Master's Degree in Environmental and Land Engineering

Academic Year 2025/2026

Graduation Session: July 2026

Cooling and freezing equipment processing for recycling: study of innovative technologies

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Acknowledgements

I would like to express my deepest gratitude to everyone who has supported me throughout my academic journey and made the completion of this master's thesis possible at Politecnico di Torino.

First and foremost, I wish to extend my profound appreciation to my thesis supervisor, Professor Rossana Bellopede, for her invaluable guidance, immense patience, and academic rigor. Her insightful feedback, constructive critiques, and continuous encouragement throughout the drafting and revision of this work have been fundamental to my development as an environmental engineer.

I am equally grateful to Transistor S.r.l. for welcoming me and allowing me to conduct my research within their organization.

Finally, I would like to thank my family and friends for their unwavering support, understanding, and motivation during these months of research and academic dedication.

ABSTRACT

Rapid cycles of technological innovation and a systemic shortening of product lifespans have made Waste Electrical and Electronic Equipment (WEEE) one of the fastest-growing solid waste streams globally. Within the European circular economy framework, temperature exchange equipment—designated as Category 1 (R1)—demands advanced end-of-life management due to the environmental hazards of processing greenhouse gases embedded within both active cooling circuits and rigid polyurethane insulation foams. While modern appliance manufacturing has successfully transitioned toward natural, low-Global Warming Potential hydrocarbons like pentane, a massive tail of legacy chlorofluorocarbon (CFC) units continues to enter regional waste streams, driving a technological shift toward high-efficiency joint processing infrastructure.

This thesis evaluates the operational, environmental, and financial dimensions of Transistor S.r.l.—a recycling enterprise managed by the Arcobaleno Social Cooperative—at its certified facility in Leinì, Turin. Employing a workforce of seventy individuals, with approximately one-third integrated through social inclusion initiatives, the facility operates under a single regional environmental permit that restricts mechanical processing exclusively to fluorine-free, pentane-insulated appliances. During the 2025 reference period, the facility received 4,092,228 kg of cooling equipment; however, due to statutory limits, 1,012,410 kg of legacy CFC-based appliances were rejected and diverted to external treatment streams. This structural bottleneck caused a 24.7% loss in regional material procurement and capped gross revenues at 862,349 €, evaluated at a flat treatment tariff of 280 € per metric ton.

To resolve these technological and regulatory constraints, this study develops a comprehensive engineering and economic blueprint for a dual-stream facility upgrade. The proposed design integrates advanced Phase 2 physical containment barriers with a modified regenerative thermal oxidizer (RTO) operating at 780 °C, coupled with downstream wet chemical scrubbing systems. This configuration successfully neutralizes highly corrosive hydrofluoric and hydrochloric acid vapors generated during the thermal cracking of fluorinated compounds, ensuring strict compliance with emission thresholds at stack EM3. Implementation of this engineering retrofit enables full internal processing of the regional waste stream, expanding annual gross revenues by 32.87% to 1,145,824 € while maintaining a constant processing throughput of 45 refrigeration units per hour.

Financial evaluation of the project quantifies the total fixed capital expenditure (CAPEX) at 798,000 €, comprising 748,000 € for specialized RTO procurement and 50,000 € for ancillary engineering works. Sensitivity analyses demonstrate that while securing non-repayable public subsidies through mechanisms such as the European Union’s LIFE Programme optimizes the project’s net present value, a secondary private debt financing scenario—utilizing a 10-year commercial bank loan—remains highly viable. Supported by a robust debt service coverage ratio driven by the expanded CFC revenue stream, the business model demonstrates structural resilience and complete bankability independent of public capital injections. Ultimately, this research provides a scalable blueprint for industrial retrofitting, illustrating how targeted environmental engineering and adaptive financial structuring can resolve regional waste

bottlenecks while securing sustainable economic growth and social integration within northern Italian social enterprises.

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CHAPTER 1: INTRODUCTION & CONTEXT

1.1 The Global and European E-Waste Crisis

Faster turnover in consumer tech signals how quickly devices are replaced today. As products cycle through hands more often, discarded electronics grow in volume - becoming a swelling fraction of global trash (Ghisellini et al., 2016). Numbers tell part of the story: 53.6 million metric tons surfaced worldwide by 2019, averaging about 7.3 kilograms for every individual. Projections suggest 74.7 million metric tons could accumulate within little over a decade. Brief lifespans add momentum here, while high demand and limited repair choices play their part. Pressure grows on urban waste systems because of this rapid turnover. Gadgets discarded contain reactive materials - yet also precious metals bound to dangerous chemicals (Milios et al., 2018). Earlier generations of industry leaned heavily on linear disposal routes. With persistent gaps in supervision, recovery efforts frequently proved ineffective; some byproducts ended up shipped abroad unchecked, exposing vulnerable populations to toxic residues (Perkins et al., 2014).

To address these severe externalities, European environmental policy transitioned toward a circular economy framework. The explicit intent is to decouple industrial growth from raw resource extraction (Ghisellini et al., 2016). This stance completely redefines how state agencies view electronic scrap. Rather than treating WEEE merely as a pollution liability to mitigate, the current regulatory consensus frames it as a primary avenue for urban mining and critical resource preservation (Cole et al., 2019). The regional volume is massive. Europe logs the highest per capita e-waste generation globally, shedding about 16.2 kg per resident annually. At the same time, the continent achieves the highest documented formal collection and recycling rate at 42.5%. This metric reflects highly developed regional waste tracking mechanisms. Through uniform statutory metrics, the European Union placed WEEE processing at the absolute center of its industrial policy. These regulations actively force discarded consumer goods up the waste hierarchy, diverting end-of-life electronics from landfills into high-efficiency mechanical and thermodynamic recovery streams (Cole et al., 2019; Maitre-Ekern and Dalhammar, 2019).

Reality on the ground often hits roadblocks that differ by region. Hitting wide-scale goals means dealing with unique logistics in each country. Even though rules such as Directive 2012/19/EU establish uniform recovery standards, how they are applied nationally varies sharply - pointed out by Hestin and team in 2016. Such mismatch in regulations creates strain, affecting big companies operating across nations along with niche recycling operations within specific areas. Out here, where things rarely fit together smoothly, Transistor S.r.l. moves on its own. Not waiting for alignment, it manages robotic systems gathering Category 1 waste while navigating strict regional rules across northern Italy. Each step follows a tangle of local laws few can untangle easily.

1.2 Refrigeration Equipment and Climate Dimensions: The Legacy of Ozone Depleting Substances and Fluorinated Gases (F-Gases)

Within the framework of WEEE regulation, temperature exchange equipment—designated as Category 1 (R1) in Europe—demands highly specialized end-of-life handling due to the environmental risks of processing fluids trapped within both active cooling circuits and rigid insulation foam layers (Vehlow and Gloël, 2020). In 2019, temperature exchange equipment accounted for nearly 11 million metric tons of the global e-waste stream, maintaining an annual growth rate of approximately seven percent. The industrial evolution of domestic and commercial refrigeration technologies has historically been bound to the development of synthetic chemical refrigerants (Glüge et al., 2024). Throughout the twentieth century, chlorofluorocarbons (CFCs) dominated the manufacturing market: Trichlorofluoromethane (R11) served as the primary blowing agent for expanding rigid polyurethane insulation foam, while Dichlorodifluoromethane (R12) was utilized as the standard refrigerant fluid within sealed hermetic compressor circuits due to its thermodynamic stability, non-toxicity, and non-flammable properties (Kjeldsen and Jensen, 2001; Glüge et al., 2024). Subsequent atmospheric research revealed that the fugitive release of these volatile halogens caused severe stratospheric ozone depletion and high radiative forcing, with global warming potentials (GWPs) thousands of times greater than carbon dioxide, leading to their global ban under the Montreal Protocol framework (Vehlow and Gloël, 2020; Glüge et al., 2024).

