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# TEMPORARY MATERIAL HUBS TO ENHANCE CIRCULAR ECONOMY: A CONCEPTUAL FRAMEWORK

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**ABSTRACT**

This study introduces the integrative concept of Temporary Material Hubs (TMHs) as a newly adapted approach to enhance long-term improvement in circularity by storing prospectively valuable waste, under current conditions not feasible or possible to recover, for future recycling capabilities. TMHs aim to optimize resource recovery by prolonging the lifespan of materials in anthropogenic cycles and avoiding premature disposal. Unlike landfilling with subsequent landfill mining (disposal and later excavation), TMHs proactively store such materials in controlled "hubs" to preserve value and enable future high-quality recovery. The conceptual framework is complemented by the known final sink concept to maintain clean material cycles. Given the lack of a clear definition of recyclability, this paper further proposes recycling pillars as guiding principles in the context of TMHs: environmental and health protection, availability of adequate recycling technologies, and economic feasibility including the availability of markets. Exemplary candidate materials for TMHs currently envisage, e.g., end-of-life wind blades and incineration residues. A SWOT analysis was used to discuss the strengths of TMHs in promoting resource optimization through postponed recycling, while identifying weaknesses such as uncertain costs and current lack of accurate technical implementation concepts. Opportunities lie in supporting European circularity goals and reducing primary material extraction, whereas threats include future regulatory uncertainties and inaccurate estimations of future waste recyclability. This study prepares the ground for future research and risk-assessment on technical, economical, and societal factors necessary for implementing TMHs on an industrial scale to ensure better functioning of the circular economy and a sustainable future.

## 1. INTRODUCTION

The waste sector is adapting to societal and environmental needs while navigating through restricting policies and remaining tightly connected to the economy. According to the European waste hierarchy, the highest priority is waste prevention and minimization (European Parliament (EP) and the Council, 2024b). However, modern society inevitably produces waste, and globally, the current waste management system still relies mainly on disposal (landfilling) (Kaza et al., 2018). New EU policies and strategies such as the European Green Deal strive for sustainable future based on the concept of circular economy, which conserves resources and keeps them in anthropogenetic cycles (European Council, 2024). Anthropogenic resources and waste are emerging as future sources of materials (Ghisellini et al., 2022).

The overall aim to foster a circular economy is compromised by the decrease in the share of secondary materials entering the global economy, from 9.1% in 2018 to 7.2% in 2023 (Fraser et al., 2024). The European circular material use rate was 11.8% in 2023 (European Environment Agency (EEA), 2025). In addition, resource consumption has increased significantly; society consumed a similar volume of resources from 2018 to 2024 as during the entire 20$^{th}$ century (582 versus 740 billion tonnes, respectively (Fraser et al., 2024)).

To counteract this trend, the European Commission (EC) sets clear targets for reuse and recycling of waste, e.g., 70% for construction and demolition waste by 2020 and a 65% target for municipal solid waste by 2035 (EP and the Council, 2024b). To further minimize environmental impact, the EU Landfill Directive restricts landfilling of recyclable waste from 2030 if suitable for material and energy recovery and caps landfilling of municipal solid waste at 10% by 2035 (EP and the Council, 2024a). Despite these efforts, 22.6% of municipal solid waste was

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still landfilled in the EU in 2019 as the primary treatment step (EC, 2020c).

Although recycling (followed by recovery) is at the bottom of the "10R" hierarchy (Vermeulen et al., 2019), it remains a cornerstone of a circular economy, keeping materials in anthropogenic cycles and maximizing their value. However, suitable markets for secondary materials are often not available. Some secondary raw material (SRM) markets, e.g., aluminium, glass and paper, are well-functioning with significant market shares of recyclates compared to raw materials (EEA, 2022, 2023). For instance, aluminium is highly circular and recyclable, maintaining its quality through repeated processing. Its primary production is very energy-intensive, but recycling saves up to 95% of energy and $CO_2$ emissions (European Aluminium, 2017, 2020).

In contrast, SRM markets for biowaste, construction and demolition waste, plastics, textiles and wood are generally less functional. The EEA attributes this to smaller market size, weaker demand, and inconsistent material specifications, hindering industrial applications (EEA, 2023). For instance, only a small percentage of construction and demolition waste is economically valuable, leading to low-quality recycling and a global recovery rate below one-third of the total amount of this waste (EEA, 2022; Ghisellini et al., 2022). While technology is available, market challenges, rather than technical limitations, appear to hinder recycling rates. The market is predominantly local (EEA, 2022).

To ensure sustainability, product designers must consider ecodesign rules embedded in the Ecodesign for Sustainable Products Regulation (EP and the Council, 2024c). Meanwhile, the waste management sector must handle already produced waste and products not yet targeted for recycling. Some materials are currently not feasibly recyclable or lack SRM markets but could become recyclable in future. However, the current waste management system prioritizes immediate processing, often through energy recovery or disposal, for materials/waste lacking immediate value, due to legal or financial issues. Storing them in specifically designed temporary deposits for postponed recycling could enhance circularity and material recovery. Already in the 1990s, ideas of prolonged storage for recyclable materials were explored. For example, a patent proposed temporarily storing plastic waste in bales within landfills (Herhof Umwelttechnik GmbH, 1992). This method aimed to reduce fire risks during storage by mixing plastic waste with low calorific value additives, such as processed construction waste or other inert materials, and bundling it into bales. The goal was to make the stored waste reusable in the future, expecting advancements in plastic recycling technology within 5 to 10 years (Herhof Umwelttechnik GmbH, 1992). However, this concept has not yet become widely established. Current concepts of temporary storage of waste are usually short-term and for specific waste streams (e.g., e-waste, hazardous waste, waste from disasters, demolition waste from military actions), which require proper disposal or recycling at a postponed date.

Conversely, legislative efforts to reduce disposal and energy recovery in favour of maximized material recovery may increase contaminated materials in anthropogenic cycles. Contaminated waste poses risks to the environment, human health, clean cycles, and high-quality secondary materials, requiring safe disposal (Kral et al., 2013). The EEA emphasizes the importance of sustaining clean material cycles for a functioning circular economy, both from a safety and an economic perspective (EEA, 2017). The Regulation on the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) promotes "safe-by-design" chemicals, substituting hazardous chemicals by safer ones. However, hazardous chemicals and so called persistent pollutants can persist in older products and recovered materials (EC, 2020b), especially within open-loop recycling systems (Pivnenko, 2016). Pivnenko (2016) proposed a hierarchy for contaminant mitigation, recommending incineration or adequate final sink (controlled landfill) when contaminant removal technologies or organizational approaches are unavailable.

This study proposes a conceptual framework to enhance circularity in the mid- to long term by introducing Temporary Materials Hubs (TMHs) for controlled, prolonged interim storage of materials/waste, targeting for the postponement of recycling until technological advancements or favourable economic conditions make it feasible and environmentally safe. By formalizing TMHs as a distinct strategy, introducing "recycling pillars" as a novel decision-making framework for evaluating recyclability, and integrating final sinks to maintain clean material cycles, this approach addresses a gap in current waste management strategies and meaningfully advances circular economy efforts.

Currently, the considerations focus on the EU, proposing a conceptual framework based on the region's waste management priorities and EU-waste hierarchy; however, with adaptations to meet legal, technical and economic conditions of other regions, the framework could reach global applicability.

## 2. MATERIALS AND METHODS

The concept is grounded in an integrative literature review, a methodological approach designed to systematically generate new concepts or ideas from existing literature (Torraco, 2016). Findings were used to create a conceptual framework and a renewed organizational approach in waste management, differentiated from existing interim storage strategies.

The integrative literature research was crucial for developing TMHs, as the explorative nature of this research required a structured yet flexible approach, studying mostly mature topics. During the literature research, we identified six key themes, which are visualized in a concept map in Figure 1, along with associated key words demonstrating the systematic process behind the analysis. Storage of radioactive waste was excluded, ensuring the focus on relevant studies. Five materials/types of waste with limited recyclability were chosen to highlight the need for this concept. Two purposes are explored in detail, and a SWOT analysis assesses the theoretical concept's performance. The TMHs concept is complemented by final sinks to ensure safe disposal of non-recyclable (e.g., asbestos, wooden railway sleepers), contaminated (e.g., textiles containing perfluoroalkyl and polyfluoroalkyl substances (PFAS)) or degraded materials in order to sustain clean material cycles and protect the environment. Detailed considerations of the final sink concept are excluded, as they are covered by existing publications (Cossu, 2016; Kral et al., 2013, 2019; Stanisavljevic & Brunner, 2021).

European Directives and national legislations were studied to examine the current legal state of waste storage and circularity, while EC documents provided data on specific waste streams. In total, 134 references are cited in our study, including peer-reviewed studies as a majority, followed by EU policy documents and research reports.

Discussions with waste management experts and scientists, mainly from Austria and Germany (e.g., concept presentation and discussion at young scientist congress hosted by DGAW), and peer groups (e.g., academic mentors, faculty members and fellows of the interdisciplinary BOKU-Doctoral School "Transitions to Sustainability" (T2S)), served as a valuable complement and provided additional input also from other disciplines. Experts individually evaluated the general concept of TMHs, no structured interviews were conducted at this stage.

## 3. CURRENT RECYCLING LIMITATIONS AND CHALLENGES

Recyclability determines whether materials/waste remain within the anthropogenic cycles. The Waste Framework Directive very generally describes recycling as "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes" (EP and the Council, 2024b), providing no criteria to assess "recyclability". In general, a single definition of recyclability is missing on the EU level. Currently only the Proposal for a Regulation on packaging and packaging waste briefly addresses this issue (EC, 2022). Similarly, the EU Landfill Directive sets restrictions for landfilling waste suitable for recycling or other material or energy recovery without defining such waste properties (EP and the Council, 2024a). Geist & Balle (2025) currently also emphasized the critical need for a conceptual basis to improve recyclability within the framework of the circular economy.

Sustainable and circular practices can be encouraged through incentives, while penalties can deter undesirable behaviours; however, enforcement of such legislation can be challenging (Fraser et al., 2024). An example of a regulatory incentive is the minimum content requirement for recycled material in packaging (EP, 2024a). The Single-Use Plastics Directive mandates that by 2025, beverage PET bottles must contain at least 25% recycled plastic, based on an average for all PET bottles sold in a Member State (EP and the Council, 2019). This legislation is expected to drive up the price of recycled PET, potentially surpassing that of virgin PET. This creates the need for high-quality recycled plastics, and the market for recycled and virgin material could be separated (EEA, 2022; Larrain et al., 2021).

