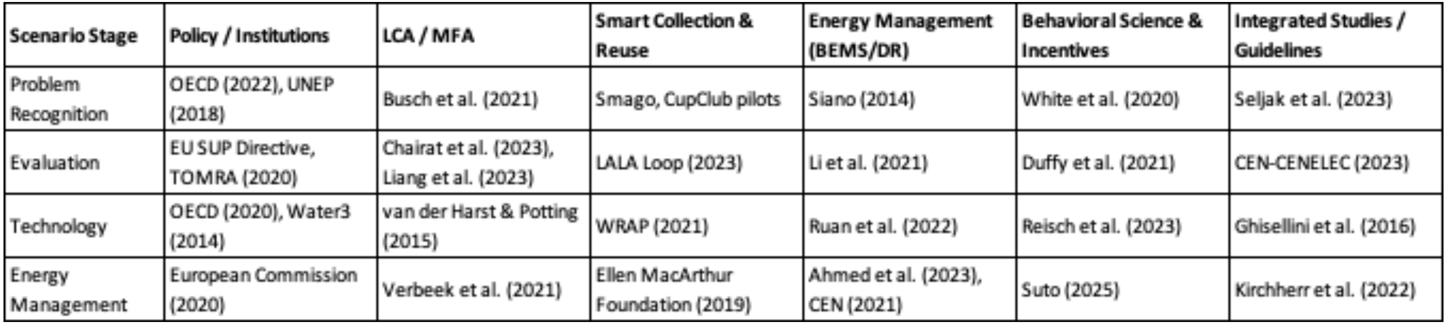
2.5 Behavioral Incentives

Behavioral science research has demonstrated that incentives and environmental scoring can influence consumer decisions. White et al. (2020 systematized the effects of social norms and information disclosure, while Duffy et al. (2021) and Reisch et al. (2023) showed that environmental scores and probabilistic rewards can trigger short-term behavioral changes. Yet, these studies generally lack integration with energy demand and supply systems. In Japan, surveys conducted under the Ministry of the Environment's Green Life Point program revealed that a majority of respondents wanted environmental points to be issued by supermarkets, nearly half by convenience stores, restaurants, and utility providers, followed by electronics retailers, fast-food chains, and home centers (MOEJ, 2019. Interestingly, although consumers typically associate such point schemes with retail or food services, 45.5% also indicated that energy utilities (electricity and gas companies) should provide environmental points. This highlights a gap between the industries where consumers most expect to receive points (retail and food service) and those where such schemes could have the greatest systemic impact (energy and infrastructure). These findings underscore the necessity of embedding environmental point mechanisms not only in consumer-facing retail contexts but also in energy management systems, thereby linking behavioral change directly with energy loops.

2.6 Integrated Perspectives and Research Gaps

Seljak et al. (2023) argued that integrating circular economy indicators with energy efficiency measures can improve resource efficiency, while CEN-CENELEC (2023) recommended standardizing such indicator integration. However, existing research remains largely focused on macro-level policy and institutional design, with few studies linking micro-level device energy consumption and consumer behavior into an integrated framework. To address this gap, this study proposes the Material – Energy - Behavior Tri-loop Framework as a new design model that unites resource circulation, energy management, and behavioral science.

Table.1 Scenario Stages and Coverage of Prior Research



Scenario Stage	Policy / Institutions	LCA / MFA	Smart Collection & Reuse	Energy Management (BEMS/DR)	Behavioral Science & Incentives	Integrated Studies / Guidelines
Problem Recognition	OECD (2022), UNEP (2018)	Busch et al. (2021)	Smago, CupClub pilots	Siano (2014)	White et al. (2020)	Seljak et al. (2023)
Evaluation	EU SUP Directive, TOMRA (2020)	Chairat et al. (2023), Liang et al. (2023)	LALA Loop (2023)	Li et al. (2021)	Duffy et al. (2021)	CEN-CENELEC (2023)
Technology	OECD (2020), Water3 (2014)	van der Harst & Potting (2015)	WRAP (2021)	Ruan et al. (2022)	Reisch et al. (2023)	Ghisellini et al. (2016)
Energy Management	European Commission (2020)	Verbeek et al. (2021)	Ellen MacArthur Foundation (2019)	Ahmed et al. (2023), CEN (2021)	Suto (2025)	Kirchherr et al. (2022)