Following the phase-out of primary ozone-depleting substances, the manufacturing market transitioned to transitionary Hydrofluorocarbons (HFCs)—such as R134a and R125—which eliminated stratospheric ozone depletion risks but still possessed high global warming potentials, prompting subsequent global phase-downs under the Kigali Amendment (Glüge et al., 2024). Consequently, modern manufacturing paradigms shifted entirely toward halogen-free natural substitutes, establishing Isobutane (R600a) as the standard circuit refrigerant and pentane isomers (primarily cyclopentane and isopentane) as the dominant blowing agents for insulation foam structures (Vehlow and Gloël, 2020; Glüge et al., 2024). While next-generation hydrofluoroolefins (HFOs) have emerged as low-GWP alternatives, their atmospheric degradation yields persistent environmental pollutants such as trifluoroacetic acid (TFA), highlighting the continuous need for strict chemical containment across all technology generations (Glüge et al., 2024).

Figure 1.1: Timeline of refrigerant and blowing agent generations and their environmental parameters.

Source: Elaboration based on environmental parameters detailed by baseline regulatory assessments (Vehlow and Gloël, 2020).

Historically, the European refrigeration market underwent a profound technological transformation following these mandates, enforcing a total ban on the manufacturing of CFC-based cooling appliances by 1995. On a global scale, contemporary manufacturing networks produce approximately 165 to 170 million domestic refrigeration units annually. Within this current global production matrix, the technological split has shifted dramatically: chlorofluorocarbons (CFCs) account for 0% of new manufacturing due to strict international regulatory bans. In contrast, natural hydrocarbons (HCs)—specifically Isobutane (R600a) for the cooling circuit and pentane isomers for the insulation foam—have achieved an absolute dominance of nearly 100% within the European domestic manufacturing sector, and capture between 75% and 80% of the total global market share. The remaining 20% to 25% of global annual production relies on transitionary hydrofluorocarbons (HFC-134a) or emerging low-GWP hydrofluoroolefins (HFOs).

However, despite a complete shift to 100% hydrocarbon-based appliance production within Europe for over three decades, a massive historical tail remains embedded within regional e-waste collection systems. In the European Union, where an active stock of roughly 258 million household refrigeration units is maintained, approximately 19 million appliances are taken out of service and disposed of each year. Due to the extreme operational longevity of these domestic assets—which frequently spans 15 to 25 years—recent European market metrics estimate that between 20% and 35% of all end-of-life cooling appliances currently entering regional collection grids still contain legacy fluorinated greenhouse gases (CFC-11 and CFC-12). This structural market distribution directly mirrors the contemporary waste intake profile audited at localized processing nodes, such as the Leinì facility, where legacy CFC equipment constitutes a significant 24.7% fraction of the total inbound mass, proving that dual-stream treatment capabilities remain a critical requirement for regional circular infrastructure.

When these end-of-life appliances are subjected to substandard mechanical processing or open-atmosphere shredding, the compressed cellular structures of the insulation foam collapse, resulting in the instantaneous volatilization of the trapped blowing agents directly into the biosphere (Vehlow and Gloël, 2020). Environmental assessments indicate that improper disposal and un-mitigated crushing of temperature exchange equipment accounted for global fugitive emissions equivalent to 98 million metric tons of CO_2 in 2019 alone. This atmospheric liability underscores the technical necessity of deploying fully encapsulated, gas-tight mechanical sizing environments coupled with downstream thermal or cryogenic destruction loops capable of capturing and neutralizing volatile organic compounds and halogenated vapors simultaneously (Ylä-Mella et al., 2014).

1.3 The Social Enterprise Model: Arcobaleno and Transistor S.r.l.

What stands out about this study is how it looks at Transistor S.r.l., a business arm tied to the Arcobaleno Social Cooperative that focuses on recycling. Started back in 1992, the cooperative built its purpose around offering lasting jobs to people held back by deep-rooted obstacles in regular work settings - those once caught up in legal troubles or struggling with addiction. Right

now, it manages nearly 300 workers spread across different roles, making sure a full third of these spots go to people taking part in reintegration efforts. Across northern Italy, the group runs several waste operations: Cartesio handles collecting paper and cardboard directly from homes in Turin, while Ingombranti deals with large household items in the same city, and Soeko works on sorting mixed recyclables near Chivasso.
Back in 2010, Transistor S.r.l. began working only with electronic waste - gathering it, handling it. Operations stretch through a web of more than 380 drop-off spots. That system covers Liguria, then cuts into Piedmont, reaches up into Valle d'Aosta. Each location ties into their regional flow. Structurally, the company separates its high-volume logistical intake from its advanced thermodynamic and mechanical processing lines. Logistical aggregation, retail drop-offs, and primary sorting take place at a specialized inter-municipal collection centre located at Via Paolo Veronese 202, 10148 Torino (Torino North), which maintains active service agreements with more than 100 municipalities across the Province of Turin. Conversely, automated mechanical size reduction, process inertization, and thermal gas recovery for Category 1 (R1) assets are centralized at its industrial treatment plant located at Via Giuseppe Peano 118, 10040 Leinì (TO). One way to look at it - Transistor S.r.l. runs with just 70 people on staff. Because so many flammable gas-cooled units arrive each week, the Leinì site now uses two work shifts instead of one for fridges. After checking numbers and design plans, leaders found that buying a fresh regenerative thermal oxidizer could handle double chemical flows. That machine would let the factory grow its throughput straight up yet keep staffing exactly where it is. Payroll stays flat, even as performance climbs.

Looking at how things move and get handled, this setup tackles key issues tied to Extended Producer Responsibility and product stewardship. Since separate recycling streams often frustrate users, getting more people involved means cutting down on how far they must go, how much work it takes, or how long it lasts when disposing of old items (Wagner, 2013). When drop-off spots sit too far away or lack access, individuals tend toward improper trash disposal - or simply keep broken goods stored indefinitely. With 380 pickup locations packed closely throughout northern Italy, Transistor S.r.l. fills the gap where ease usually fails. Evidence shows efficient recovery of materials from used products aligns well with ethical business practices - also revealing regulatory adherence might open paths to broader community involvement.

1.4 Problem Statement: The Technical and Regulatory Mismatch

Even though markets now favor hydrocarbon-cooled fridges, today's disposal setups must handle two very different appliance types at once. Owing to their long service life - often thirty years or more - many homes still run old refrigerators packed with CFCs (Vehlow and Gloël, 2020). As a result, recycling centers keep pulling outdated models out of everyday waste flows. Alongside these are newer units filled with non-toxic yet flammable gases. So while recent designs pose lower environmental harm during operation, they bring fresh safety concerns when scrapped. Meanwhile, earlier-generation devices remain problematic due to ozone-damaging contents (Vehlow and Gloël, 2020).