Environmental and health protection is pivotal and should be the primary determinant of waste recyclability. Adequate recycling technologies often lag behind the development of new materials. For instance, while Bakelite, the first synthetic mass-produced plastic, was synthetized in 1907 and polyethylene in 1935 (Andrady & Neal, 2009; Plastics Europe, 2021), plastic recycling only began in the 1970s (Hopewell et al., 2009), and even after more than 50 years, it is still not established comprehensively. The widespread application of recycling technologies is tightly connected to economic feasibility. Even in the absence of contamination and with available recycling technologies, economic factors can hinder recycling. The main

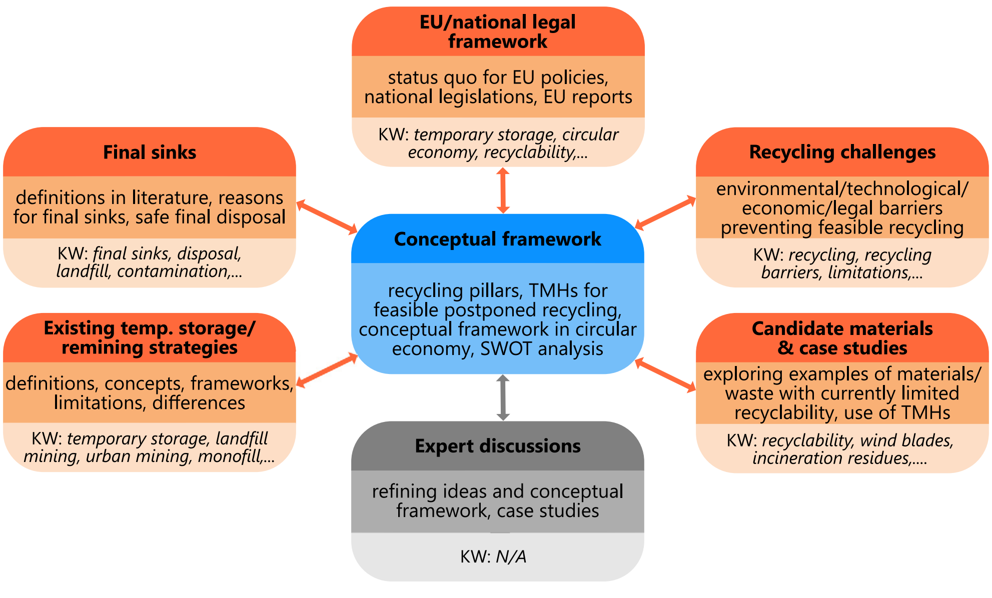


**FIGURE 1:** A concept map visualizing the six key themes and the methodological approach of the integrative literature review and the development of conceptual framework.

**TABLE 1:** Exemplary limitations and challenges affecting recycling efforts divided into four categories, then in alphabetical order.

| Category | Limitations and challenges |
|---|---|
| Environmental issues | • Increasing number of substances identified as harmful (European Chemicals Agency, 2024)<br>• Waste contamination by hazardous substances, despite labelled as "absolute non-hazardous" (European Environmental Bureau, 2017) |
| Technical issues | • Compromised quality of recycling outputs (EEA, 2022; European Environmental Bureau, 2017; Johansson et al., 2020; Kusenberg et al., 2022; Larrain et al., 2021)<br>• Lack of capacity of recycling facilities (EP, 2024b; Xie et al., 2024)<br>• Lack of end-of-life considerations from product designers (missing "design for recycling") (Sommer et al., 2020)<br>• Potential contamination of waste streams and presence of hazardous substances – affecting e.g., food contact product safety (EC, 2024; EEA, 2022)<br>• Quality of collected waste (EEA, 2022) |
| Economic issues | • Competition with energy recovery (EEA, 2022)<br>• Difficult assessment of potential environmental benefits of recycling in monetary terms (Larrain et al., 2021)<br>• Higher value of virgin material compared to recycled feedstock (EEA, 2022; Hestin et al., 2015)<br>• Lack of economic incentives to prioritize recyclability in product design (EEA, 2022)<br>• Prices of recycled plastic products are coupled to oil prices (Larrain et al., 2021)<br>• Volatility of primary raw market and consequently impaired stability of SRM market development (EEA, 2022) |
| Legislative issues | • Insufficient end-of-waste legislation and lack of EU-wide quality standards (EEA, 2022, 2023)<br>• Lack of legislation regarding the provision of information about the presence and nature of hazardous substances in "end-of-life-products" (European Environmental Bureau, 2017)<br>• Lack of regulatory incentives to prioritize recyclability in product design (EEA, 2022)<br>• Lack of taxes to strengthen competitiveness of recycled materials (EEA, 2023)<br>• Limitations in waste classification (European Environmental Bureau, 2017) |

limitations and challenges influencing recycling efforts are summarized in Table 1.

Given the current lack of a universal definition of recyclability at the EU level and as guiding principles in the context of the proposed conceptual framework, this study defines the key factors determining recyclability to be: (1) contribution to environmental and health protection, (2) availability of adequate recycling technologies and capacities, and (3) economic feasibility, including the existence of markets. The combination of all these pillars makes materials/waste theoretically recyclable (Figure 2). Legislation plays a crucial role in supporting or hindering these pillars and consequently recycling efforts by setting targets and restrictions.

Figure 2 shows, for example, that if a SRM market is unavailable or recycling is generally not economically feasible, waste is prone to be disposed of in landfills or subjected to thermal treatment (upper left grey triangle in Figure 2). This applies to, e.g., some types of plastic waste (Lim et al., 2023). Similarly, some materials/waste lack adequate recycling technologies (upper right grey triangle in Figure 2), e.g., the recycling outputs do not reach sufficient quality – such as in the case of composites (EC, 2023c). The lack of feasible recycling options can be addressed by TMHs (represented by the light green triangles in Figure 2). Vice versa, if recycling technologies are available and SRM markets exist but the recycling outputs do not comply with existing environmental standards, final sinks should be employed to keep the material cycles clean.

To improve the broader applicability of the concept of recycling pillars, it is necessary on the mid-term to define specific quantitative indicators. Such indicators might include, for example, the technology readiness level (to assess the availability of adequate recycling technologies), carbon footprint reductions or toxicity risk score (to evaluate environmental and health impacts) or a range of mar-

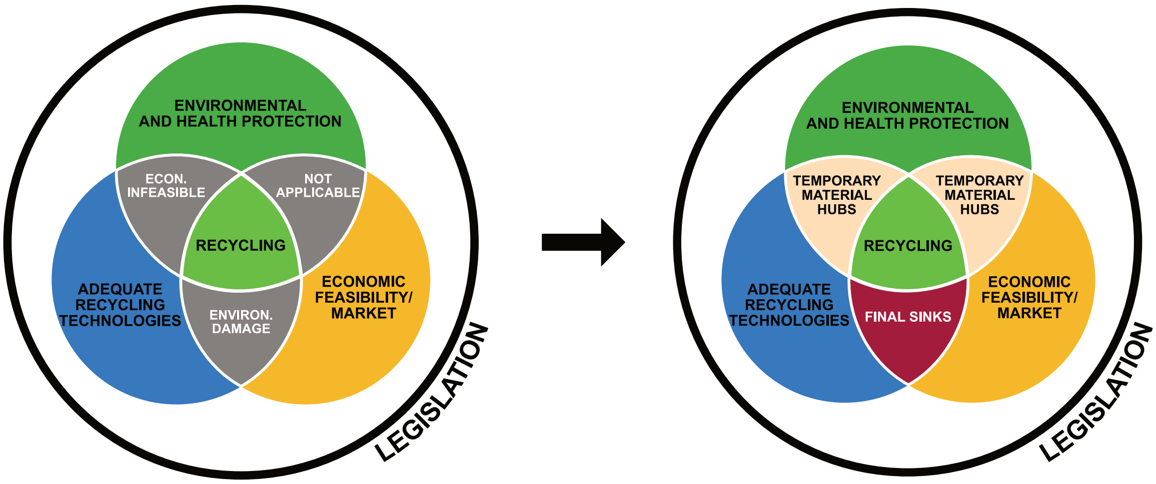


**FIGURE 2:** Visualisation of "recycling pillars" and gaps (grey areas) as well as Temporary Material Hubs and final sinks as a proposal to fill in these gaps in an improved circular economy.

ket indicators such as break-even virgin material price (to determine economic feasibility). However, to develop new, adapt or apply existing indicators is quite use-case specific and must be done individually for the considered material/waste. Van Nielen et al. (2022) developed a framework assessing recyclability of minor metals and defined a set of specifically related factors/indicators for this use case. The following chapter explains the concept of TMHs complemented by final sinks in a bigger detail.

## 4. THE CONCEPT OF TEMPORARY MATERIAL HUBS

### 4.1 Conceptual framework

The scheme of a circular economy desired by the EU (Figure 3 a) is a semi-closed loop where most materials circulate, some raw materials enter the cycle and a portion is disposed of as residual waste (EP, 2023). This model effectively utilizes currently valuable waste but directs materials with potential future value (examples listed in 4.2), to disposal or energy recovery, which is problematic as primary resources depletion accelerates (Jensen et al., 2012).

A new enhanced material recovery loop (Figure 3 b) replaces residual waste proposed for disposal with TMHs, designed to temporarily store materials/waste unsuitable for immediate recycling within the present waste management infrastructure and market situation. These materials are intended for targeted re-mining followed by further processing (recycling), meaning remining is not just an option, it is the focused obligation. Diverting materials/waste from disposal (or thermal treatment) to storage for future recycling is logical given scarcity of natural resources and advancing recycling technologies. This concept demands storage periods exceeding current legislation, such as the 3-year limit in EU (EP and the Council, 2024a).

TMHs support the ambitious goals outlined in the Waste Framework Directive and the Landfill Directive to increase the amount of waste recycled and reduce the amount of (municipal) waste sent to landfills (EP and the Council, 2024a, 2024b). They align with the new Circular Economy Action Plan by aiming to lower the demand for extraction of primary resources and increase the circular material use (EC, 2020a).

TMHs can be categorized into two types based on the properties of the stored material/waste and the processes and operations taking place during the storage period: static and dynamic. In static TMHs, materials/waste are stored in an intact state with optional pre-treatment and remain unchanged until remining and recycling. These TMHs are adequate for inert materials/waste. On the other hand, materials/waste in dynamic TMHs undergo desirable and engineered transformations before re-entering recycling options and material cycles and might require additional monitoring and regulation.

A comprehensive database and mapping of stored materials/waste ensures targeted excavation/remining with the intention of postponed recycling, making TMHs more cost-effective than landfill mining due to upfront planning allowing feasible and environmentally safe extraction of stored materials/waste. Examples of candidate materials/waste for both types of TMHs are listed in Table 2, with detailed purposes in subsections 4.2 and 4.3.