3. METHODOLOGY: DESIGN OF EVALUATION INDICATORS

To validate the proposed Material - Energy - Behavior Tri-loop Framework, it is necessary to establish quantitative indicators for each of the three loops: resource circulation (Material), energy management (Energy), and behavior change (Behavior). The design of these indicators draws upon the Japanese Ministry of the Environment's Environmental Accounting Guidelines (MOE, 2019) and the calculation methods adopted in the Green Life Point Program . The guidelines classify environmental conservation effects into four categories, each with illustrative metrics:

- Resource Inputs: total energy consumption (J), water resource input (m^3), input of specific substances (t).
- Emissions and Waste Outputs: greenhouse gas emissions ($t\text{-}CO_2eq$), total waste generation (t), NOx and SOx emissions (t).
- Products and Services: energy consumed during use (J), emissions at disposal (t), recovered and reused packaging or containers (t).

- Other Effects: transport-related emissions (t·km), noise/vibration levels (dB), water quality indicators (BOD/COD).

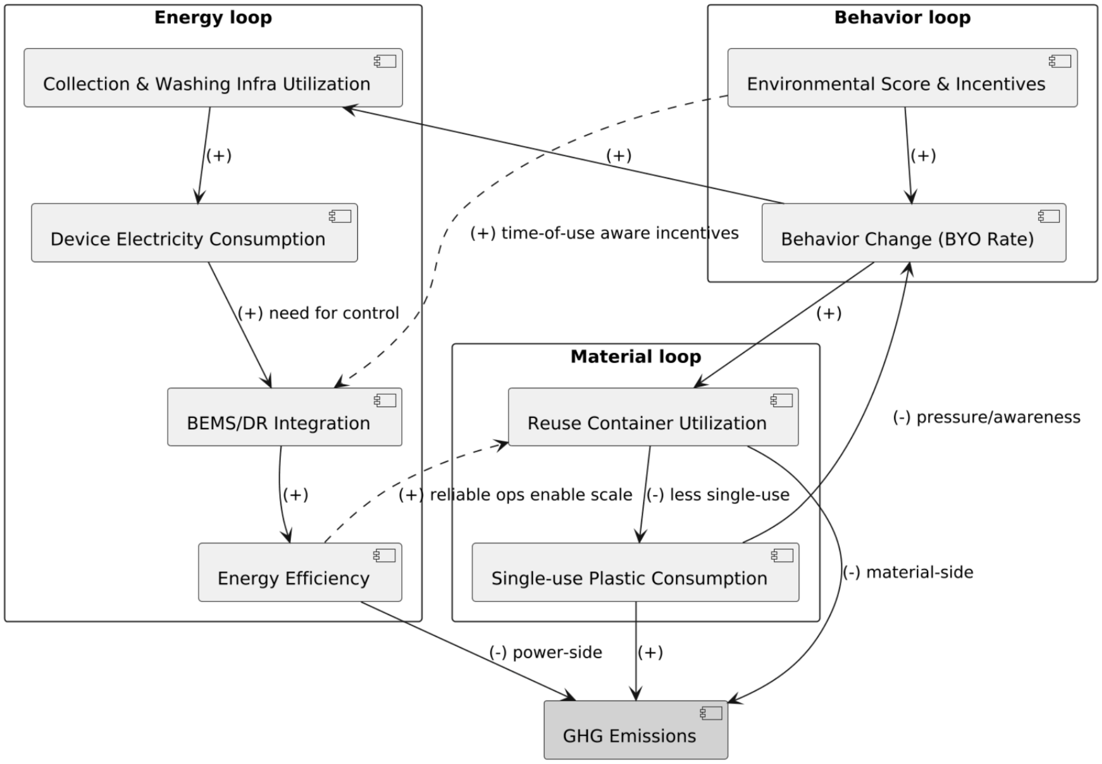


Fig. 1 Causal Loop of Material, Energy and Behavior

(+) : Positive impact (increase → increase / decrease → decrease)
(–) : Negative impact (increase → decrease / decrease → increase)
Solid line : Main causal link
Dashed line : Indirect / supportive link

Importantly, the framework also requires consideration of secondary negative impacts, such as increased electricity demand or waste generation resulting from plastic reduction initiatives or IoT deployment. This trade-off perspective is particularly relevant for evaluating refill vending machines and smart collection devices.