Most processing sites built just for oil and gas work cannot manage the complex systems required to trap, cool into liquid form, or separate unstable fluorinated compounds. If a recycling center can only deal with pentane-based equipment, rejecting older CFC-containing devices becomes inevitable - jeopardizing local pickup quotas - while releasing such substances by mistake may weaken broader EU environmental aims under Directive 2012/19/EU.

This challenge stems from limits set by chemistry and physics. When cutting up cooling units sealed with hydrocarbons, trapped cyclopentane or mixtures of pentanes inside hard polyurethane foam pose risks - so operators flood the area with nitrogen gas to suppress oxygen before shredding, avoiding ignition near the minimum explosion threshold. Following release, those extracted fumes travel straight into a basic ceramic-bed burner running hot at 780 °C, where intense heat splits long-chain molecules into harmless water vapor and carbon dioxide.

However, if legacy volatile fluorinated carbons (VFCs) such as R-11 or R-12 are introduced into this single-stream loop, high-temperature combustion undergoes a radically different chemical path, releasing highly toxic and corrosive secondary effluents, specifically hydrofluoric acid (HF) and hydrochloric acid (HCl). These aggressively attack internal structural metals, inducing severe flue-gas side corrosion and inducing rapid catalytic fouling of the unlined ceramic regenerator beds.

This technical barrier translates into an immediate regulatory restriction. The active Environmental Integrated Authorization (Autorizzazione Integrata Ambientale - AIA) permit issued to the Leinì facility legally restricts its automated mechanical lines to handle only Category 1 Sub-category 1B appliances configured for volatile hydrocarbons. Grinding chlorofluorocarbon units without an authorized downstream wet chemical scrubber or an integrated sub-zero cryogenic condensation loop would violate point-source chimney limits and breach the active AIA charter. To avoid severe administrative and criminal sanctions under Italian Legislative Decree 49/2014, Transistor S.r.l. is currently legally forced to automatically reject **24.7%** of the total inbound regional market volume at its gates, creating a severe operational bottleneck.

1.5 Thesis Objectives and European Funding Paradigm

This study aims to build a clear, evidence-based model combining technical and economic analysis, designed to back Transistor S.r.l.'s request for EU co-financing to grow its processing capacity. Since integrating CFC recovery demands high investment in tailored pollution control and sealed handling units, access to public funding - like the EU LIFE initiative - becomes critical for cost balance. Rather than treating technology and regulation separately, it ties plant design directly to current European ecological standards through open assessment covering operations, risk protocols, ecosystem impact, legal compliance, and budget structure. Through close review of linked factors, findings form a practical guide for expansion, showing how directed grants might remove key barriers in local electronic waste treatment networks (Deng et al., 2024).

Despite market swings in scrap pricing, retrofitting older recycling facilities brings persistent cost hurdles (Cole et al., 2019). From early records logged during 2025 operations, nearly four million kilograms of household cooling devices entered the site. Of that volume, machines using pentane made up three million kilograms processed without issue. Yet environmental regulations required staff to turn away just over one million kilograms tied to outdated CFC models. Because disposal fees remain locked at 280 euros per ton across the region, income stayed limited to under 863,000 euros. That ceiling meant more than a million euros in possible returns never reached accounts. Year after year, compliance with current law drains roughly 283,500 euros from actual earnings.

This thesis develops a comprehensive techno-economic analysis (TEA) and capital allocation model to evaluate the project's long-term financial viability through key performance indicators, specifically the internal rate of return (IRR) and asset amortization schedules (Deng et al., 2024). Because the high initial capital expenditure (CAPEX) required for specialized emissions containment and alkaline neutralization infrastructure lengthens private payback timelines, securing non-repayable public capital through the EU LIFE Program acts as a vital mechanism to de-risk the investment lifecycle (Deng et al., 2024; Ghisellini et al., 2016). The proposed retrofitting resolves the regional waste bottleneck by allowing Transistor S.r.l. to cleanly absorb the entire inbound volume, driving a precise gross revenue expansion of **32.87%** while maintaining a stable mechanical throughput capacity of 45 refrigerators per hour.

1.6 Structure and Organization of the Thesis

To provide a systematic comparative analysis between the existing baseline operations and the proposed industrial expansion, this master's thesis is organized into seven distinct, interrelated chapters:

- **Chapter 1: Introduction & Context** establishes the overarching global and European e-waste crisis, details the thermodynamic and environmental hazards of legacy ozone-depleting substances, integrates local factory per-capita metrics, and outlines the primary co-funding objectives of the research project.
- **Chapter 2: Regulatory Framework & WEEE Management** provides an academically dense review of European directives, Extended Producer Responsibility (EPR) mathematical equations, CENELEC normative guidelines, and the regional constraints of the Italian Legislative Decree 49/2014.
- **Chapter 3: Technical Methodology & Plant Leinì Technical Layout** provides the exact engineering blueprint of the Leinì site, detailing the Phase 1 circuit vacuum depollution and Phase 2 nitrogen gas-tight process inertization loops.
- **Chapter 4: Emission Control & Comparative Performance (Pentane vs. CFC)** executes a full comparative analysis contrasting volatile hydrocarbons against legacy chlorofluorocarbons, modeling the chemical reactions of acid gas generation (HF and HCl) and examining downstream alkaline scrubbing loops.
- **Chapter 5: Case Study: Transistor S.r.l.** transitions the research into an active industrial audit by documenting existing plant throughput, mass balances, labor deployment across the second shift, and precise factory locations.
- **Chapter 6: Economic Evaluation & Funding Case** executes a data-driven financial comparison between the plant's current operational baseline and the proposed dual-stream expansion, evaluating cash flow variations, CAPEX outlays, and the final business case for EU LIFE co-funding.
- **Chapter 7: Conclusions & Strategic Recommendations** synthesizes the core engineering, environmental, and financial findings of the research, defining risk mitigation protocols, Quality Health, Safety, and Environment (QHSE) roadmaps, and future circular economy directions for the regional social enterprise.

CHAPTER 2: REGULATORY FRAMEWORK & WEEE MANAGEMENT

2.1 Supranational Legislative Foundations: The European WEEE Directive

Across the European single market, control of discarded electronics follows Directive 2012/19/EU on WEEE. Though earlier regulations existed, this update reshaped how used devices are managed - aiming at lower ecological harm alongside faster reuse of materials.

The Asymmetrical Transposition History

The implementation of these cross-border regulations encountered consistent delays across multiple member states. Though Brussels drew a firm line on February 14, 2014, scrutiny shows twenty nations among the twenty-eight missed that mark entirely. Germany, then Poland, held off enacting local legislation until well into 2015 - spawning stretches of misaligned rules inside the shared economy. Behind every delayed statute stood months where businesses faced uneven ground.

A key shift in the regulatory landscape emerged when the list of ten temporary product groups gave way to a tighter framework of just six open-scope classes. Though the official deadline was set for August 15, 2018, countries took different routes. Some nations - Bulgaria, Hungary, Poland, and Slovenia - chose to apply the revised system earlier, starting it all on January 1, 2018. On the opposite end, the UK pushed implementation forward by months, opting for a January 1, 2019, start. Meanwhile, Denmark never fully adopted the updated categories at all, using internal data adjustments after the fact to meet EU reporting obligations.