To complement TMHs and the enhanced material recovery loop, waste unsuitable for both immediate and postponed recycling is directed to a safe disposal – final sinks (Figure 3 b). While a harmonized definition of final sinks is lacking, Kral et al. (2013) defined them as "a sink that either destroys a substance completely, or that holds a substance for a very long time period". Stanisavljevic & Brunner (2021) perceive (final) sinks as a crucial part of the circular economy as they accommodate hazardous materials/waste without economic value. Final sinks serve to safely remove materials or waste unsuitable for recycling from the material cycles, even as efforts focus on reducing landfilling and increasing material recovery. For instance, this regards paper products that remain contaminated by polychlorinated biphenyls even after chemical cleaning, as well as contaminated polymers or paperboard recyclates (EEA, 2017; Mofokeng et al., 2024; Pivnenko, 2016; Zhong et al., 2025). Besides contamination, there are also limitations caused by material degradation during the repeating recycling processes (e.g., cellulose, polymer or carbon fibres after several recycling cycles) (Isa et al., 2022; Yang &

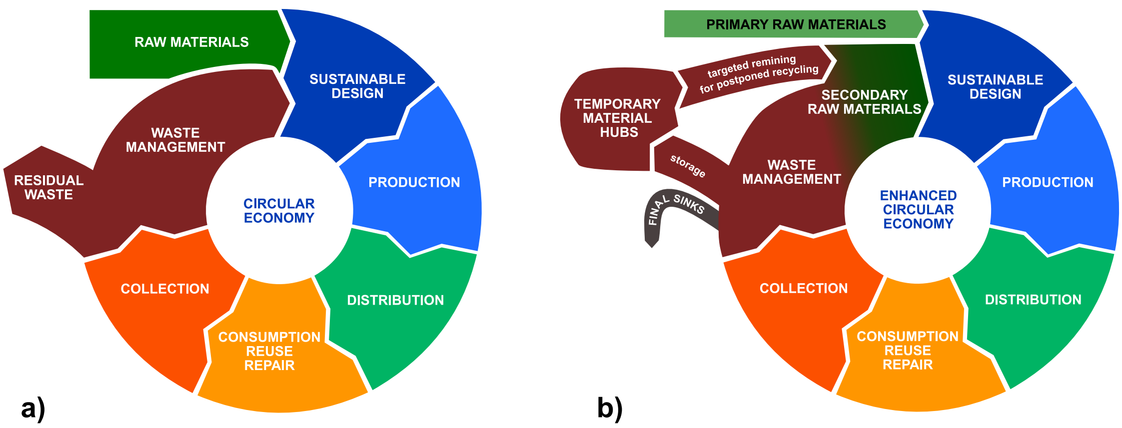


**FIGURE 3:** An innovative concept of a circular economy; a) currently desired circular economy loop (adapted from EP, 2023); b) circular economy loop including TMHs and final sinks.

Berglund, 2020). Kral et al. (2013) emphasize the need for safe final sinks for all unwanted substances, mandating a reassessment of material design strategies when suitable sinks are unavailable.

Final sinks can be both, natural or anthropogenic (Stanisavljevic & Brunner, 2021). An appropriate anthropogenic final sink for most organic pollutants, such as polybrominated diphenyl ethers, is state-of-the-art waste incineration; as it is for many other hazardous organic substances (Stanisavljevic & Brunner, 2021; Vyzinkarova & Brunner, 2013). According to Stanisavljevic & Brunner (2021), even inorganic substances can use incineration plants as their final sinks. Furthermore, controlled landfills operating based on the concept of a multi-barrier system (Stief, 1989) serve as today's final sinks. To maintain clean cycles and functional industry, society should focus on delivering the optimal amount of secondary resources rather than the maximal amount (Kral et al., 2013).

## 4.2 Exemplary candidate materials/waste for Temporary Material Hubs

In order to assess the need for TMHs and to roughly estimate their future demand, a screening of the current situation regarding the generation of "new or future waste streams" within the EU was carried out. Candidate materials/waste for TMHs are summarized in Table 2, together with their waste code, the amount currently generated and disposed in the EU, and also the related waste management and recycling issues. With respect to the proposed concept shown in Figure 2, these respective streams fall within the grey zones between recycling pillars.

Two examples (end-of-life wind blades and incineration residues) are then used as exemplary purposes in subsections 4.3 and 4.4.

## 4.3 Exemplary purpose for static Temporary Material Hubs

Diverse complex materials previously used in specific applications are becoming widely present in waste management – e.g., carbon fibre-reinforced polymers. Being used in wind blades, they are expanding due to the boom of renewable energy sources aimed at achieving net-zero emissions of greenhouse gases by 2050 (EP, 2021). Wind blades are also made of glass-reinforced polymers (the majority). Altogether, these materials are known as composites; they are resistant towards severe weather conditions with a usual life-span of 20-25 years (National Grid, 2023; Spini & Bettini, 2024). Estimates for wind blade waste generation in the EU between 2020 and 2030 vary widely. Sommer et al. (2020) project 570,000,000 tonnes of

**TABLE 2:** Currently relevant candidate materials/waste for TMHs; alphabetical order (DTMHs – dynamic TMHs; STMHs – static TMHs).

| Material/waste/ product | Waste code | Amount generated in the EU | Disposal rate in the EU | Waste management and recycling issues | Type of TMHs |
|---|---|---|---|---|---|
| Composites/ wind blades | 17 02 03[1] or 17 09 04[2] | Differs:<br>185,000 tonnes by 2030[3];<br>570 million tonnes by 2030[4];<br>350,000 tonnes by 2030[5] | • Lack of reliable data[1,6–10]<br>• Landfilling or incineration without energy recovery of all composites: approximately 40-70% (160-280,000 tonnes/year)[6] | • The majority is co-processed in cement kilns, incinerated or landfilled[1,7–10]<br>• Material degrades during recycling[11]<br>• Virgin material is more valuable[11] | STMHs |
| Incineration residues | 19 01 11*, 19 01 12[12] | 19-31.8 million tonnes/ year[13,14] | • Landfilling: 11.3-16 million tonnes/year[14] | • Few environmentally safe recycling methods[15]<br>• Environmentally challenging use of recyclates, often resulting in additional landfill waste[16] | DTMHs |
| PVC | 02 01 04, 20 01 39[12] | 2.5-4.1 million tonnes/ year[17] | • Incineration with energy recovery: 46% (1.5-1.9 million tonnes/ year)[17]<br>• Landfilling or incineration without energy recovery: 19% (0.5-0.8 million tonnes/year)[17] | • Primarily incinerated rather than recycled; landfilling is restricted[18,19]<br>• Incineration: danger of dioxin production[19]<br>• Recycling technologies: limited by costs, high energy consumption, environmental impact, problematic quality of produced feedstock, low yield and the need for further research[20] | STMHs |
| Textiles/ clothing | 20 01 10[12] | 5.2 million tonnes/year[21] | • Incineration or landfilling: 78% (4.1 million tonnes/year)[21] | • The majority is incinerated, landfilled or exported to low-income countries[22]<br>• Costly sorting and separation; low-quality secondary feedstock[23]<br>• Contamination, e.g., by per- and polyfluoroalkyl substances[24] | STMHs |
| Tires | 16 01 03[12] | 300 million pieces/year [25,26];<br>over 3.5 million tonnes/ year[26] | • Landfilling is prohibited[27]<br>• Incineration for energy production: 40% (1.4 million tonnes/year)[28] | • The majority is incinerated or recycled for low-value applications[26]<br>• Recycling technologies: high investments costs, low efficiencies or being a threat to the environment[29]<br>• Ongoing landfilling despite its unsuitability (banned in the EU)[27,30,31] | STMHs |

[1] WindEurope (2020), [2] LAGA (2019), [3] Lichtenegger et al. (2020), [4] Sommer et al. (2020), [5] WindEurope (2021), [6] EuCIA (2023), [7] EC (2023c), [8] Gast et al. (2024), [9] Spini & Bettini (2024), [10] Volk et al. (2021), [11] Composites UK (2016), [12] EC (2014), [13] Lamers (2015), [14] Zero Waste Europe (2022), [15] Cao et al. (2024), [16] Fellner et al. (2015), [17] EC & Ramboll (2022), [18] Lahl & Zeschmar-Lahl (2024), [19] Miliute-Plepiene et al. (2021), [20] Ait-Touchente et al. (2024), [21] EC (2023a), [22] Stipanovic et al. (2023), [23] Andini et al. (2024), [24] Umweltbundesamt (2024), [25] EC (2023b), 26 Roetman et al. (2024), [27] EP and the Council (2024a), [28] Allen (2024), [29] Wu et al. (2024), [30] Dobrotă et al. (2020), [31] Guo et al. (2024)

wind blade waste to be generated between 2020 and 2030. The number was also cited in an EU article (EC, 2023c); however, the respective study shows some inconsistencies in data provided and therefore, this high number should be considered with caution. Lichtenegger et al. (2020) concluded that there will be approximately 185,000 tonnes of wind blade waste by 2030. WindEurope (2021) expects this amount to be around 350,000 tonnes. The installed capacity is predicted to increase from 255 GW in 2022 to a total capacity of 384 GW in 2027 (Gast et al., 2024; Sommer et al., 2020; WindEurope, 2023). Nonetheless, wind blade composites shall account for only 10% of thermoset polymer composite waste in Europe by 2025 (WindEurope, 2020).

Recycling of wind blades (approx. 2-5% of the wind turbine by mass) poses industrial challenges that are not satisfactorily resolved (Alves Dias et al., 2020; Schmidt, 2024; WindEurope, 2020). The majority of wind blade waste is currently co-processed in cement kilns, incinerated or landfilled, although data on the final destination of dismantled blades is scarce (EC, 2023c; Gast et al., 2024; Spini & Bettini, 2024; Volk et al., 2021; WindEurope, 2020). While virgin material is more valuable due to the degradation of recycled fibres (Composites UK, 2016), recycled feedstock can be used in industries tolerating lower quality and length of carbon fibres, such as the manufacture of hobby products for sports and leisure time, as suggested by Limburg and Quicker (2016). The costs of carbon fibres obtained from pyrolysis are up to four times lower than the costs of virgin material (approximately 5,000 EUR per tonne compared to approximately 20,000 EUR per tonne, respectively) (LAGA, 2019). The precursor used to manufacture carbon fibres significantly influences the final costs (Nunna et al., 2019), contributing over 50% to the total costs of the final product (Ellringmann et al., 2016; Nunna et al., 2019). Producing virgin carbon fibres is highly energy-intensive, requiring approximately 1,150 MJ/kg, whereas fibre recycling needs only 10% of this energy (Salas et al., 2023). Wind blades were labelled as "future waste" – a waste stream that is usually created by long-lived products that have already entered anthropogenic cycles in significant quantities. These are expected to increase in the future together with an increase in waste generation, and there are no feasible recycling technologies for them yet (Pomberger & Ragossnig, 2014).

Materials as composites cannot be currently feasibly recycled because the outputs from mechanic recycling do not reach sufficient quality; while chemical methods come with high implementation costs and consume vast amounts of energy (EC, 2023c). The outputs of thermal recycling methods bear disadvantages of compromised fibre length together with low polymer recovery rate. Due to their rather stable properties, dismantled wind blades could be stored in static TMHs and extracted when favourable recycling conditions are reached.

### 4.4 Exemplary purpose for dynamic Temporary Material Hubs

Out of 229 million tonnes of municipal waste generated in the EU in 2022, 59 million tonnes (26%) were incinerated (Eurostat, 2024). Incineration residues are unavoidable mineral products of waste incineration and contain, e.g., metals and rare earth elements. One ton of waste produces approximately 0.2-0.25 tonnes of incineration residues (Chen et al., 2023; Lamers, 2015; Reig et al., 2023). The main management option remains landfilling (Margallo et al., 2015), the most practical reuse option appears to be in road or embankment constructions (Oehmig et al., 2015).

