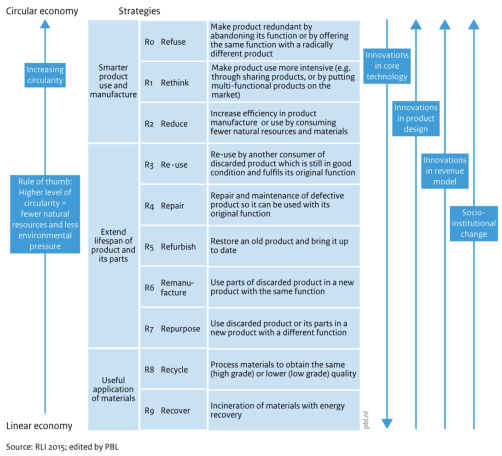
Rethinking Residual Waste: The Future of Circularity in Milan and beyond

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Milan already operates a high-performing separate-collection system, yet approximately 231,000 tonnes of municipal waste per year remain in the mixed residual stream. This project investigated whether additional material recovery could be achieved before that residual stream is sent to energy recovery. The work combined waste-composition data, particle-size distributions, technology-specific separation efficiencies and material sustainability factors in a modular mass-balance model developed with input from AMSA and A2A. Individual technologies, including bag opening, trommel screening, ferromagnetic separation, eddy-current separation, near-infrared spectroscopy, manual picking and AI-enabled robotic sorting, were first assessed separately and then combined into integrated plant configurations. In its current state, the model projects a recovery of approximately 64,342 tonnes per year, corresponding to 27.9% of the residual stream. Plastics and paper/cardboard account for most of this recovery. Using material proxy factors from Ansys Granta, the model estimates approximately 42.0 kt CO_2/y avoided through substitution of virgin production and a further 77.7 kt CO_2/y of avoided fossil combustion emissions, for a combined result of about 119.8 kt CO_2/y. Gross primary-energy savings are estimated at 1.73 million GJ/y; after deducting foregone waste-to-energy electricity, the model retains a net energy benefit of 1.24 million GJ/y. A gross avoided virgin-production water footprint of roughly 59.7 million m^3/y is also calculated, although this indicator is more uncertain and should not be interpreted as a direct local water saving. The project delivered a modular, mass-balance-based model that can convert heterogeneous waste data into a transparent decision model for residual-waste sorting and circularity planning.

1. Introduction

Municipal waste management is increasingly being framed as a resource-management problem rather than only a disposal problem. In a linear system, products are manufactured from primary resources, used, and then discarded. Circular-economy strategies, however, seek to retain the value of products, components and materials for longer. The 10R framework illustrated below places recycling below higher-value strategies such as refusal, reuse and repair, but above energy recovery in the circularity hierarchy. For a residual municipal waste stream, where most opportunities for prevention and source separation have already passed, the practical question is therefore whether additional material recovery can still be achieved before combustion. In effect, for residual waste, the question would be whether, by implementing innovative and technological solutions, the waste can be moved one step up the chain, from R9 *Recover* to R8 *Recycle* (Potting et al., 2017).



Source: RLI 2015; edited by PBL

The European regulatory context also increasingly reinforces circularity thinking. Directive (EU) 2018/851 requires preparation for reuse and recycling of municipal waste to reach at least 55% by weight by 2025, 60% by 2030 and 65% by 2035. Directive (EU) 2018/850 complements this trajectory by requiring municipal waste sent to landfill to fall to 10% or less by 2035. These targets do not imply that all residual waste should be mechanically sorted; rather, they create pressure to improve source separation, material quality and downstream recovery while avoiding infrastructure choices that lock recyclable material into lower levels of the waste hierarchy.

Milan provides a particularly relevant case because its separate-collection performance is already high. AMSA, the entity responsible for waste management in Milan, and our partner in this project, reports approximately 638 kt of municipal waste collected annually, of which 63.8% is separately collected and 36.2% remains unsorted. The latter corresponds to approximately 231 kt/y of mixed residual waste. In other words, the city's remaining opportunity is not a conventional "build a recycling system from scratch" problem; it is a marginal-recovery problem within a relatively mature collection system. The residual fraction is heterogeneous, contains a mixture of potentially recyclable and non-recyclable materials, and is currently routed in its entirety to energy recovery after collection (AMSA, 2026).