Technical Isolation and the R1 Category

Under this open-scope framework, temperature exchange equipment is explicitly isolated under Category 1 (R1). This category isolates cooling and climate control units due to their specialized thermodynamic architecture and the hazardous chemical compositions of their cooling circuits and blowing agents.

To bridge the gap between statutory text and actual shop-floor execution, the WEEE Forum initiated the WEEELABEX project in 2009. This project established an integrated package of technical and administrative requirements for collection facilities, logistics systems, and processing plants. The WEEELABEX treatment standard dictates strict operational guidelines to achieve the following environmental and market objectives:

- **Pollution Prevention:** Facilities must achieve effective and efficient de-pollution to minimize point-source emissions into air, water, or soil.
- **Resource Preservation:** Processing lines must maximize the mass yield and quality of recovered secondary raw materials.
- **Flow Traceability:** Operators must maintain downstream monitoring to prevent undocumented cross-boundary shipments of hazardous electronic fractions.

- **Fair Competition:** The standard imposes uniform technical specification checks to prevent uncompliant operators from undercutting the market.

This technical oversight is vital for R1 units, where the mechanical crushing of polyurethane insulation matrices requires continuous gas extraction and nitrogen process inertization to handle volatile fluorinated hydrocarbons and volatile hydrocarbons safely.

Standard Harmonization and Market Leakage

Under Article 8(5) of the directive, the European Commission assigned CENELEC mandate M/518 to convert voluntary industry guidelines into formal European standards - this led to the creation of the EN 50625 series. Despite this step, the absence of immediate EU-wide enforcement triggered sharp inconsistencies across markets. Countries including France, Ireland, and the Netherlands responded by introducing national laws requiring approved recycling centers to follow the EN 50625 series. Most other Member States chose a different path: they refrained from passing legislation, making adherence optional rather than required.

This imbalance in rules weakens what the circular economy aims to achieve. Over fifty percent of electronic waste produced in the European Union today fails to meet the directive's standards for handling. Where enforcement of rigorous EN 50625 procedures becomes compulsory, expenses for processing rise within that area. As a result, large amounts of discarded electronics shift illegally into regions lacking enforced regulations. Out here, where rules barely exist, scrap handlers skip expensive cleanup processes - instead smashing electronics recklessly just to grab large metal chunks fast. Such cross-border flow of discarded tech warps fair competition among recyclers while draining valuable materials from reuse cycles. A single EU enforcement framework becomes unavoidable when safety gaps appear everywhere at once.

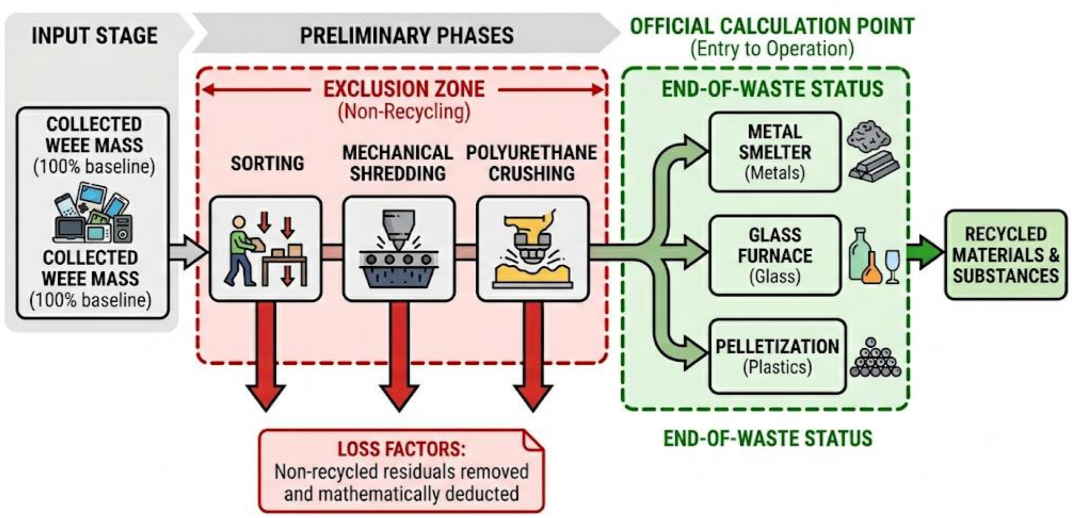


Figure 2.1: Legal boundary definitions for WEEE recycling calculation metrics

Source: Elaboration based on treatment processing variants modeled by European single market design frameworks (Milios et al., 2018).

2.2 Extended Producer Responsibility (EPR) & Mathematical KPI Collection Dynamics

The operational and financial architecture of European e-waste systems relies fundamentally on the principle of Extended Producer Responsibility (EPR), transforming post-consumer end-of-life management from a public municipal burden into an internalized corporate compliance obligation (Milios et al., 2018). This structural shifting of economic liability away from local governments operates across distinct financial mechanisms. Globally, three generic financing variations dominate the administrative arena: upfront compliance fees exacted when an item is initially placed on the market, end-of-life disposal fees levied directly on the last holder at the point of discard, and a dynamic market-share approach designed to recoup operational treatment outlays collectively.

By requiring manufacturers and importers to internalize these post-consumer costs, the framework attempts to instantiate specific Key Performance Indicators (KPIs) at both national and enterprise levels to track the efficacy of separate collection networks (Wagner, 2013). In real industrial configurations, however, the wholesale outsourcing of physical recovery operations to collective Producer Responsibility Organizations (PROs) creates a systemic decoupling. Rather than steering upstream technical innovations or encouraging longer product lifespans, the collective structure frequently reduces the economic incentive to a mere administrative fee transaction, framing WEEE primarily through a linear waste-disposal lens instead of an active loop resource strategy.

To enforce harmonized compliance oversight across diverse national boundaries, the European Union mandates precise mathematical target methodologies to evaluate whether Member States satisfy these annual statutory collection KPIs (Collection-rates-of-WEEE.pdf, 2014). Pursuant to Article 7(1) of Directive 2012/19/EU, national competent authorities are empowered to select one of two mathematical options to calculate and verify national WEEE collection performance. The primary methodology evaluates national intake against the historical volume of products placed on the market (POM) over the preceding triennial period, formally expressed as (Collection-rates-of-WEEE.pdf, 2014):

$$R_{\text{collection, POM}} = \frac{\text{WEEE}_{\text{collected},t}}{\frac{1}{3}\sum_{i=1}^{3}\text{POM}_{t-i}} \times 100\% \geq 65\%$$

Where $WEEE_{collected,t}$ represents the total mass of electronic waste successfully captured within the target reference year t , and POM_{t-i} represents the total mass of EEE placed on the market in the three years prior to the reference period. The directive dictates that this ratio must meet an absolute minimum KPI threshold of 65% since 2019, following a transitional 45% target established in 2016 . Alternatively, Member States may opt for an evaluation framework based directly on the total volume of e-waste dynamically generated within their boundaries, requiring an 85% collection rate KPI (Magalini et al., 2014).

The operational meaning of **mathematical collection dynamics** refers directly to the kinetic, time-variant distortions and volatile fluctuations that arise within these rate equations due to changing socioeconomic and consumption velocities. This dynamic friction is highly evident when analyzing the triennial POM formula during periods of market expansion (Magalini et al., 2014). Aggregate data across the European single market shows that the collection rate calculated via the WEEE Generated method rose from 40% in 2014 to 54% in 2021, showing steady real progress in formal recovery operations (Baldé et al., 2022). Conversely, when applying the triennial POM method, the regional collection rate decreased from 50% in 2016 to 44% by 2020 (Baldé et al., 2020).