There are currently few environmentally safe recycling methods (Cao et al., 2024). Current technologies enable the extraction of valuable compounds from incineration residues or the removal of harmful substances – e.g., metals can be extracted by leaching in acids and further used in industry (Cao et al., 2024; Reig et al., 2023). While some European countries (Netherlands, Switzerland) have attempted to recycle incineration residues, they have encountered environmental challenges, often resulting in additional landfill waste (Fellner et al., 2015). Incineration residues could benefit from the concept of dynamic TMHs, although considering that a large mass of residues must be handled, sufficient storage space must be provided.

A similar concept has already been described by Sapsford et al. (2023). Their ASPIRE concept is inspired by natural lithospheric weathering and pedogenetic processes, aiming to mimic those with waste, as observed in mine tailings and smelter residues. Carbon dioxide might be mitigated through ash weathering and ash could be reused as cement mixture or in agri-/silviculture as source of nutrients given its content of critical elements and minerals. Stored material could be "cleaned" or concentrated during its time in a facility and after the defined time period, it can be remined (Sapsford et al., 2023).

Weathering significantly changes the properties of incineration residues (Chimenos et al., 2003). Chen et al. (2023) and Chimenos et al. (2003) state that reactive substances in waste residues react and form physically and chemically stable phases with reduced release of heavy metals. This is in harmony with findings made by Obernberger and Supancic (2024) who have described ageing of incineration ashes during storage periods, and Mostbauer et al. (2008) who analysed the chemical weathering of waste incineration residues and the sequestration of $CO_2$ through the so-called BABIU process (Bottom Ash for Biogas Upgrading). Processes taking place during ash ageing/weathering include reduction of pH, Ca solubility reduction and volume stabilization (Gori et al., 2013; Obernberger & Supancic, 2024). While natural weathering and pedogenetic processes last long time periods, the processes in TMHs have to be usable for anthropogenically relevant timescales. Although incineration residues show reduced carbonation efficiencies compared to reference materials (e.g., composite of spent refractories with uptake up to 438 kg of $CO_2$ per ton of material), they absorb $CO_2$ (Schinnerl et al., 2024). In the case of bottom ash, the uptake is approximately 60 kg of $CO_2$ per ton of material (ibid.).

## 5. DISCUSSION

The lack of a clear recyclability definition at the EU level complicates recycling efforts. Defining recyclability would simplify deciding whether a material shall be kept in anthropogenetic cycles (either to be recycled directly or to be kept in TMHs) or if it should find its final sink. Pomberger and Bezama (2024) discussed the need for redefinition and sharpening of the term recyclability and pointed out the differences between theoretical, technical and real recyclability. Esguerra et al. (2024) describe recyclability as the potential for sorting out and subsequent recycling in corresponding facilities, thus focussing on the technical issues. The non-profit initiative RecyClass names a definition stating that plastics considered recyclable must meet conditions similar to those in the Proposal for a Regulation on packaging and packaging waste (RecyClass, 2024).

Recycling options and efforts are tightly connected to regulative challenges. There is, for example, a need for improved end-of-waste legislation and inclusion of EU-wide technical standards assuring that recycling operators produce material of stable quality (EEA, 2022, 2023). The competitiveness of recycled materials needs to be enhanced by the implementation of taxes or subventions, and the implementation of reasonable quotes to include recyclates in new products (EEA, 2023).

## 5.1 Previous concepts on remining and temporary storage

Storage of waste described in previous literature and regulations is usually connected to subsequent utilization or disposal in a short time. According to the EU Waste Framework Directive, temporary storage means storing waste before transportation to a waste treatment facility (EP and the Council, 2024b). The EU Landfill Directive states that storage of waste prior to disposal for over 1 year, and prior to recovery or treatment for over 3 years, is legally considered a landfill (EP and the Council, 2024a). In that case, the site has to comply with landfill regulations (Lehmphul, 2024).

Such time periods might not be sufficient as certain emerging waste streams need longer times in storage before their feasible utilization. Thus, TMHs have a clear intention of postponed recycling of the material/waste, unlike the current concepts of storage that can in certain cases serve to postpone disposal.

The case studies in literature emphasize the importance of further research of storage solutions for postponed resource recovery, that highlight the potential application and necessity of TMHs. One notable example is sewage sludge incineration and the subsequent treatment of ashes. Research has shown that, especially in case of mono-incineration, the storage of ashes should be considered, since the recovery of phosphorus from sewage sludge ash is not feasible at the present phosphorus market price (Bagheri et al., 2024; Montag et al., 2015). However, it can become economically feasible if the phosphorus price rises. Companies such as EasyMining with its Ash2Phos technology are on the way towards the commercialization of phosphorus recovery, with their recovery plant to start operations in early 2027 (EasyMining, 2025).

A step towards partial implementation of this concept can already be seen in the city of Zurich, which operates a sewage sludge mono-incineration plant with a future dedication to store produced ashes and enable future phosphorus recovery and recycling (Eicher, 2025; Montag et al., 2015).

A similar approach can be observed in the wind energy sector. Several European companies involved in wind blade decommissioning are already postponing disposal while independently researching economically feasible solutions or anticipating their emergence in the near future. This strategy underscores the justification for the costs associated with storage or potential postponed disposal (Nagle et al., 2022).

The German federal state waste working group LAGA (2019) addresses the storage of carbon fibre-reinforced material until adequate recycling routes are available. The need for temporary material storage before recovery is supported by the concern that carbon-reinforced polymers' fibre dust might be carcinogenic and have negative effects on health similar to those of as asbestos. Therefore, further research is needed to assure appropriate handling (LAGA, 2019).

The Austrian ministry is planning to temporarily allow previously forbidden landfilling of carbon- and glass-reinforced polymers. This decision is based on the current lack of recycling capacity or its insufficient performance (BMK, 2024). This intent contradicts the wind industry's goal to have landfilling of decommissioned wind blades banned by 2025 (WindEurope, 2021).

The few temporary storage concepts previously described in international literature are usually related to specific cases and waste streams (Table 3). The concepts range from disaster management, short-term storage of demolition waste from military actions and hazardous waste on drilling sites to so-called monofills for future mining. However, they do not necessarily lead to subsequent recycling (Table 3).

The "dead storage" of products is a specific and special case of unintended and undesirable temporary storage. This practice has negative effects on the circular economy as valuable substances remain in drawers rather than in recycling facilities and cannot become secondary feedstock (Wilson et al., 2017). The products lose their economic value with the duration of storage (Inghels & Bahlmann, 2021); engineered TMHs should have the reverse effect – the value of material/waste is unlocked with age.

The concept of TMHs shares similarities with approaches such as urban mining, landfill mining and monofilling, but key distinctions set TMHs apart. Urban mining is primarily driven by the aim to recover materials directly from the urban environment (Ghisellini et al., 2022). TMHs complement urban mining by providing storage for materials from deconstruction or building mining that lack immediate market demand. The ultimate purpose of TMHs is to prevent disposal in a landfill altogether and make postponed use of materials already present in anthropogenic deposits.

Landfill mining, as a subcategory of urban mining (Johansson et al., 2013), addresses disposal as the least desired option in the waste hierarchy and aims to "reverse" its effects (Ghisellini et al, 2022). Enhanced landfill mining builds upon this concept by considering the valorisation of

**TABLE 3:** Previous concepts on remining and temporary storage; alphabetical order.

| Concept | Description | Reference |
|---|---|---|
| Hibernation/dead storage of products | Retention of small end-of-life electronics (e.g., mobile phones) by their users to have the security of a substitution device in case the primary one breaks down or else | Inghels and Bahlmann (2021); Wilson et al. (2017) |
| Landfill mining | Extraction of minerals or other solid resources from previously (often uncontrolled) disposed waste | Krook et al. (2012) |
| Monofills | Separate disposal of single waste fractions on landfills (compartments); e.g., monofills of e-waste for future mining due to current limitations in availability of treatment/recycling technologies; incineration ash monofills | Kahhat & Kavazanjian (2010); Liu et al. (2022) |
| Temporary storage | Storage of mineral-rich waste materials for future re-mining of valuable materials | Sapsford et al. (2023) |
| Temporary storage device | Storage of hazardous waste on drilling sites | Liu et al. (2023) |
| Temporary storage of demolition waste from military actions | Storage of waste to protect the environment and assure the best possible treatment after the termination of martial law | Cabinet of Ministers of Ukraine (2022) |
| Temporary storage sites | Storage of waste during disasters before it can be adequately treated | Lontoc et al. (2023) |
| Urban mining | "Systematic reuse of materials from urban areas" | Brunner (2011) |

mined waste for both material and energetic use (Jones et al., 2013; Parrodi et al., 2020). The key distinction between TMHs and landfill mining lies in TMHs' strict commitment to material recovery. In landfill mining, remining is an option, while TMHs make it an obligation. Moreover, the physical space of TMHs is not only limited to "landfill area", also further options like unused factories, storage halls, brownfields etc can be adapted and used.

Monofills, in contrast, are landfills or compartments of landfills designed to dispose a single type of waste. Examples include e-waste monofills proposed by Kahhat & Kavazanjian (2010) and also incineration residue monofills (Roessler et al., 2017). Mining a monofill to recover materials is similar to landfill mining, but the homogenous nature of waste in monofills may simplify the mining efforts compared to mixed waste landfills. TMHs differ in that remining is inherent to their design, and they are intended to be employed for restricted time periods, offering a flexible and potentially modular solution for efficient remining. Nevertheless, well-considered and specifically planned monofills, if designed for high-quality remining, can act as a transitional form of TMHs, bridging the gap between current and future recycling advancements.

### 5.2 Factors impacting the performance of the Temporary Material Hubs

Several factors must be considered, researched and clarified to allow a successful implementation and integration of TMHs into the circular economy in practice. As part of this exploratory study, a conceptual SWOT analysis was conducted to assess the theoretical potential performance of TMHs based on the data acquired from literature screening and discussions with experts and peer groups (Figure 4).

The biggest strength of the TMHs concept lies in the optimization of resource use and the reduction of waste going to (final) disposal, and due to the need of a comprehensive database of stored waste, material traceability should be enhanced.

However, a key weakness is the current difficulty in estimating the economic situation (prospective costs and revenues) due to the lack of detailed technical implementation concepts, suitable siting and adequate storage capacities.

The opportunity in the use of TMHs is the support of the European circularity goals, allowing feasible recycling of currently non-valuable materials/waste, thereby unlocking their value in the future. This would lead to a reduction in raw material extraction. TMHs may also help balancing the ratio of materials to be recycled and the available recycling capacities by retaining a certain amount of material. Extended Producer Responsibility (EPR) schemes for certain waste streams might support TMHs by ensuring the financing of the storage for postponed proper handling and recycling. Despite challenges in measuring their effectiveness, EPR systems generally yield positive outcomes (The Environmental Research & Education Foundation, 2025).