The project objective was to translate this residual stream into a technically explicit model: what materials are present, in what quantities and size fractions, which sorting technologies can target them, what proportion could plausibly be recovered, what would be the economic value of the extracted waste and what environmental consequences follow if recovered output displaces virgin-material production and some waste-to-energy treatment. The study was implemented as a modular mass-balance model rather than a single deterministic plant design. This allows assumptions on composition, particle size, separation efficiency and recoverability to be altered without rebuilding the analysis from first principles, and ensures that the model can be applied across multiple separate waste-collection contexts.

It must be noted that, although assessing *economic viability* was a central objective of the model, this aspect is not discussed in this paper because the calculation of ultimate value relies on sensitive information provided by AMSA and A2A.

Research question:

"To what extent can Milan's mixed residual municipal waste be converted into secondary material streams through an integrated sequence of sorting technologies, and what economic and environmental benefits could result?"

2. Research and technology scouting

The research phase started with a technology-by-technology review. The EU BAT reference document on the installation of waste treatment was used as a primary source to identify processes suitable for mixed municipal waste, after which operational assumptions were formulated on the basis of industry research. These assumptions were later cross-checked against information available from A2A and equipment specifications used in a study on waste separation equipment by Li et al. (2026) . The key finding from this phase was structural: no individual machine could address more than a subset of Milan's residual-waste composition. This drove the transition from standalone technology analyses to an integrated sorting-line model.

Technology	Function in the model	Primary target / role
Bag opener	Controlled pulling and shearing opens closed bags before separation.	Preparation step; exposes bagged material.
Trommel screen	Separates material by particle size before material-specific sorting.	Creates size-based flows with different material profiles.
Overband magnet	Uses magnetic attraction above the conveyor.	Ferrous metals, principally iron and steel.
Eddy-current separator	Induces currents in conductive non-ferrous objects, creating a repulsive force.	Aluminium / susceptible non-ferrous metals.
NIR / SWIR spectroscopy + air jets	Classifies materials from wavelength-dependent reflectance and ejects targets pneumatically.	Paper, plastics, textiles, glass and selected organics depending on configuration.
AI vision + robotic arm	Detects individual objects and physically picks selected targets.	Optional coarse-stream recovery / quality control.
Manual picking	Human identification and removal of target items.	Operational benchmark for object-level picking.

Table 1. Technology set investigated in the model.

The bag opener and trommel were treated as enabling technologies rather than recovery technologies in their own right. The bag opener was assigned a 95% opening rate, while the trommel partitioned the stream according to particle size. Metal recovery was divided between ferrous and non-ferrous mechanisms. The model assumed that the mixed metal category contained 60.32% iron, 11.11% aluminium and 28.57% other metals, based on the regional composition proxy adopted in the study (ARPA Lombardia, 2026).. Overband magnets were modelled at 90% simple recovery efficiency, while the eddy-current separator was modelled at 92.5% efficiency for susceptible non-ferrous material. This distinction was important because treating all 'metals' as one recoverable category would overstate the role of any single separation technology.

Spectroscopy was evaluated in four configurations, Basic NIR, Basic SWIR, hyperspectral NIR and hyperspectral SWIR, to test the value of broader spectral range and denser spectral sampling. The final reference plant used the Basic NIR configuration out of economic consideration. Material-specific recognition efficiencies were combined with 99% jet accuracy; representative model values were 87% for paper/cardboard, 86% for plastics, 77% for textiles, 68% for organics and 70% for glass. More advanced spectral configurations produced higher recovery in the standalone modules, but the integrated plant analysis also had to respect downstream material quality and recoverability constraints.

Robotic and manual picking were investigated as alternatives for coarse objects. The robotic module assumed 76% simple efficiency and approximately 52.5 picks per minute, equivalent to only about 0.09 t/h per unit under the modelled average object weight. This highlighted a fundamental scale issue: object-by-object picking can be valuable for quality control or targeted recovery but becomes capacity-intensive when asked to process a bulk municipal stream, and may therefore be economically inefficient. Manual picking showed an even stronger economic limitation and was and was therefore retained principally as a benchmark rather than as the core plant architecture.