This trend moving downward isn't about less waste actually being gathered. It stems instead from how the math works: every year, rising device purchases add roughly 2.5 million metric tons to circulation, swelling the total product mass far quicker than collected e-waste can keep pace. Since electronics stay in homes for differing lengths - patterns shaped by Weibull models - the rate at which old items return lags well behind new ones entering use. When fresh sales spike, that imbalance shrinks the ratio used to measure performance, making recycling systems appear short of targets even when they handle more material than before (Magalini et al., 2014; Baldé et al., 2022).

What counts as real recycling in Europe hinges on tight legal definitions, drawn clearly away from mere waste compression by EU standards (Commission Implementing Decision (EU) 2019/2193). Though often confused, shrinking bulk does not meet the bar - only actual material reuse qualifies under these rules. Pursuant to Commission Implementing Decision (EU) 2019/2193, preliminary industrial interventions—including manual sorting, dismantling, mechanical crushing, or high-velocity shredding aimed at segregating bulk streams—are legally excluded from counting toward the final recycling targets. Mass metrics can only be registered as officially recycled at the exact spatial point where the separated fractions enter a final reprocessing operation that transforms waste materials back into products, substances, or secondary raw materials.

For glass, this boundary is qualified at the point of entry into a glass furnace or the production of insulation media. For bulk metals, it is the entry into a smelting furnace. For plastics, mass can only be validated at the exact point of entry into pelletization, extrusion, or moulding lines. Materials removed during preliminary extraction that do not undergo subsequent reprocessing are automatically deduced from the final metrics. This regulatory confinement ensures statistical accountability, stopping operators from inflating their compliance tracking with raw, contaminated shredder inputs or down-cycled residues that fail to substitute virgin material stock.

2.3 Strict Normative Treatment Standards: WEEELABEX and EN 50625

Meeting Europe's climate goals demands alignment between e-waste handling and strict environmental rules. Established in 2011 through collaboration among industry players, the WEEELABEX system sets benchmarks for safe dismantling practices. Later, the CENELEC EN 50625 standards expanded on those guidelines, detailing how dangerous materials should be managed. Uniform procedures aim to balance operations across member states, yet participation has often been optional. Without mandatory adoption, inconsistencies emerge - some waste flows outside regulated channels. In poorly monitored areas, cost-cutting overrides safety measures during material recovery. Hazardous gases escape routinely when profit incentives outweigh containment protocols.

Processing under Category 1 follows defined technical guidelines involving separate mechanical and thermodynamic stages for removing pollutants. Although focused on the cooling system, initial treatment pulls out gaseous fluorocarbons and light hydrocarbons together with oil from compressors using suction pressure. Efficiency standards demand recovery of at least 90% of stored coolant - commonly measured as 115 grams of R-12 in sealed units. After separation, residual oil is tested; should halogen levels rise above 0.2% by mass, it fails eligibility for standard reuse pathways. Instead, such contaminated batches proceed directly to intense heat-based disposal designated for dangerous materials.

Second stage deals with breaking down the stiff insulating material into smaller pieces. Because tiny trapped gases inside polyurethane cells can escape easily, shredding happens in a sealed chamber under vacuum pressure. Leftover gas levels in the resulting fine particles or compacted bits cannot go beyond 0.2 percent of total mass. When separating materials later, any leftover polyurethane sticking to metal scraps - iron-based or otherwise - must stay under 0.3 percent by weight. Plastic batches coming out of processing also face restrictions; they may carry no more than half a percent contamination from polyurethane residue. Grinding operations rarely spotlight containment - yet it defines how emissions behave. What escapes into air ties back to what stays captured.

Running large test batches forces plant supervisors to verify operational boundaries firsthand. When performance trials require a minimum of one,000 units - first under continuous cooling in Phase One, followed by an equal number during Phase Two - real conditions shape results. From start to finish, material flows are traced: initial mass compared against all outgoing streams like collected liquids, airborne emissions, solid scraps, and filtered leftovers. Only when total recovery exceeds 97 percent is compliance confirmed. Accuracy here ensures dangerous compounds remain monitored, making the aims of EU Rule 2012/19/EU tangible - not just on paper, but in protecting both upper atmosphere stability and worker well-being at ground level.

2.4 National Transposition: The Italian Legislative Decree 49/2014

Carried out via Legislative Decree 49 of March 14, 2014, EU-level directives enter Italy's national framework as binding law - this sets up how electronic waste moves, who pays, and who gets certified at processing sites. Although framed around broader environmental goals, D.Lgs. 49/2014 specifically activates Extended Producer Responsibility, making producers cover disposal expenses once products reach end-of-use. Instead of acting alone, most companies join approved group programs to meet obligations; doing so independently demands rare permission. While rooted in European policy, enforcement plays out entirely within Italy's administrative structure. Producers cannot pass on recycling costs directly - they must absorb them upfront.

The national architecture governing WEEE flows is structurally managed by the **Centro di Coordinamento RAEE (CdC RAEE)**, an operational and regulatory clearing-house institution established by law to ensure that collection obligations are fulfilled in a transparent and non-discriminatory manner across all regional jurisdictions. The CdC RAEE functions as the primary national hub, allocating collected waste loads from municipal centers to certified treatment facilities based on the producers' respective market shares and the national recovery targets.

Getting permission to work here means following strict environmental rules written into Italian law from a broader European policy on factory pollution. What keeps Transistor S.r.l. running legally is a detailed license that controls how much trash it can handle each year along with exact caps on air pollutants released at specific spots. Even though licenses allow operation, they also lock the company into hard numbers - especially for yearly waste volume and smokestack emissions. At its plant in Leinì, the firm has to act like a fully certified recovery site, built strong enough to manage old fridges packed with risky gases. Handling devices loaded with flammable or climate-damaging chemicals requires gear and protocols far beyond standard junkyard setups. Meeting those standards isn't optional; it's baked into the terms of their active operating permit. Because refrigerants involved are unstable, any slip could trigger leaks, fires, or worse - so safeguards matter deeply. Their approval doesn't just cover general activity but forces compliance down to individual machines and gas types. Rules tied to the license shape everything: from daily routines to emergency plans when something goes sideways. Without this level of control, working with pressurized, hazardous vapors would pose unacceptable risks nearby. The setup demands constant vigilance, not only because laws require it but because consequences of failure spread fast. Each batch of scrapped coolers processed ties back to limits spelled out in official documents stamped years ago. Despite changes over time, one thing holds steady - what happens onsite must stay inside legal lines drawn clearly ahead of time. No exceptions appear anywhere in the paperwork, leaving little room for improvisation during operations. Following every line of the permit becomes part of routine, almost invisible until something threatens to break alignment. Still, staying compliant depends less on paper promises than actual hardware performance day after day. Machines need monitoring just as closely as output totals, since filters failing once count more than perfect logs elsewhere. While oversight comes from outside bodies, enforcement lives mostly in choices made internally by staff on shift. They carry responsibility whether readings fall within range or drift toward thresholds nobody wants to touch. So long as equipment runs, margins remain tight between normal function and breach territory.