The biggest threats stem from uncertainties faced by the concept, such as uncertain material flows in the future, as well as market situation and future changes in regulations. Another threat lies in the estimation of storage duration, meaning if and when materials/waste will become recyclable, and if/when markets will emerge. These issues will need a thorough assessment. Moreover, similar to all waste management facilities, underperforming TMHs might pose a threat to the environment.

Future research must focus on the duration of storage, technical and siting properties, and the estimation of costs/revenues, market development and risk-assessment. An adaptation of the regulatory framework would be also needed to allow the implementation of such concept.

#### *5.2.1 Duration of storage*

The proposed conceptual framework supports the long-term sustainability goals, producing results that extend beyond short-term objectives, such as those tied to 5-year policy cycles (EEA, 2024). The duration of storage must be tailored to specific materials/waste and respective recycling technologies and infrastructure. For example, a study by the EC expects that the performance of solvolysis and pyrolysis for recycling wind-turbine blade waste will improve in the near future (EC, 2023c). Garcia-Gutierrez et

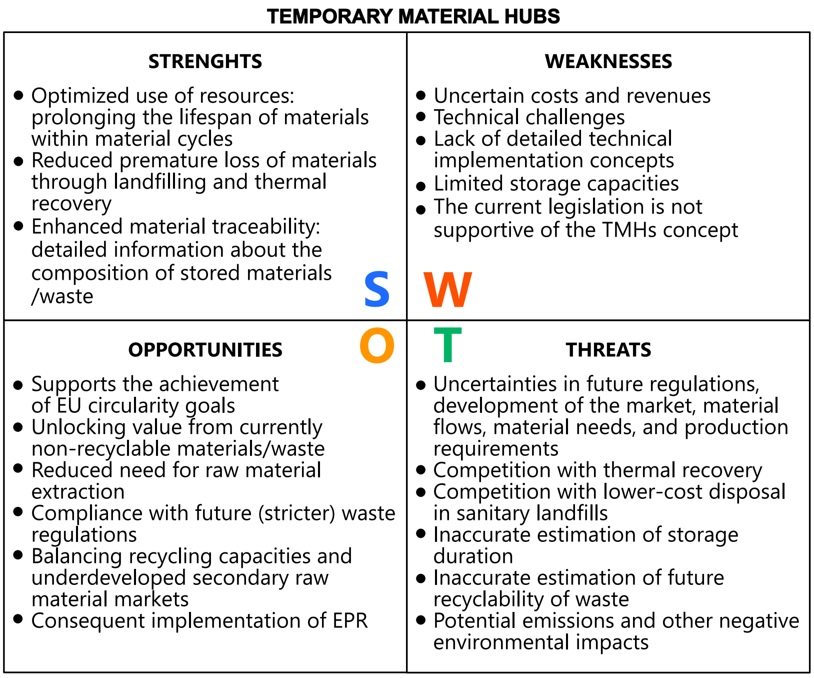


**FIGURE 4:** SWOT analysis of the potential performance of TMHs.

al. (2023) and Werner et al. (2022) estimate that most polymer chemical-recycling technologies will reach positive net earnings before 2040 (methanolysis in 2025, pyrolysis in 2033). The projections are based on expected cost reduction in recycling technologies (37.5% in the case of chemical recycling technologies, mechanical recycling costs are expected to remain the same) and increased costs of virgin material (increase by 71%). However, the authors acknowledge significant uncertainties in the estimates (Garcia-Gutierrez et al., 2023; Werner et al., 2022) and according to Islam et al. (2025), methanolysis is still in need of further research and optimisation. Based on the predictions, the storage time of certain plastic waste streams in TMHs may last up to ~ 15 years from 2025. Furthermore, conditions of potential premature remining (before the expiration of designated storage time) in case of favourable conditions must be determined.

The storage duration estimations might be based on the technology readiness level (TRL) of respective technologies. Rybicka et al. (2016) researched the TRL of composite management technologies, concluding that in 2016, incineration and landfilling were the most advanced, achieving the highest (maximal) TRL 9, pyrolysis (carbon fibres) and mechanical grinding of fibres (glass fibres) achieved TRL 8, while pyrolysis of glass fibres and mechanical grinding of carbon fibres were at TRL 6-7. Most composite recycling technologies, however, remained in the early stages, with TRLs of 3-4 (Rybicka et al., 2016). Within past years, none of the composite recycling technologies achieved a TRL allowing industrial-scale application (WindEurope, 2020), and there is still a lack of effective solution (Tortorici et al., 2025).

Generally, storage should last as long as necessary to achieve feasible recycling conditions but as short as possible to minimize the storage costs (Obernberger & Supancic, 2024). However, we propose that "temporary" in this concept may cover a time frame of about 5 to max. 20 years.

The duration of storage introduces a potential risk of unwanted alteration and degradation of the stored material/waste, which could jeopardize subsequent material recovery. To mitigate the risk, the facilities must be designed to withstand adverse impacting conditions, e.g., weather conditions, and prevent damage over time. One example of such degradation is corrosion. Even for very rigid and highly durable materials such as wind blades, this risk must be considered, especially if the blades are already degraded at the end of their life cycle (Muntenita et al., 2024).

The general framework for the decision-making under which conditions waste should be "remined" from the TMHs and reintroduced into material cycles is provided by the three pillars addressing "recyclability" (see Figure 2). However, we emphasize that each case (waste type) needs to be assessed individually, taking into account its specific conditions and pre-selected indicators, as mentioned in chapter 3.

### *5.2.2 Technical design and infrastructure*

It is pivotal to know the composition of stored waste to ensure safety of storage and the effective option of future remining. This might require chemical analyses, assessment of potential contamination and thorough mapping and documentation, e.g., similar to the procedure for hazardous waste disposal in German underground landfills in Ordinance on Landfills and Long-Term Storage (Bundesministerium der Justiz, 2009). Based on the composition, static or dynamic TMHs are employed.

Static TMHs should be controlled and engineered to ensure that stored waste does not undergo any unwanted alteration or degradation during storage time. Certain abandoned facilities could be employed (such as old industrial or military buildings), inspiration could be found in underground disposal of hazardous waste as mentioned above.

For the preparation of Refused Derived Fuels (RDF) intended for energy recovery in diverse industries, storage facilities are already often needed and applied. Storage options for TMHs can be based on this, but require further (sometimes more complex) conditions, especially as they are intended to be stored for much longer periods of time. Thus, THMs would be more stringent than facilities for RDF storage. This is due to the clear intention of subsequent material recovery, which demands different, mainly higher quality standards compared to energy recovery. For instance, while Romaszewski and Fitas (2024) noted that open-air storage has no adverse effects on the thermal recovery of RDF, the same approach might not be suitable for TMHs, where material integrity is critical for future recycling processes.

Dynamic TMHs need to be engineered and monitored to allow stored waste to undergo certain desired processes. Those are, for example, the weathering processes of incineration residues for which controlled landfill sites with fading landfill-gas generation (with remaining high $CO_2$ concentrations; compare BABIU Process (Mostbauer et al., 2008) and state-of-the-art barriers could be used.

In certain cases, an Environmental Impact Assessment may be required to avoid potential adverse impacts on the environment.

It is important to note that TMHs may require a substantial area, which could lead to challenges such as land-use conflicts and competing interests (Montag et al., 2015). In theory, facilities such as mined (empty) landfills could be employed if environmental protection and properties allowing secure storage of materials/waste are assured. Consideration should be given to the option of "reusing" such facilities and adapting them to various types of materials/waste in parallel or subsequently rather than aiming for one-time employment. Additionally, case-specific pre-treatment would affect the design of the storage and the infrastructure setting. The quality and amount of the regarded waste stream and the status of the existing infrastructure will determine whether local or centralized TMHs should be created and if additional infrastructure needs to be established. The most significant transportation load is expected at the beginning of storage process and when remined. The extent of pre-treatment and transportation involved will also affect the overall costs of the concept.

*5.2.3 Economic and legal factors*

The costs of storage for postponed recycling might be higher than those of conventional waste management options. Competing with the TMHs are waste-to-energy facilities for thermal recovery of materials/waste, and landfills presenting a cheap yet environmentally/circularly unfavourable waste management alternative. Potential (mid- to long-term) environmental benefits of (postponed) recycling compared to energy recovery, landfilling and also primary raw material extraction must be considered. When considering the negative environmental externalities, the concept of TMHs may compete with the conventional waste management options in monetary terms. Furthermore, unlocking the value of currently non-valuable materials/waste may create revenues in the future that need to be estimated. Such estimations are currently a source of uncertainties and pose a potential weakness of TMHs. However, further research and modelling of cost scenarios shall reduce these economic risks.

A key priority for future research is conducting a comprehensive cost-benefit analysis, particularly to compare TMHs with thermal treatment and landfilling. This will require detailed modelling to account for variables such as market development and resource scarcity. Furthermore, an LCA analysis is recommended to evaluate and compare the environmental impacts of these addressed waste management strategies, providing a more holistic understanding of their long-term viability.

Platforms like digital marketplaces could facilitate the recycling of stored materials by enhancing their visibility and enabling trading. However, these platforms can only function if a market already exists, which is one of the challenges waste recycling might face, as explained in Figure 2. For this reason, TMHs should be implemented prior to the establishment of digital markets. Some platforms already enable the resale of dismantled wind blades for reuse, such as "Business in Wind" (2025).

To implement the TMHs concept, both national and European legislation would need to be adapted. One of the most critical changes would involve extending the duration of waste storage beyond the currently permitted periods outside a landfill regime (EP and the Council, 2024a). Moreover, implementing taxes or levies on primary raw materials could help improve the competitiveness of recycled materials (EEA, 2023), which would support the concept of TMHs.

## 6. CONCLUSIONS AND OUTLOOK

Optimizing resource use is a crucial step towards enhancing the circular economy. Unlike traditional waste management strategies, this study introduces a forward-looking approach for storing prospectively valuable waste streams for future recycling, rather than relying on immediate disposal or energy recovery. While it builds on existing concepts, it introduces several theoretical advancements: it (1) formalizes the concept of TMHs as a distinct strategy for bridging the temporal gap between current technological and economic capabilities and future advancements, (2) proposes the recycling pillars as a novel decision-making framework for evaluating recyclability, and (3) integrates the concept of final sinks to maintain clean material cycles. The comprehensive and integrative considerations of these diverse aspects in one central concept represent a meaningful progress, which has not been systematically addressed in previous literature.

This study provides a theoretical foundation for further use-case-specific research and practical implementation of the TMHs concept. Further details and application specifications, which may have a strong impact on the realisation of such a concept, have still to be researched and defined. However, the authors are of the opinion that it is important to disseminate the concept now in order to initiate a discussion within the scientific community and among diverse stakeholders in the waste and resource management sectors. Storing materials/waste for postponed recycling appears justifiable based on the current and prospective advancements in recycling technologies and secondary markets. A SWOT analysis, as outlined in this study, can be used to assess the principal feasibility of the TMHs concept for specific applications and cases – considering factors such as waste type, existing infrastructure, location, storage duration, and financial viability. Additionally, this analysis helps to identify uncertainties that may challenge implementation while also highlighting potential opportunities and benefits.