3. Methodology

3.1 Waste baseline and composition

The mass balance begins with 638,000 t/y of total municipal waste and isolates the residual fraction collected through three routes: door-to-door collection, street bins and other sources. Together these streams represent 36.21% of total municipal waste, or 230,983 t/y. Door-to-door and street-bin streams use distinct composition profiles. For the 'other sources' stream, composition was assumed to be the same as door-to-door collection because a dedicated composition dataset was not available. This assumption affects roughly one quarter of the residual-waste stream and is therefore one of the important uncertainties in the baseline.

Residual material	Modelled mass (t/y)	Share of residual stream
Paper & cardboard	70,676	30.6%
Plastic bottles & packaging	43,913	19.0%
Other	44,402	19.2%
Textiles	19,376	8.4%
Plastic bags	16,653	7.2%
Paper towels & tissues	12,615	5.5%
Food & organics	11,852	5.1%
Metals	5,656	2.4%
Rigid plastics	4,557	2.0%
Glass	1,283	0.6%

Table 2. Weighted composition of the modelled residual stream. Values may not sum exactly because of rounding.

Paper and cardboard form the largest single fraction, at roughly 31% of the residual stream. Plastic bottles and other plastic packaging and the 'other' category each contribute approximately 19%. Organics represent only about 5.1%, consistent with Milan's extensive source-separated organics collection having already removed much of the biodegradable fraction from residual waste. This composition profile matters because the technical value of a sorting line depends on both the abundance of a material and its physical separability.

Particle-size allocation was not available at the same local resolution as composition. The model therefore transposed size-distribution data from ADEME's French residual-household-waste dataset (ADEME, n.d.) onto the Milan composition classes. For the two-stream reference configuration, the size model grouped material into <60 mm and >60 mm fractions, separated by the trommel screen. The three-stream model further split the >60 mm fraction into 60–200 mm and >200 mm categories. This was a pragmatic way to capture the strong relationship between particle size and material type; fines contain more organics and sanitary material, while larger fractions contain more paper, plastics and textiles, and coarse fractions are more readily able to be picked by a human picker or robotic arm, but it should be understood as a proxy rather than a Milan-specific measurement.

Furthermore, wo alternative size-separation configurations were developed around the trommel screen. In the two-stream configuration, the incoming residual waste is divided into a smaller fraction below 60 mm and a larger fraction above 60 mm, after which each stream is directed to the relevant downstream recovery technologies. The three-stream configuration introduces an additional split within the larger

material, separating the waste into <60 mm, 60–200 mm and >200 mm fractions. This third, coarse fraction was created specifically to test whether very large individual items could be recovered using an AI-enabled robotic picking arm. The two-stream configuration was selected as the quantitative reference case because it provides a simpler and higher-throughput process and does not depend on the relatively low object-by-object processing capacity of robotic picking. The three-stream configuration was therefore retained as an alternative design for testing the potential role of robotic sorting on coarse material, rather than as the basis for the reported reference results.

3.2 Sequential mass-balance logic



Figure 1. Simplified sequence used in the final reference model.

Each processing stage was implemented as a separate module. Incoming tonnes of each material were multiplied by the relevant opening, size-allocation or recovery parameter, and unrecovered material was passed to the next stage. This prevents the same tonne from being recovered twice and allows the residual composition to evolve through the line. The approach also makes the model auditable: a change to a technology efficiency or a composition assumption propagates through the remaining stages rather than being applied only to a top-level total. It is important to note that each stage may represent a multitude of the same machines.

The reference line was deliberately modelled as a predominantly dry mechanical-sorting process. Mixed-waste treatment plants often introduce wet/dry separation or biological conditioning when organics and moisture are major contaminants. Milan's residual stream is different: food and organics represent only about 5.1% of the modelled residual mass because source-separated organics collection already removes most biodegradable material upstream. This relatively low organic loading reduces the expected need for a wet separation stage and supports testing a simpler dry-processing configuration.