Right off the bat, Italian law 49/2014 requires anyone handling waste to follow strict safety steps before recovering reusable parts - especially when dealing with dangerous stuff like mercury, lead, or certain harmful gases. From there on out, every step must lock down those risky components first. Tracking happens through detailed records; each operator has to log exactly how much waste arrives, what gets turned into usable output, and what ends up disposed. Because of this system, authorities compare Italy's recycling results with EU goals using real numbers. When facilities skip rules - either on paperwork or actual methods - they face serious fines or lose their right to operate. In practice, keeping a license means proving day after day that everything's documented and environmentally sound. So long as reports stay accurate and tech standards met, operations continue without interference.

2.5 Local Plant Authorization: The Autorizzazione Integrata Ambientale (AIA)

Across Europe, rules from Brussels mix with Italy's own law - D.Lgs. 49/2014 - to shape how factories run day to day. The AIA, a full environmental license that locks in tough limits on pollution and emissions. This document pulls EU standards into real-world operations, making sure industry follows clear lines. At Transistor S.r.l., work happens in two separate spots, each cleared under this system. First, there is the central spot for gathering and sorting materials - found at Via Paolo Veronese 202, right in Turin. Then comes the larger facility, an R1-approved site where automation handles advanced processing. That one sits further out, along Via Giuseppe Peano 118, tucked inside Leinì, province of Turin.

Because of rules written into its present AIA setup, the site can only process a set amount of waste each year, along with fixed caps on air emissions from single sources. It just so happens that what Transistor S.r.l. is allowed to do ties directly to how their machines are built - right now those systems work exclusively with Category 1, Sub-category 1B devices containing VHCs or pentane used during foam production.

Because the current plant layout lacks the advanced chemical containment and gas scrubbing infrastructure required to mitigate the highly corrosive hydrogen fluoride (HF) and hydrogen chloride (HCl) byproducts generated by fluorinated molecules, the existing AIA legally prohibits the acceptance or processing of legacy chlorofluorocarbon (VFC/CFC) units. This regulatory limitation forces an operational bottleneck, whereby the plant must reject nearly one-quarter of its inbound regional volume to maintain compliance with its authorized emission profiles. Consequently, achieving a dual-stream configuration requires a coordinated transition involving both significant physical engineering modifications—specifically the integration of a Regenerative

Thermal Oxidizer (RTO) capable of acid gas neutralization—and a formal regulatory expansion of the AIA permit to authorize the specialized handling of hazardous, ozone-depleting substances.

2.6 Strategic EU Funding Mechanisms

One reason older pentane facilities struggle to manage hazardous CFC waste is the need for costly upgrades - cryogenic systems, targeted emissions safeguards, plus neutralization setups must be installed. Although income streams emerge from salvaged metals and recycled polymers, such returns fall short of covering upfront costs. Financial support shaped by EU policy frameworks steps in where private funding lags, balancing risk while enabling operational continuity.

Initiatives like the EU LIFE Programme channel funds toward industrial efforts meeting Europe’s circular economy and emissions targets. Because public money shares project costs, companies such as Transistor S.r.l. adopt high-end green systems they normally could not afford. When regulation meets support, factories gain routes to expand - turning required actions into practical steps forward (Milios et al., 2018).

Because funding tools are built into Transistor S.r.l.’s long-term plan, the firm can handle gaps in technology and rules when dealing with older ozone-damaging materials arriving through local waste channels. If those supports vanish, area collection goals could fail - recycling sites might turn away old CFC devices or accidentally release harmful gases, weakening EU climate efforts. So it goes: smart use of shared EU funds pushes industry growth forward, clears environmental hurdles, and boosts job opportunities tied to Arcobaleno Social Cooperative’s work approach.

CHAPTER 3: TECHNICAL METHODOLOGY & PLANT LEINÌ TECHNICAL LAYOUT

3.1 Technical Overview of Category 1 WEEE Treatment Foundations

The industrial processing of Category 1 WEEE, specifically domestic and commercial refrigeration appliances, represents one of the most technologically demanding segments of the recycling sector. Unlike other e-waste streams that primarily require coarse mechanical liberation and density-based sorting, temperature exchange equipment possesses a structural duality of hazardous chemical containment. This requires a processing methodology split into two distinct containment and treatment challenges: the extraction of fluids from the active thermodynamic cooling circuit, and the liberation and capture of gas expanding agents trapped within the insulating polyurethane (PU) rigid foam matrix.

The facility architecture at Transistor S.r.l.'s Leinì site is purpose-built to manage this structural anatomy through a phased industrial process, ensuring that hazardous substances are systematically isolated before any high-velocity mechanical down-cycling occurs. At the Leinì plant, the treatment of refrigerators is strictly divided into three phases, designed to achieve full depollution in compliance with WEEELABEX norms.

Phase 1: Refrigerant Circuit Depollution

Starting off, active refrigerant liquids are drawn out from the pressurized cooling loop. With care, technicians apply a special clamp - fitted with both a sealed barrier and piercing probe - to access the copper pipe. From here, a suction setup pulls away refrigerant vapor along with engine grease, channeling them into a balanced-pressure tank. Inside that chamber, low pressure heating splits vapors from oils. Thanks to this phase, oil retains less than 0.1 percent residual coolant by mass, clearing the way for taking out compressors while preserving usable lubricants. Following separation, captured gas undergoes compression, shifts to liquid form, then moves into storage units ready for later purification.

Phase 2: Inertized Mechanical Size Reduction

Once the circuit has been stripped of pollutants, the fridge casing - its main refrigerant now removed - moves toward size reduction through mechanical means. Inside a sealed chamber deprived of oxygen, the process unfolds, avoiding any chance of sudden combustion. Onsite-produced nitrogen, roughly 97 percent pure and flowing at about 165 cubic meters per hour, floods key zones: the feed inlet of the shredder, the exit auger, and the compaction press, keeping flames unlikely. Sensors track levels of combustible vapors and available oxygen without pause; should vapor concentration hit 25 percent of the lower explosive limit, feeding halts by itself. A rise to 40 percent forces everything to cease operation across the facility. Without such protection, danger grows - not from today's stabilized pentane foams directly - but if those gases escape amid normal air, ignition becomes possible.

Phase 3: Thermal Gas Destruction

Gas collected during grinding moves steadily at 5,000 m³/h toward a three-chamber regenerative thermal oxidizer. At its core, this stage halts most emissions before release. Burning takes place under steady heat - 780 °C - a level set precisely to break down pentane molecules. Though fine for now, today's setup only handles pentane well. Without a built-in wet scrubber or extra-hot second burn zone, older CFC compounds remain risky. These demand more intense conditions: above 850 °C, plus special treatment for acidic exhaust like HF and HCl. Left unmanaged, such byproducts eat away at the ceramic parts inside the RTO. Soon, planned upgrades will add those features. With them, the site shifts function - not just refining one type of waste gas but handling two distinct flows. Outcomes stretch beyond capacity; it reshapes what the building can do long term.

3.2 Thermodynamic Foundations: The Vapor-Compression Refrigeration Cycle

Starting with how home fridges work helps explain why special vacuum systems make sense in factories. Not only does the fridge move heat around, but it also depends on strict physics rules tied to energy flow and change. Instead of just pushing fluids through pipes, these units carefully control when liquids turn into gases - and back again - inside sealed loops. Rather than using complex machinery, they rely on shifts between high and low pressure areas to pull warmth out from inside. Even older coolants like R-12 behaved this way, though today's models often use simpler substances such as R-600a. Through repeated cycling, heat gets pulled inward at one stage then released outside later. Because each transformation follows predictable patterns, engineers can borrow those principles elsewhere. Without steady phase switches, the whole process would stop working entirely.