Based on this foundation, the following Tri-loop indicators are proposed:

- Material loop: plastic reduction (t), collection rate (%), reuse turns per container.
- Energy loop: device electricity consumption (kWh/dispense), contribution to peak load (%), demand response (DR) flexibility score.
- Behavior loop: reusable bottle utilization rate (%), environmental score adoption rate (%), behavioral persistence rate (%).
- Integrated indicators: GHG emissions per serving (g-CO_2eq), joint achievement index combining behavior change effectiveness and energy savings.

By anchoring the indicator design in established national policy frameworks and extending them to cover energy and behavioral dimensions, this methodology ensures that the Tri-loop Framework is grounded in both scientific and policy contexts. Linking resource circulation metrics with preliminary indicators of energy flexibility highlights the potential for smart circular economy systems to contribute not only to waste reduction but also to energy-efficient operations. While empirical validation is still limited, this integrated perspective provides a basis for future research on connecting circularity, energy management, and user behavior

4. APPLIED EXPERIMENTAL SYSTEMS

In order to demonstrate the applicability of the proposed Material–Energy–Behavior Tri-loop Framework, it is important to connect theoretical design with potential real-world systems. While this study does not present practical pilot results, it anchors its methodological foundations in two ongoing initiatives.

First, the Iida patent (Iida, 2019) serves as a conceptual basis for linking beverage purchase systems with environmental scoring. This patented design enables the allocation of environmental scores when consumers use refillable containers, thereby directly coupling consumer behavior (Behavior loop) with material efficiency (Material loop). The energy dimension (Energy loop) is not yet implemented, but the system concept provides a foundation for integration with BEMS/DR in the future.

Second, the Fills system, developed in Japan, represents a business-oriented implementation of reusable container services that integrates digital tracking and user incentives. Although empirical pilot data are not included in this paper, the system demonstrates how smart refill vending and IoT-enabled collection could serve as experimental targets for evaluating the Tri-loop Framework. In particular, the combination of refill behavior, machine-level electricity consumption, and environmental scoring offers a fertile ground for future experimental research.

Beyond the Fills initiative, several existing reuse and recycling systems—such as Water^3 in Australia, CupClub in the UK, and Oysterable in Korea—illustrate different approaches to integrating user behavior, material circulation, and energy management. A comparative overview of these systems is presented in Table 4, followed by a discussion of their systemic asymmetries.

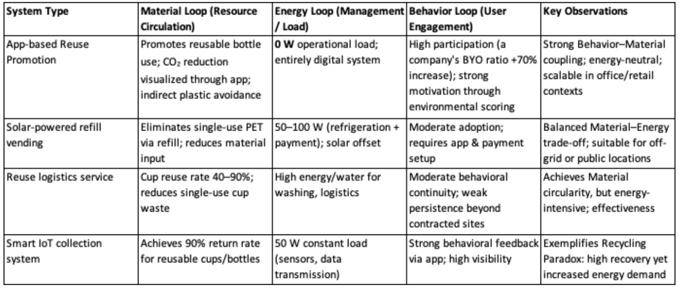
The four case studies (Fills, Water3, CupClub, and Oysterable) were compared under the three-loop lens of Material, Energy, and Behavior. Rather than assigning arbitrary weights, the analysis focused on empirical contrasts among systems. Fills demonstrated strong behavioral participation and zero operational energy, representing a behavior-driven but energy-neutral model.

In contrast, Oysterable and CupClub achieved higher material circularity through IoT and logistics systems but introduced continuous energy loads. Water3 represented an intermediate case, where refill-type vending required moderate electricity yet encouraged stable reuse.