3.3 Recoverability and output quality

Mechanical or optical separation is not identical to production of a market-ready secondary material. To represent contamination, downstream acceptance and the fact that some technically identifiable material may not be suitable for recycling, the model applied a final recoverability factor to the sorted fractions. In the model, plastic bottles/packaging, rigid plastics, metals and glass were assigned a 100% recoverability factor; paper/cardboard 50%, textiles 25% and plastic bags, sanitary paper, organics and the 'other' category 0%: these numbers were provided as a reference efficiency by AMSA. These factors are consequential: they convert gross sorting output into the tonnes ultimately counted as recovered in the reference case. They also explain why the final recovered quantity is materially lower than the amount that the spectroscopy module can physically identify and eject.

Material group	Final recoverability factor
Paper & cardboard	**50%**
Plastic bottles & packaging	**100%**
Rigid plastics	**100%**
Metals	**100%**

Textiles	**25%**
Glass	**100%**
Plastic bags	**0%**
Paper towels & tissues	**0%**
Food & organics	**0%**
Other	**0%**

Table 3. Recoverability factors used to convert sorted output into reported recovered material.

3.4 Environmental accounting

$$\textit{Energy benefit}_i = \textit{Recovered tonnes}_i \times (\textit{Primary energy}_i - \textit{Recycling energy}_i)$$

Because the baseline residual stream is routed to waste-to-energy (WtE), diverting recyclable material also removes combustible energy from the incinerator. The model therefore estimates the electricity that would have been generated from the recovered combustible fraction using material heat-of-combustion values and a 35% gross electrical efficiency, corresponding to the upper end of the BAT-associated range for municipal solid waste incineration. The reported net energy indicator is gross primary-energy saving minus this foregone WtE electricity.

$$\textit{Net energy benefit} = \Sigma\ \textit{gross recycling energy benefit} - \Sigma\ \textit{foregone WtE electricity}$$

Greenhouse-gas effects were calculated through two mechanisms. First, the model compares the CO_2 footprint of primary production with the CO_2 footprint of recycling. Second, for fossil-derived combustible materials such as plastics, it adds the fossil CO_2 emissions avoided because the recovered material is no longer burned at WtE. The two mechanisms are additive in the model, but the result is a scenario estimate rather than a complete life-cycle assessment.

Water was treated differently. The water calculation multiplies recovered tonnes by the virgin-production water-use factor of the corresponding proxy material. It does not account for the geography or scarcity context of water use. Accordingly, the water indicator is reported in this report as a gross avoided virgin-production water footprint, not as a direct or local water saving. This distinction is particularly important for paper and textiles, whose proxy water factors dominate the result.

4. Results and interpretation

4.1 Material recovery

The reference case yields 64,341.6 t/y of recovered material from 230,983.2 t/y of residual waste, equivalent to a 27.9% recovery rate for the residual stream. Relative to all municipal waste collected in Milan, the recovered quantity is approximately 10.1%.

Recovered material	Recovered (t/y)	Share of recovered output
Plastic bottles & packaging	29,587	46.0%
Paper & cardboard	24,490	38.1%
Metals	3,469	5.4%
Textiles	3,360	5.2%
Rigid plastic items	3,166	4.9%
Glass	271	0.4%

Table 4. Composition of recovered output in the reference case.

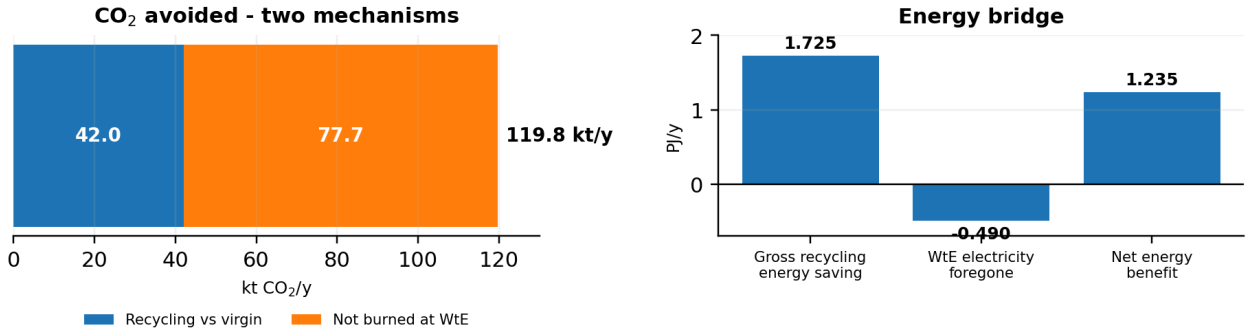
Two material families dominate. Plastic bottles and packaging account for approximately 29.6 kt/y and paper/cardboard for 24.5 kt/y, together representing about 84% of reported recovered output. Metals,

textiles and rigid plastics contribute several thousand tonnes each, while glass is comparatively small. Plastic bags, sanitary paper, organics and the ‘other’ fraction are not credited as recovered in the reference case because their recoverability factors were set to zero. The model therefore distinguishes between the technical ability to separate an item and the decision to count that item as an accepted recyclable output.