Work put into the system shapes how much energy moves through this sealed cycle. That flow follows strict accounting rules tied to what's added mechanically. The total balance hinges on that incoming effort. Energy does not appear out of nowhere here. What comes in must match changes inside. This relationship defines the cycle's core behavior. Nothing extra gets counted. Everything connects back to the starting push.

$$q_L + w = q_H$$

Where q_L represents the specific thermal energy extracted from the refrigerated internal environment (evaporator cooling load), ω denotes the specific net mechanical work input delivered by the compressor, and q_H signifies the total thermal energy rejected through the rear heat exchanger (condenser heat rejection).

As illustrated in the systemic flowchart of **Figure 3.1**, the refrigerant fluid moves through a continuous path, altering its pressure, temperature, and physical state as it passes through four primary components:

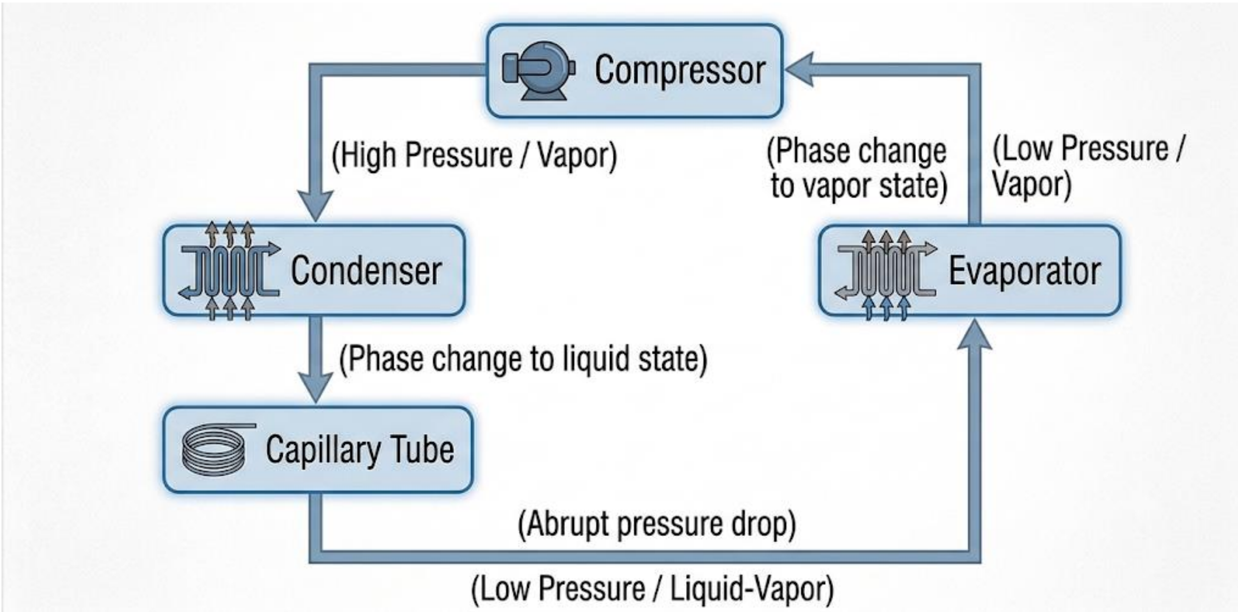


Figure 3.1: Schematic representation of the standard vapor-compression refrigeration cycle.

Source: Author's own elaboration based on standard vapor-compression refrigeration cycle principles and classical engineering thermodynamic frameworks.

According to the thermodynamic loop detailed in **Figure 3.1**, the cycle operates through four consecutive processing stages:

- **1**. Starting off, cold low-pressure vapor leaves the storage area and moves into a sealed compressor. Because of added energy, its volume drops fast while pressure climbs. As that happens, the gas gets hotter and more packed together. Now under high pressure and heat, it shifts toward the next stage of the system. Movement continues because the compressed fluid pushes ahead on its own.
- **2**. Wrapped around the back of the unit, the condenser's pipes carry in steam that runs hot. Picture 3.1 shows how it gives off hidden warmth - labeled qH - to the nearby air. Pressure stays steady during this shift, so the flow changes fully from vapor to liquid. Once done, what exits is dense, chilled, and still under force.
- **3**. A narrow copper tube, built tight on purpose, slows down pressurized liquid squeezing through it. Because the space shrinks fast, the fluid loses pressure right away, yet nothing powers anything else during this shift. As pressure falls sharply, some liquid instantly turns to vapor, skipping normal boiling steps. That change cools what stays behind, dragging temperatures downward quickly. Out comes a mix - chilled, partly gaseous, still holding leftover droplets - all now light on both heat and force.
- **4**. Isobaric Evaporation (The Evaporator): This ultra-chilled mixture enters the internal evaporator coils lining the insulated interior cabinet walls. As mapped in the lower loop of Figure 3.1, the refrigerant absorbs thermal energy (q_H) directly from the internal storage volume, utilizing this heat flux as the latent energy required to drive its own vaporization.

This constant-pressure absorption cools the internal cabinet while converting the fluid back into a low-pressure vapor, which is subsequently drawn back into the compressor inlet to restart the thermodynamic lifecycle.

Understanding this thermodynamic layout is vital for the design of decommissioning protocols at the Leinì facility. Because the refrigerant fluid and the viscous compressor lubricating oil circulate in continuous physical contact under high pressures, a significant mass fraction of the volatile gas remains dynamically dissolved within the oil matrix over decades of operation. Consequently, standard atmospheric venting or rudimentary line shearing is prohibited by environmental law. The industrial extraction architecture must target the lowest gravitational node of this closed loop—the compressor oil sump—applying a localized pneumatic puncture under deep vacuum to safely isolate the volatile fractions without triggering fugitive emissions or explosive flashing.

3.2.1 Operational Duality: The Pentane vs. CFC Challenge

Today's production sites, including Transistor S.r.l., function amid two parallel flows. Even though demand now favors natural, fluorine-free substances - like isobutane (R-600a) used in refrigeration and cyclopentane for foam expansion - the materials arriving at the Torino North location still come in varied forms. Though industry trends lean one way, supply deliveries follow a different pattern.When it comes to breaking down physically, the needs for these two different materials quickly move apart.

VHC/pentane stream (current standard): Today's systems rely on cyclopentane within polyurethane foam - a substance prone to ignition yet harmless to the ozone layer compared to older CFCs. At Leinì, nitrogen gas keeps the air inside equipment stripped of oxygen, blocking fire risks through continuous blanketing. Escaping vapors are then diverted into a high-temperature oxidizer, where they break down at 780 °C.

Despite their durability, older systems often house CFC-based foaming chemicals. When fed into a standard pentane-compatible thermal oxidizer setup, complications arise quickly. Burning such compounds at 780 °C releases fluorine and chlorine elements as HF and HCl gases. Absent robust gas-cleaning technology and hotter follow-up chambers - usually above 850 °C - these emissions eat away at critical parts inside the RTO. Ceramic heat recovery modules and core support structures degrade fast under such exposure.