These patterns reveal the asymmetry across current reuse and recycling systems — behavioral effectiveness often accompanies increased energy dependency, highlighting the need for integrated design logic rather than partial optimization.

Thus, while this study is limited to presenting the conceptual framework, both the Iida patent and the Fills initiative establish a practical context that can support future validation of the Tri-loop model. These examples highlight the feasibility of integrating resource circulation, energy management, and behavioral change into one coherent design system.

Table 4. Comparative Analysis of Reuse and Recycling Systems under the Tri-loop Perspective



System Type	Material Loop (Resource Circulation)	Energy Loop (Management / Load)	Behavior Loop (User Engagement)	Key Observations
App-based Reuse Promotion	Promotes reusable bottle use; CO_2 reduction visualized through app; indirect plastic avoidance	**0 W** operational load; entirely digital system	High participation (a company's BYO ratio +70% increase); strong motivation through environmental scoring	Strong Behavior–Material coupling; energy-neutral; scalable in office/retail contexts
Solar-powered refill vending	Eliminates single-use PET via refill; reduces material input	50–100 W (refrigeration + payment); solar offset	Moderate adoption; requires app & payment setup	Balanced Material–Energy trade-off; suitable for off-grid or public locations
Reuse logistics service	Cup reuse rate 40–90%; reduces single-use cup waste	High energy/water for washing, logistics	Moderate behavioral continuity; weak persistence beyond contracted sites	Achieves Material circularity, but energy-intensive; effectiveness
Smart IoT collection system	Achieves 90% return rate for reusable cups/bottles	50 W constant load (sensors, data transmission)	Strong behavioral feedback via app; high visibility	Exemplifies Recycling Paradox: high recovery yet increased energy demand

5. DISCUSSION

5.1 Identified Gaps

Existing scholarship has produced a substantial body of macro-level policy research on circular economy and waste reduction, particularly concerning regulatory frameworks such as deposit return schemes and extended producer responsibility (European Commission, 2020; OECD, 2022). However, relatively little attention has been paid to the micro-level, where the energy consumption of devices and the dynamics of behavioral change must be jointly examined (Siano, 2014; Li et al., 2021). Current reuse services and pilots such as smart collection systems or subscription-based cup reuse models—tend to emphasize the linkage between material circulation and consumer behavior (Islam et al., 2021; CupClub, 2021; LALA Loop, 2022), while the energy dimension remains largely absent. This imbalance highlights the need for an integrative framework that explicitly connects all three loops.

5.1.1 Comparative Analysis of Four Circular Systems

A comparative assessment of four representative cases, Fills (Japan), Water3 (Australia), CupClub (UK), and Oysterable (South Korea) reveals a structural asymmetry in current reuse and recycling system design when analyzed through the Materia-Energy-Behavior Tri-loop Framework.

(1) Behavioral dependence with weak energy integration.

App-based systems such as Fills effectively trigger behavioral change without additional energy demand. In contrast, IoT-based collection systems (Oysterable, CupClub) acquire valuable behavioral and material data but neglect energy optimization in their design phase. Thus, behavioral success often comes at the cost of increased electricity use, a clear trade-off in modern circular services.

(2) The Recycling Paradox.
High-performing collection systems such as *Oysterable* achieve return rates approaching 70%, yet constant sensor and communication loads (50 W) offset part of their environmental gain. This highlights a recycling paradox: *recycling itself consumes energy*, complicating the net benefit of CO_2 reduction.

(3) Separation between Reuse and Recycle logic.
Fills (reuse) and *Oysterable* (recycle) represent distinct stages within the Material Loop, pre-consumption behavioral control versus post-consumption energy-intensive recovery. However, policies and studies often conflate both under the single term “circularity.” The Tri-loop Framework explicitly distinguishes these stages, enabling integrative assessment of energy and behavioral efficiency.

(4) Partial optimization across cases
Each system excels in one or two loops but lacks total integration. Fills *shows strong Material–Behavior coupling but no energy layer;* Oysterable *connects Material an*d Behavior but is energy-intensive; *CupClub* integrates Energy - Material but relies weakly on user behavior.