To build on this groundwork, future research should include case-based modelling and real-world pilot studies to quantitatively assess the concept's feasibility and consider cost- and risk-assessment approaches, and potential pre-treatment requirements for the stored waste. Furthermore, engaging with stakeholders – such as manufacturers, waste sector operators and policy makers – through interviews, would expand the study's perspective beyond academia, incorporating practical and industry-relevant insights. For successful implementation, both European and national legal frameworks must be adapted, particularly concerning the definition of recyclability, the extension of the permitted storage time, as well as the creation of conditions that foster secondary raw material markets. In addition to these technical, economic and legal considerations, future research should address the social dimensions to better understand societal implications and acceptance.

This study serves as a blueprint for innovative approaches to enhance the circular economy and aims to initiate a debate on the need for both, temporary material/waste storage and safe final sinks.

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## REFERENCES

Ait-Touchente, Z., Khellaf, M., Raffin, G., Lebaz, N., & Elaissari, A. (2024). Recent advances in polyvinyl chloride (PVC) recycling. Polymers for Advanced Technologies, 35(1), e6228. https://doi.org/10.1002/pat.6228

Allen, M. (2024). Recycling tyres and plastics with an ancient heating method | Horizon Magazine. https://projects.research-and-innovation.ec.europa.eu/en/horizon-magazine/recycling-tyres-and-plastics-ancient-heating-method

Alves Dias, P., Pavel, C., Plazzotta, B., & Carrara, S. (2020). Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system. Publications Office of the European Union. https://data.europa.eu/doi/10.2760/160859

Andini, E., Bhalode, P., Gantert, E., Sadula, S., & Vlachos, D. G. (2024). Chemical recycling of mixed textile waste. Science Advances, 10(27), eado6827. https://doi.org/10.1126/sciadv.ado6827

Andrady, A. L., & Neal, M. A. (2009). Applications and societal benefits of plastics. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526), 1977–1984. https://doi.org/10.1098/rstb.2008.0304

Bagheri, M., Gómez-Sanabria, A., & Höglund-Isaksson, L. (2024). Economic feasibility and direct greenhouse gas emissions from different phosphorus recovery methods in Swedish wastewater treatment plants. Sustainable Production and Consumption, 49, 462–473. https://doi.org/10.1016/j.spc.2024.07.007

BMK. (2024). Novelle der Deponieverordnung CFK und GFK Abfälle. https://www.wko.at/oe/news/0119-tf-wfa-novelle-deponievo.pdf

Brunner, P. H. (2011). Urban Mining A Contribution to Reindustrializing the City. Journal of Industrial Ecology, 15(3), 339–341. https://doi.org/10.1111/j.1530-9290.2011.00345.x

Bund/Länder-Arbeitsgemeinschaft Abfall (LAGA). (2019). Entsorgung faserhaltiger Abfälle—Abschlussbericht. https://proenvi.de/recht/LAGA/Bericht-Laga-Entsorgung-faserhaltige-abfaelle_201907.pdf

Bundesministerium der Justiz. (2009). § 1 DepV - Einzelnorm. Bundesministerium der Justiz. https://www.gesetze-im-internet.de/depv_2009/DepV.pdf

Business in Wind. (2025). Business in Wind—Sharing commitment. Business in Wind. https://businessinwind.com/

Cabinet of Ministers of Ukraine. (2022). On Approval of the Procedure for Waste Management Generated in Connection with Damage (Destruction) of Buildings and Structures as a Result of Hostilities, Terrorist Acts, Sabotage or Works to Eliminate Their Consequences and Amendments to Certain Resolutions of the Cabinet of Ministers of Ukraine.

Cao, C., Yuan, Z., Liu, H., Fei, X., Esteban, J., & She, Q. (2024). Insights into the usage of biobased organic acids for treating municipal solid waste incineration bottom ash towards metal removal and material recycling. Separation and Purification Technology, 353, 128330. https://doi.org/10.1016/j.seppur.2024.128330

Chen, B., Perumal, P., Illikainen, M., & Ye, G. (2023). A review on the utilization of municipal solid waste incineration (MSWI) bottom ash as a mineral resource for construction materials. Journal of Building Engineering, 71, 106386. https://doi.org/10.1016/j.jobe.2023.106386

Chimenos, J. M., Fernández, A. I., Miralles, L., Segarra, M., & Espiell, F. (2003). Short-term natural weathering of MSWI bottom ash as a function of particle size. Waste Management, 23(10), 887–895. https://doi.org/10.1016/S0956-053X(03)00074-6

Composites UK. (2016). Composites Recycling – Where are we now? End of Life and Recycling | Composites UK. https://compositesuk.co.uk/industry-support/environmental/end-of-life-and-recycling/

Cossu. (2016). Back to Earth Sites: From "nasty and unsightly" landfilling to final sink and geological repository. Waste Management, 55, 1–2. https://doi.org/10.1016/j.wasman.2016.07.028

Dobrotă, D., Dobrotă, G., & Dobrescu, T. (2020). Improvement of waste tyre recycling technology based on a new tyre markings. Journal of Cleaner Production, 260, 121141. https://doi.org/10.1016/j.jclepro.2020.121141

EasyMining. (2025). The world's first Ash2Phos plant. https://www.easymining.com/projects/plant-projects/Ash2Phos-plant-schkopau/

Eicher, N. (2025). Klärschlammbehandlung. Kanton Zürich. https://www.zh.ch/de/umwelt-tiere/abfall-rohstoffe/abfaelle/abfallanlagen/klaerschlammbehandlung.html

Ellringmann, T., Wilms, C., Warnecke, M., Seide, G., & Gries, T. (2016). Carbon fiber production costing: A modular approach. Textile Research Journal, 86(2), 178–190. https://doi.org/10.1177/0040517514532161

Esguerra, J. L., Carlsson, A., Johansson, J., & Anderberg, S. (2024). Characterization, recyclability, and significance of plastic packaging in mixed municipal solid waste for achieving recycling targets in a Swedish city. Journal of Cleaner Production, 468, 143014. https://doi.org/10.1016/j.jclepro.2024.143014

EuCIA. (2023). EuCIA launches European Composites Waste & Recycling Survey—JEC. Https://Www.Jeccomposites.Com/. https://www.jeccomposites.com/news/spotted-by-jec/eucia-launches-european-composites-waste-recycling-survey/

European Aluminium. (2017). Activity Report 2016. https://european-aluminium.eu/wp-content/uploads/2022/10/activity-report-2016_web.pdf

European Aluminium. (2020). Circular Aluminium Action Plan—Executive summary. https://european-aluminium.eu/wp-content/uploads/2022/08/european-aluminium-circular-aluminium-action-plan.pdf
European Chemicals Agency. (2024). All news—ECHA. https://echa.europa.eu/news-and-events/news-alerts/all-news/-/asset_publisher/yhAseXkvBI2u/
European Commission. (2014). 2014/955/EU: Commission Decision of 18 December 2014 amending Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC of the European Parliament and of the Council Text with EEA relevance. http://data.europa.eu/eli/dec/2014/955/oj/eng
European Commission. (2020a). A new Circular Economy Action Plan. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN
European Commission. (2020b). Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions A new Circular Economy Action Plan For a cleaner and more competitive Europe. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN
European Commission. (2020c). Strategic Plan 2020-2024. https://commission.europa.eu/system/files/2020-10/env_sp_2020_2024_en.pdf
European Commission. (2022). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022PC0677
European Commission. (2023a). Circular economy for textiles [Text]. European Commission - European Commission. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_3635
European Commission. (2023b). LIFE project aims to revolutionise Europe's approach to recycling end-of-life tyres. - European Commission. https://cinea.ec.europa.eu/news-events/news/life-project-aims-revolutionise-europes-approach-recycling-end-life-tyres-2023-12-14_en
European Commission. (2023c). More circular, less carbon: Chemical recycling holds promise for wind-turbine blade waste. https://environment.ec.europa.eu/news/more-circular-less-carbon-chemical-recycling-holds-promise-wind-turbine-blade-waste-2023-10-19_en
European Commission. (2024). Plastic Recycling—European Commission. https://food.ec.europa.eu/food-safety/chemical-safety/food-contact-materials/plastic-recycling_en
European Commission & Ramboll. (2022). The use of PVC (poly vinyl chloride) in the context of a non-toxic environment: Final report. Publications Office of the European Union. https://data.europa.eu/doi/10.2779/375357
European Council. (2024). European Green Deal. European Council. https://www.consilium.europa.eu/en/policies/green-deal/
European Environment Agency. (2017). Circular by design—Products in the circular economy—European Environment Agency (Publication 6/2017). https://www.eea.europa.eu/publications/circular-by-design
European Environment Agency. (2022). Investigating Europe's secondary raw material markets—European Environment Agency [Publication]. https://www.eea.europa.eu/publications/investigating-europes-secondary-raw-material
European Environment Agency. (2023). Markets for many commonly recycled materials struggle in the EU. European Environment Agency. https://www.eea.europa.eu/en/newsroom/news/markets-commonly-recycled-materials-struggle
European Environment Agency. (2024). Europe's sustainability transitions outlook (TH-AL-24-011-EN-N; p. 70). European Environment Agency. https://www.eea.europa.eu/publications/europes-sustainability-transitions-outlook
European Environment Agency. (2025). Circular material use rate in Europe. European Environment Agency. https://www.eea.europa.eu/en/analysis/indicators/circular-material-use-rate-in-europe
European Environmental Bureau. (2017). Keeping it clean: How to protect the circular economy from hazardous substances - EEB - The European Environmental Bureau. https://eeb.org/library/keeping-it-clean-how-to-protect-the-circular-economy-from-hazardous-substances/
European Parliament. (2021). European Parliament resolution of 15 January 2020 on the European Green Deal (2019/2956(RSP)). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020IP0005
European Parliament. (2023). Circular economy: Definition, importance and benefits. https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits
European Parliament. (2024a). Deal on new rules for more sustainable packaging in the EU. News - European Parliament. https://www.europarl.europa.eu/news/en/press-room/20240301IPR18595/deal-on-new-rules-for-more-sustainable-packaging-in-the-eu
European Parliament. (2024b). Plastic waste and recycling in the EU: Facts and figures. Topics | European Parliament. https://www.europarl.europa.eu/topics/en/article/20181212STO21610/plastic-waste-and-recycling-in-the-eu-facts-and-figures
European Parliament and the Council. (2019). Directive—2019/904—EN - SUP Directive—EUR-Lex. https://eur-lex.europa.eu/eli/dir/2019/904/oj
European Parliament and the Council. (2024a). Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. http://data.europa.eu/eli/dir/1999/31/2024-08-04/eng
European Parliament and the Council. (2024b). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance) Text with EEA relevance. http://data.europa.eu/eli/dir/2008/98/2024-02-18/eng
European Parliament and the Council. (2024c). Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC (Text with EEA relevance). http://data.europa.eu/eli/reg/2024/1781/oj/eng
Eurostat. (2024). Municipal waste statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Municipal_waste_statistics
Fellner, J., Lederer, J., Purgar, A., Winterstetter, A., Rechberger, H., Winter, F., & Laner, D. (2015). Evaluation of resource recovery from waste incineration residues – The case of zinc. Waste Management, 37, 95–103. https://doi.org/10.1016/j.wasman.2014.10.010
Fraser, M., Conde, Á., & Laxmi, H. (2024). The Circularity Gap Report. https://www.circularity-gap.world/2024#download
Garcia-Gutierrez, P., Amadei, A. M., Klenert, D., Nessi, S., Tonini, D., Tosches, D., Ardente, F., & Saveyn, H. (2023). Environmental and economic assessment of plastic waste recycling. JRC Publications Repository. https://doi.org/10.2760/0472
Gast, L., Meng, F., & Morgan, D. (2024). Assessing the circularity of onshore wind turbines: Using material flow analysis for improving end-of-life resource management. Resources, Conservation and Recycling, 204, 107468. https://doi.org/10.1016/j.resconrec.2024.107468
Geist, H., & Balle, F. (2025). Recyclability: Redefining the concept for the circular economy. Journal of Industrial Ecology, 29(5), 1505–1522. https://doi.org/10.1111/jiec.70082
Ghisellini, P., Ncube, A., Casazza, M., & Passaro, R. (2022). Toward circular and socially just urban mining in global societies and cities: Present state and future perspectives. Frontiers in Sustainable Cities, 4. https://doi.org/10.3389/frsc.2022.930061
Gori, M., Bergfeldt, B., Reichelt, J., & Sirini, P. (2013). Effect of natural ageing on volume stability of MSW and wood waste incineration residues. Waste Management, 33(4), 850–857. https://doi.org/10.1016/j.wasman.2012.12.005
Guo, Z., Qiu, J., Kirichek, A., Zhou, H., Liu, C., & Yang, L. (2024). Recycling waste tyre polymer for production of fibre reinforced cemented tailings backfill in green mining. Science of The Total Environment, 908, 168320. https://doi.org/10.1016/j.scitotenv.2023.168320
Herhof Umwelttechnik GmbH. (1992). Verfahren zur Zwischenlagerung von Kunststoffabfällen (European Union Patent EP0500007A2). https://patents.google.com/patent/EP0500007A2/de
Hestin, M., Faninger, T., & Milios, L. (2015). Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment. Plastic Recyclers Europe. http://www.plasticsrecyclers.eu/wp-content/uploads/2022/10/increased-eu-plastics-recycling-targets.pdf