4.2 Energy and greenhouse-gas effects

The model estimates 1.725 million GJ/y of gross primary-energy savings from replacing virgin material production with recycling. This is equivalent to approximately 479 GWh/y. Diverting combustible material from WtE reduces electricity production by an estimated 0.490 million GJ/y (about 136 GWh/y). After this subtraction, the net energy benefit remains 1.235 million GJ/y, or approximately 343 GWh/y. Plastics are the dominant contributor because the gap between virgin and recycled production energy is large relative to most other modelled materials.

For CO_2, the production-versus-recycling comparison yields approximately 42.0 kt/y of avoided emissions across the materials for which both factors were available. Avoided fossil combustion at WtE adds approximately 77.7 kt/y, producing a combined model result of 119.8 kt CO_2/y. The WtE component is driven mainly by plastics, which carry both a fossil carbon content and a high heat of combustion. The result should therefore be read as a consequence of the specified baseline: if recovered plastics are not burned, their fossil combustion emissions are avoided, but some electricity generation is simultaneously foregone and is captured separately in the energy bridge.



4.3 Water footprint

The gross avoided virgin-production water footprint is approximately 59.7 million m³/y. Roughly 41.7 million m³/y of this total is associated with paper/cardboard and 13.3 million m³/y with textiles; all other quantified materials together account for a much smaller share. The textile proxy used in this calculation assumes an average of cotton and polyester fabric’s water footprint, while cotton has a water factor orders of magnitude larger than most industrial materials. The number is therefore useful as a directional resource-footprint indicator, but it should not be presented as 59.7 million m³ of physical water saved in Milan.

5. Limitations

The model should be interpreted as a screening framework rather than a final plant design. The residual waste baseline is subject to composition uncertainty because the “other sources” stream adopts the door to door profile, while particlesize fractions are transferred from an ADEME French dataset rather than measured directly in Milan. Technology efficiencies are informed by literature, vendor information and expert input and may vary with belt loading, moisture, contamination, object overlap and maintenance. A

further modelling judgement concerns the recoverability factors that convert sorted output into accepted secondary material, especially the 50% factor for paper and 25% for textiles; these should be validated with downstream recyclers and quality specifications. The environmental calculations are also bounded: they compare virgin production, recycling and WtE displacement but do not constitute a full ISO lifecycle assessment because sortingplant electricity emissions, civil works, transport changes and downstream yield losses are not comprehensively netted. Finally, although both two and threestream architectures were explored, the reported 64.3 kt/y recovery and associated environmental results correspond to the two stream quantitative reference case; the threestream model is a more granular alternative for testing coarsefraction routing and robotic picking.

6. Conclusion

The project demonstrates that meaningful material recovery remains possible even in a city with comparatively high source separation. Starting from approximately 231 kt/y of mixed residual waste, the final reference model identifies up to 64.3 kt/y of additional recoverable material, with plastics and paper/cardboard providing the largest contribution. The analysis also shows why system design matters: bag opening and size classification prepare the stream; magnets and eddy-current separators remove specific metal fractions; and spectroscopy addresses the broader paper, plastic, textile and glass mix. No single technology is sufficient on its own. The environmental calculations indicate a substantial potential reduction in virgin-material energy demand and greenhouse-gas emissions, even after explicitly accounting for electricity no longer generated at WtE. The model's strongest contribution is therefore methodological as much as numerical: it provides a transparent framework in which waste composition, physical sorting, downstream recoverability and environmental effects are linked through a sequential mass balance. The final model is transferable across different waste-collection settings, and may therefore be used to explore in which contexts, or under which conditions, it is economically and environmentally favorable to engage in the sorting of residual waste.

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