5.1.2 Future directions

This comparison suggests three priorities:

(a) optimize reuse systems to leverage behavioral engagement with minimal energy use (e.g., Fills + BEMS integration);

(b) apply demand-response strategies to control peak loads in recycling devices; and

(c) introduce policy-based “Circular Scores” that incorporate energy indicators (e.g., Japan’s Green Life Point program).

Collectively, these findings underline the necessity of the Tri-loop Framework as a holistic design theory bridging behavioral, material, and energy dimensions in circular infrastructures.

5.2 Tri-loop Framework Implications

The Material – Energy - Behavior Tri-loop Framework proposed in this study offers a means of bridging the divide between macro-level policy design and micro-level device implementation. By addressing resource circulation, energy management, and behavioral guidance simultaneously, the framework moves beyond the partial optimizations that characterize most existing approaches (Seljak et al., 2023). Instead, it provides a pathway toward system-wide optimization in which consumer incentives, operational energy management, and material recovery are mutually reinforcing.

5.3 Research and Policy Recommendations

The findings suggest several directions for both research and policy. On the research side, small-scale pilot projects should be designed to integrate Building Energy Management Systems (BEMS) and demand response (DR) with reuse and refill infrastructure, thereby demonstrating their technical feasibility (Ruan et al., 2022; Ahmed et al., 2023). From a policy perspective, environmental scoring and point-based incentive schemes could be explicitly linked with demand-side energy rewards (White et al., 2020; Duffy et al., 2021; Reisch et al., 2023), encouraging both sustainable consumption and flexible energy use. Academically, further investigation is required to establish causal relationships between behavioral patterns and energy dynamics, supported by mathematical modeling and quantitative evaluation.

5.4 Limitations

This paper has not presented pilot test results. While the framework is grounded in both literature and policy analysis, empirical validation remains an important next step. Future work will build on ongoing developments, including patented systems for bottle-based beverage sales (Iida, 2019) and experimental demonstrations such as the Fills project (Oysterable, 2023), in order to provide concrete data for testing the proposed

5.5 Future Research Direction

Building on the comparative analysis of reuse and recycling systems, the next stage of this research will focus on quantifying the trade-off between decarbonation effects and energy demand in digital and automated circular infrastructures. Specifically, the study will develop simulation models incorporating the electricity consumption of vending and refill machines, examining how the introduction of IoT-based resource circulation devices affects both operational energy loads and CO_2 reduction performance. By integrating demand-response scenarios and renewable power inputs, the model aims to identify the optimal balance point where behavioral participation and energy efficiency can coexist without offsetting each other’s environmental benefits.

Through this approach, the study seeks to advance the Material – Energy - Behavior Tri-loop Framework from conceptual design toward quantitative validation, contributing to the broader field of energy management within the circular economy.

6. CONCLUSION

In this study, the author presented the Material-Energy-Behavior Tri-loop Framework as a conceptual and design model for integrating plastic reduction and energy management. While existing systems and services have primarily focused on resource circulation and behavioral guidance, they have lacked an explicit energy perspective. Notably, the EU's Deposit Return Scheme demonstrates strong alignment between Material and Behavior loops, yet Energy integration remains absent. Other initiatives show that waste reduction can inadvertently increase energy consumption when integration is not systematically considered.

The Tri-loop Framework proposed in this paper reframes plastic reduction not as an isolated resource problem but as a system design challenge that brings materials, energy related to facilities/utilities and human behavior. Rather than presenting a single technological solution, this study emphasizes a generalized model that can guide the evaluation and design of diverse systems and services. Future research should focus on demonstrating the integration of BEMS/DR with resource circulation infrastructures, verifying the causal links between behavioral incentives and energy flexibility, and connecting micro-level experiments to macro-level institutional design.

ACKNOWLEDGEMENT

The author would like to express their gratitude to Fills Inc., Oysterable Inc. and the Ministry of Environment Japan for their valuable input and references that informed this research. Special thanks are also to Professor Yoshiaki Ohkami for his academic guidance, and to colleagues and stakeholders who supported the development of this study.

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