Hopewell, J., Dvorak, R., & Kosior, E. (2009). Plastics recycling: Challenges and opportunities. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526), 2115–2126. https://doi.org/10.1098/rstb.2008.0311

Inghels, D., & Bahlmann, M. D. (2021). Hibernation of mobile phones in the Netherlands: The role of brands, perceived value, and incentive structures. Resources, Conservation and Recycling, 164, 105178. https://doi.org/10.1016/j.resconrec.2020.105178

Isa, A., Nosbi, N., Che Ismail, M., Md Akil, H., Wan Ali, W. F. F., & Omar, M. F. (2022). A Review on Recycling of Carbon Fibres: Methods to Reinforce and Expected Fibre Composite Degradations. Materials, 15(14), 4991. https://doi.org/10.3390/ma15144991

Islam, Md. M., Haque, N., Lau, D., Bhuiyan, M., & Pramanik, B. K. (2025). Comparative life cycle assessment of end–of–life strategies for post–consumer polylactic acid waste: Environmental trade–offs and uncertainty analysis. Chemical Engineering Journal, 522, 167057. https://doi.org/10.1016/j.cej.2025.167057

Jensen, D., Clover, J., Lonergan, S., Levy, M., Bowling, B., Bromwich, B., Halle, S., Barefoot, N., Hamro-Drotz, D., Mourad, B., & Sexton, R. (2012). Renewable Resources and Conflict. UN Interagency Framework Team for Preventive Action. https://www.un.org/en/land-natural-resources-conflict/renewable-resources.shtml

Johansson, N., Krook, J., Eklund, M., & Berglund, B. (2013). An integrated review of concepts and initiatives for mining the technosphere: Towards a new taxonomy. Journal of Cleaner Production, 55, 35–44. https://doi.org/10.1016/j.jclepro.2012.04.007

Johansson, N., Velis, C., & Corvellec, H. (2020). Towards clean material cycles: Is there a policy conflict between circular economy and non-toxic environment? Waste Management & Research: The Journal for a Sustainable Circular Economy, 38(7), 705–707. https://doi.org/10.1177/0734242X20934251

Jones, P. T., Geysen, D., Tielemans, Y., Van Passel, S., Pontikes, Y., Blanpain, B., Quaghebeur, M., & Hoekstra, N. (2013). Enhanced Landfill Mining in view of multiple resource recovery: A critical review. Journal of Cleaner Production, 55, 45–55. https://doi.org/10.1016/j.jclepro.2012.05.021

Kahhat, R. F., & Kavazanjian, E. (2010). Preliminary feasibility study on the use of mono-disposal landfills for e-waste as temporary storage for future mining: 2010 IEEE International Symposium on Sustainable Systems and Technology, ISSST 2010. Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology, ISSST 2010. https://doi.org/10.1109/ISSST.2010.5507740

Kaza, S., Yao, L. C., Bhada-Tata, P., & Van Woerden, F. (2018). What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Washington, DC: World Bank. https://doi.org/10.1596/978-1-4648-1329-0

Kral, U., Kellner, K., & Brunner, P. H. (2013). Sustainable resource use requires "clean cycles" and safe "final sinks." Science of The Total Environment, 461–462, 819–822. https://doi.org/10.1016/j.scitotenv.2012.08.094

Kral, U., Morf, L. S., Vyzinkarova, D., & Brunner, P. H. (2019). Cycles and sinks: Two key elements of a circular economy. Journal of Material Cycles and Waste Management, 21(1), 1–9. https://doi.org/10.1007/s10163-018-0786-6

Krook, J., Svensson, N., & Eklund, M. (2012). Landfill mining: A critical review of two decades of research. Waste Management, 32(3), 513–520. https://doi.org/10.1016/j.wasman.2011.10.015

Kusenberg, M., Eschenbacher, A., Djokic, M. R., Zayoud, A., Ragaert, K., De Meester, S., & Van Geem, K. M. (2022). Opportunities and challenges for the application of post-consumer plastic waste pyrolysis oils as steam cracker feedstocks: To decontaminate or not to decontaminate? Waste Management, 138, 83–115. https://doi.org/10.1016/j.wasman.2021.11.009

Lahl, U., & Zeschmar-Lahl, B. (2024). More than 30 Years of PVC Recycling in Europe—A Critical Inventory. Sustainability, 16(9), Article 9. https://doi.org/10.3390/su16093854

Lamers, F. (2015). Treatment of Bottom Ashes of Waste-to-Energy Installations – State of the Art. TK Verlag - Fachverlag Für Kreislaufwirtschaft. https://ask-eu.de/Artikel/27666/Treatment-of-Bottom-Ashes-of-Waste-to-Energy-Installations-State-of-the-Art-.htm

Larrain, M., Van Passel, S., Thomassen, G., Van Gorp, B., Nhu, T. T., Huysveld, S., Van Geem, K. M., De Meester, S., & Billen, P. (2021). Techno-economic assessment of mechanical recycling of challenging post-consumer plastic packaging waste. Resources, Conservation and Recycling, 170, 105607. https://doi.org/10.1016/j.resconrec.2021.105607

Lehmphul, K. (2024). Landfill. Umweltbundesamt; Umweltbundesamt. https://www.umweltbundesamt.de/en/topics/waste-resources/waste-disposal/landfill

Lichtenegger, G., Rentizelas, A. A., Trivyza, N., & Siegl, S. (2020). Offshore and onshore wind turbine blade waste material forecast at a regional level in Europe until 2050. Waste Management, 106, 120–131. https://doi.org/10.1016/j.wasman.2020.03.018

Lim, J., Ahn, Y., & Kim, J. (2023). Optimal sorting and recycling of plastic waste as a renewable energy resource considering economic feasibility and environmental pollution. Process Safety and Environmental Protection, 169, 685–696. https://doi.org/10.1016/j.psep.2022.11.027

Limburg, M., & Quicker, P. (2016). Entsorgung von Carbonfasern – Probleme des Recyclings und Auswirkungen auf die Abfallverbrennung – [Print, online]. Berliner Abfallwirtschafts- und Energiekonferenz 2016, Nietwerder. TK-Verlag.

Liu, Y., Mendoza-Perilla, P., Clavier, K. A., Tolaymat, T. M., Bowden, J. A., Solo-Gabriele, H. M., & Townsend, T. G. (2022). Municipal solid waste incineration (MSWI) ash co-disposal: Influence on per- and polyfluoroalkyl substances (PFAS) concentration in landfill leachate. Waste Management, 144, 49–56. https://doi.org/10.1016/j.wasman.2022.03.009

Lontoc, G. D., Diola, Ma. B. L. D., & Peralta, M. H. T. (2023). Multi-criteria evaluation of suitable locations for temporary disaster waste storage sites: The case of Cavite, Philippines. Journal of Material Cycles and Waste Management, 25(5), 2794–2808. https://doi.org/10.1007/s10163-023-01705-9

Margallo, M., Taddei, M. B. M., Hernández-Pellón, A., Aldaco, R., & Irabien, Á. (2015). Environmental sustainability assessment of the management of municipal solid waste incineration residues: A review of the current situation. Clean Technologies and Environmental Policy, 17(5), 1333–1353. https://doi.org/10.1007/s10098-015-0961-6

Miliute-Plepiene, J., Fråne, A., & Almasi, A. M. (2021). Overview of polyvinyl chloride (PVC) waste management practices in the Nordic countries. Cleaner Engineering and Technology, 4, 100246. https://doi.org/10.1016/j.clet.2021.100246

Mofokeng, N. N., Madikizela, L. M., Tiggelman, I., & Chimuka, L. (2024). Chemical profiling of paper recycling grades using GC-MS and LC-MS: An exploration of contaminants and their possible sources. Waste Management, 189, 148–158. https://doi.org/10.1016/j.wasman.2024.08.014

Montag, D., Everding, W., Malms, S., Pinnekamp, J., Reinhardt, J., Fehrenbach, H., Arnold, U., Trimborn, M., Goldbach, H., Klett, W., & Lammers, T. (2015). Bewertung konkreter Maßnahmen einer weitergehenden Phosphorrückgewinnung aus relevanten Stoffströmen sowie zum effizienten Phosphoreinsatz. Umweltbundesamt. https://www.umweltbundesamt.de/publikationen/bewertung-konkreter-massnahmen-einer-weitergehenden

Mostbauer, P., Lenz, S., & Lechner, P. (2008). MSWI Bottom Ash for Upgrading of Biogas and Landfill Gas. Environmental Technology, 29(7), 757–764. https://doi.org/10.1080/09593330801987061

Muntenita, C., Titire, L., Chivu, M., Podaru, G., & Marin, R. (2024). Wind Turbine Blade Material Behavior in Abrasive Wear Conditions. Polymers, 16(24), 3483. https://doi.org/10.3390/polym16243483

Nagle, A. J., Mullally, G., Leahy, P. G., & Dunphy, N. P. (2022). Life cycle assessment of the use of decommissioned wind blades in second life applications. Journal of Environmental Management, 302, 113994. https://doi.org/10.1016/j.jenvman.2021.113994

National Grid. (2023). Can wind turbine blades be recycled? | What happens to old wind turbine blades? | National Grid Group. https://www.nationalgrid.com/stories/energy-explained/can-wind-turbine-blades-be-recycled

Nunna, S., Blanchard, P., Buckmaster, D., Davis, S., & Naebe, M. (2019). Development of a cost model for the production of carbon fibres. Heliyon, 5, e02698. https://doi.org/10.1016/j.heliyon.2019.e02698

Obernberger, I., & Supancic, K. (2024). FACT-SHEET: Zwischenlagerung von Pflanzenaschen. https://www.forstholzpapier.at/images/FHP-Arbeitskreise_/AK_Energie/FACTSHEET_Forststra%C3%9Fenbau.pdf

Oehmig, W. N., Roessler, J. G., Blaisi, N. I., & Townsend, T. G. (2015). Contemporary practices and findings essential to the development of effective MSWI ash reuse policy in the United States. Environmental Science & Policy, 51, 304–312. https://doi.org/10.1016/j.envsci.2015.04.024

Parrodi, J. C. H., Vollprecht, D., & Pomberger, R. (2020). Case study on enhanced landfill mining at Mont-Saint-Guibert landfill in Belgium: Physico-chemical characterization and valorization potential of combustibles and inert fractions recovered from fine fractions. Detritus, 10, 44. https://doi.org/10.31025/2611-4135/2020.13941
Pivnenko, K. (2016). Waste material recycling: Assessment of contaminants limiting recycling. https://doi.org/10.13140/RG.2.1.2202.0722
Plastics Europe. (2021). History of plastics. Plastics Europe. https://plasticseurope.org/plastics-explained/history-of-plastics/
Pomberger, R., & Bezama, A. (2024). About theoretical, technical and real recyclability. Waste Management & Research, 42(9), 713–714. https://doi.org/10.1177/0734242X241267184
Pomberger, R., & Ragossnig, A. (2014). Future waste – waste future. Waste Management & Research, 32(2), 89–90. https://doi.org/10.1177/0734242X14521344
RecyClass. (2024). RecyClass Recyclability Methodology. https://recyclass.eu/wp-content/uploads/2024/03/RECYCLASS-RECYCLABILITY-METHODOLOGY_v.2.3.pdf
Reig, M., Vecino, X., Valderrama, C., Sirés, I., & Luis Cortina, J. (2023). Waste-to-energy bottom ash management: Copper recovery by electrowinning. Separation and Purification Technology, 311, 123256. https://doi.org/10.1016/j.seppur.2023.123256
Roessler, J. G., Townsend, T. G., & Kanneganti, A. (2017). Waste to energy ash monofill mining: An environmental characterization of recovered material. Journal of Hazardous Materials, 328, 63–69. https://doi.org/10.1016/j.jhazmat.2017.01.011
Roetman, E., Joustra, J., Heideman, G., & Balkenende, R. (2024). Does the Rubber Meet the Road? Assessing the Potential of Devulcanization Technologies for the Innovation of Tire Rubber Recycling. Sustainability, 16(7), Article 7. https://doi.org/10.3390/su16072900
Romaszewski, T., & Fitas, J. (2024). Properties of RDF after Prolonged Storage. Sustainability, 16(5), Article 5. https://doi.org/10.3390/su16052051
Rybicka, J., Tiwari, A., & Leeke, G. A. (2016). Technology readiness level assessment of composites recycling technologies. Journal of Cleaner Production, 112, 1001–1012. https://doi.org/10.1016/j.jclepro.2015.08.104
Salas, A., Berrio, M. E., Martel, S., Díaz-Gómez, A., Palacio, D. A., Tuninetti, V., Medina, C., & Meléndrez, M. F. (2023). Towards recycling of waste carbon fiber: Strength, morphology and structural features of recovered carbon fibers. Waste Management, 165, 59–69. https://doi.org/10.1016/j.wasman.2023.04.017
Sapsford, D. J., Stewart, D. I., Sinnett, D. E., Burke, I. T., Cleall, P. J., Harbottle, M. J., Mayes, W., Owen, N. E., Sardo, A. M., & Weightman, A. (2023). Circular economy landfills for temporary storage and treatment of mineral-rich wastes. Proceedings of the Institution of Civil Engineers - Waste and Resource Management. https://doi.org/10.1680/jwarm.22.00008
Schinnerl, F., Sattler, T., Noori-Khadjavi, G., & Lehner, M. (2024). Direct aqueous mineral carbonation of secondary materials for carbon dioxide storage. Journal of CO2 Utilization, 88, 102942. https://doi.org/10.1016/j.jcou.2024.102942
Schmidt, B. (2024, 11). Klimastrategie 2040. VOEB - Future Waste, Wien.
Sommer, V., Stockschläder, J., & Walther, G. (2020). Estimation of glass and carbon fiber reinforced plastic waste from end-of-life rotor blades of wind power plants within the European Union. Waste Management, 115, 83–94. https://doi.org/10.1016/j.wasman.2020.06.043
Spini, F., & Bettini, P. (2024). End-of-Life wind turbine blades: Review on recycling strategies. Composites Part B: Engineering, 275, 111290. https://doi.org/10.1016/j.compositesb.2024.111290
Stanisavljevic, N., & Brunner, P. H. (2021). Megacities need both: Circular economy and final sinks! Waste Management & Research, 39(12), 1437–1439.
Stief, K. (1989). Strategy in landfilling solid wastes. In P. Baccini (Ed.), The Landfill (pp. 275–291). Springer. https://doi.org/10.1007/BFb0011268
Stipanovic, H., Bäck, T., & Tischberger-Aldrian, A. (2023). Characterisation of post-consumer textiles using near-infrared spectrometers: NIR 2023.
The Environmental Research & Education Foundation. (2025). Extended Producer Responsibility Literature Review. www.erefdn.org
Torraco, R. J. (2016). Writing Integrative Literature Reviews: Using the Past and Present to Explore the Future. Human Resource Development Review, 15(4), 404–428. https://doi.org/10.1177/1534484316671606
Tortorici, D., Adriani, A., & Laurenzi, S. (2025). Development of a sustainable chemical recycling process of carbon fibers from epoxy-based composites. Composites Science and Technology, 270, 111295. https://doi.org/10.1016/j.compscitech.2025.111295
Umweltbundesamt. (2024). Ewigkeitschemikalien PFAS in Abfällen. Umweltbundesamt; Umweltbundesamt. https://www.umweltbundesamt.de/themen/ewigkeitschemikalien-pfas-in-abfaellen
van Nielen, S. S., Kleijn, R., Sprecher, B., Miranda Xicotencatl, B., & Tukker, A. (2022). Early-stage assessment of minor metal recyclability. Resources, Conservation and Recycling, 176, 105881. https://doi.org/10.1016/j.resconrec.2021.105881
Vermeulen, W., Reike, D., & Witjes, S. (2019). Circular Economy 3.0—Solving confusion around new conceptions of circularity by synthesising and re-organising the 3R's concept into a 10R hierarchy. 2019. https://www.researchgate.net/publication/335602859_Circular_Economy_30_-_Solving_confusion_around_new_conceptions_of_circularity_by_synthesising_and_re-organising_the_3R's_concept_into_a_10R_hierarchy
Volk, R., Stallkamp, C., Herbst, M., & Schultmann, F. (2021). Regional rotor blade waste quantification in Germany until 2040. Resources, Conservation and Recycling, 172, 105667. https://doi.org/10.1016/j.resconrec.2021.105667
Vyzinkarova, D., & Brunner, P. H. (2013). Substance Flow Analysis of Wastes Containing Polybrominated Diphenyl Ethers. Journal of Industrial Ecology, 17(6), 900–911. https://doi.org/10.1111/jiec.12054
Werner, M., Narayanan, A., Rabenschlag, O., Nagarajan, P., Saboo, R., Banatao, R., Moedritzer, S., Zilnik, D., Wong, T., & Meza, M. (2022). Closing the Plastics Circularity Gap—Full Report. Google. https://bbia.org.uk/wp-content/uploads/2022/04/closing-plastics-gap-full-report.pdf
Wilson, G. T., Smalley, G., Suckling, J. R., Lilley, D., Lee, J., & Mawle, R. (2017). The hibernating mobile phone: Dead storage as a barrier to efficient electronic waste recovery. Waste Management, 60, 521–533. https://doi.org/10.1016/j.wasman.2016.12.023
WindEurope. (2020). Accelerating Wind Turbine Blade Circularity. WindEurope. https://windeurope.org/intelligence-platform/product/accelerating-wind-turbine-blade-circularity/
WindEurope. (2021). How to build a circular economy for wind turbine blades through policy and partnerships. WindEurope. https://windeurope.org/policy/position-papers/how-to-build-a-circular-economy-for-wind-turbine-blades-through-policy-and-partnerships/
WindEurope. (2023). Wind energy in Europe: 2022 Statistics and the outlook for 2023-2027. WindEurope. https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2022-statistics-and-the-outlook-for-2023-2027/
Wu, Q., Zhang, Q., Chen, X., Song, G., & Xiao, J. (2024). Life cycle assessment of waste tire recycling: Upgraded pyrolytic products for new tire production. Sustainable Production and Consumption, 46, 294–309. https://doi.org/10.1016/j.spc.2024.02.029
Xie, S., Lim, Y. T., Wang, H., Yi, W., & Antwi-Afari, M. F. (2024). Location and Capacity Optimization of Waste Recycling Centers: Mathematical Models and Numerical Experiments. Applied Sciences, 14(16), Article 16. https://doi.org/10.3390/app14167039
Yang, X., & Berglund, L. A. (2020). Recycling without Fiber Degradation—Strong Paper Structures for 3D Forming Based on Nanostructurally Tailored Wood Holocellulose Fibers. ACS Sustainable Chemistry & Engineering, 8(2), 1146–1154. https://doi.org/10.1021/acssuschemeng.9b06176
Zero Waste Europe. (2022). Incineration Residues: The dust under the carpet - Zero Waste Europe. Zero Waste Europe. https://zerowasteeurope.eu/press-release/incineration-residues-the-dust-under-the-carpet/
Zhong, H.-N., Su, Q.-Z., Chen, S., Li, D., Sui, H., Zhu, L., Dong, B., Wu, S., & Wang, X. (2025). Revealing contaminants in China's recycled PET: Enabling safe food contact applications. Resources, Conservation and Recycling, 212, 107947. https://doi.org/10.1016/j.resconrec.2024.107947