3.2.2 Impact on Plant Throughput & Financial Efficiency

Right off the bat, equipment limitations hit Transistor S.r.l.'s bottom line and daily workflow. Backed by verified 2025 data, incoming materials totaled 4,092,228 kilograms of cooling units. Because permitted thresholds cap capacity - and without systems to handle corrosive emissions - only part got processed: 3,079,818 kg made it through mechanical plus heat-based methods, solely the hydrocarbon load. Meanwhile, a leftover chunk, exactly 1,012,410 kg containing outdated CFCs, never entered; turned away upon arrival.With a typical regional rate of 280 euros per ton, today's setup brings in just 862,349 euros. Yet if the plant could run two separate recovery processes, including one that handles old CFC leftovers, it might process all 4,092,228 kilograms. That shift would lift income to 1,145,824 euros. Year after year, nearly 283,475 euros slips away

- lost only because outdated tech can't handle older fluorine-based materials. Even though industry now claims to rely solely on hydrocarbons, pollution systems still must deal with past chemical burdens. Instead of simplifying things, this change demands equipment built for both tasks at once: clearing up yesterday's messes while handling massive flows of modern fuels.

3.3 Industrial Feedstock Transition: From Fluorinated Legacy Assets to Hydrocarbon Standards

Old fridges still show up in today's trash. That happens because machines made before the 1990s can last more than three decades. Their cooling systems once ran on R12, while their foam insulation was formed using R11. These chemicals were standard across nearly every refrigerator worldwide during much of the 1900s. Then came new rules shaped by a global treaty meant to protect the atmosphere. Factories started switching coolants - first trying HCFCs, later moving to HFCs such as R134a. Those newer substances did less harm to the ozone layer. Yet they trapped heat in the air just as aggressively. So even though production stopped long ago, old units keep arriving at recycling centers. Each one carries outdated gases inside. Over time, these emissions leak out slowly, feeding an ongoing cycle few foresaw.Later on comes a shift tied closely to how stuff behaves when it heats up. Step by step, what happens lines up with how risky certain vapors become during manufacturing stages - seen clearly in the layout labeled Figure 3.2. Before that point though, everything stayed steady without major swings.

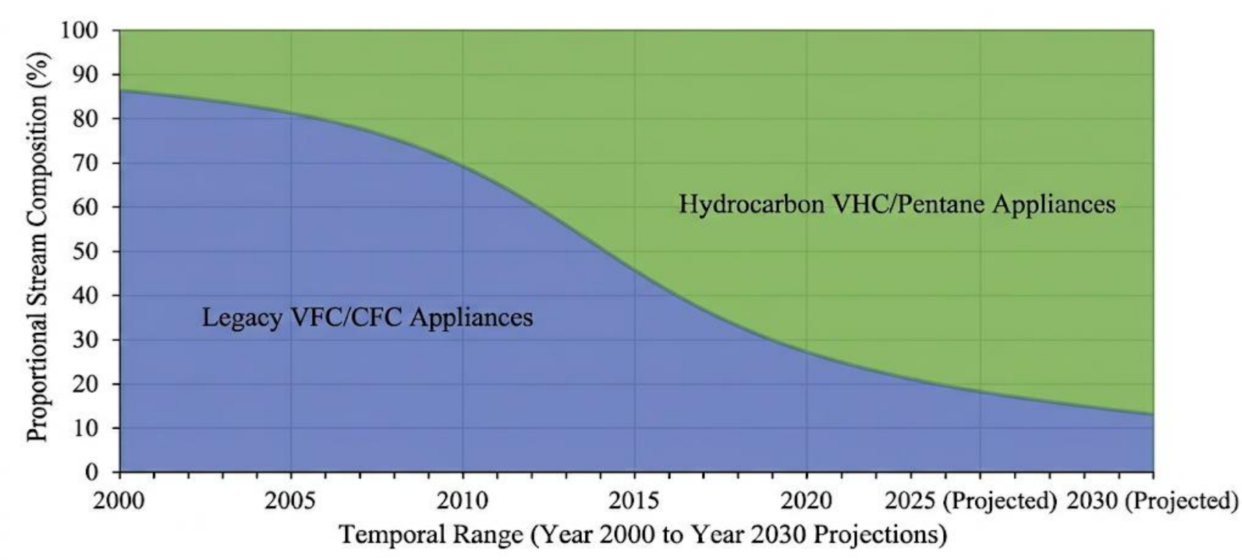


Figure 3.2: Conceptual decay curve and composition shift of the R1 WEEE category entering European recycling networks

Source: Projections adapted from long-term regional waste stream characterization logs (Vehlow and Gloël, 2020).

Back in time, as seen in Figure 3.3, Europe's way of making things shifted fully - away from fluorine-based chemicals. Instead, today's factories rely on lighter carbon compounds; take isobutane (R600a), now common inside fridges. For foam used in insulation, cyclopentane steps in - or sometimes teams up with isobutane. These choices mark how production operates across much of the region nowadays.

Out here, the stuff showing up at plants looks nothing like before. Old fridges full of CFCs? They're fading out slowly. Now most loads are packed with refrigerants that ignite easily. Workers don't have to wrestle strict rules on ozone killers anymore. That part is easier. Yet fire danger spikes fast when gases catch light without warning. Factories must seal systems tight, watch air constantly, stop sparks everywhere - just to keep things stable around explosive mixes.

3.4 Transistor S.r.l. "As-Is" Operational Layout

Out past Turin, Transistor S.r.l. runs a layered system for handling waste electronics, keeping initial sorting separate from advanced recovery work. Instead of combining steps, they funnel collected items through different stages at distinct sites. At Via Paolo Veronese 202, a central drop-off point collects city-level e-waste, supported by smaller storage units nearby plus a publicly accessible Ecocentro. This location gathers flows before sending materials onward. Over in Leinì, down the road at Via Giuseppe Peano 118, another site takes charge - this one built only for heavy-duty tasks like robotic disassembly, gas removal under open air, and splitting core components apart. While machines handle intense separation jobs there, people stay mostly out of the loop. Across both places, just seventy workers manage daily operations.

Inside the Leinì plant, space gets split - on purpose - into separate zones where each handles a different kind of leftover material. Each area works alone, shaped by how trash types differ across the production run.

Figure 3.3: Industrial layout and processing cell allocation at the Leinì R1/R4 facility.

Source: Author's own elaboration based on technical plant specifications and internal process layouts provided by Transistor S.r.l.

As illustrated in the high-level structural layout in **Figure 3.3**, the facility is divided into two autonomous production environments:

- **Sector R4 (Small Electronics):** Dedicated to the manual pre-sorting, liberation, and mechanical size reduction of small consumer appliances via a heavy hammer mill shredding assembly and downstream automated sorting rows.
- **Sector R1 (Cooling Appliances):** Configured as a highly specialized reclamation line engineered to execute the depollution and volume reduction of domestic and commercial refrigeration units.

According to the operational workflow shown in **Figure 3.3**, the Sector R1 line operates as a sequential three-stage technical chain, moving from the initial Phase I vacuum pump station, through a gas-tight inerted shredding unit, and terminating at a thermal 3-chamber regenerative thermal oxidizer (RTO) emissions barrier. The R1 reclamation line maintains a certified throughput capacity of approximately 50 post-consumer cooling units per hour.

To trace the precise material tracking and physical gas separation pathways executed inside this R1 environment, a granular engineering analysis of the line configuration is required.

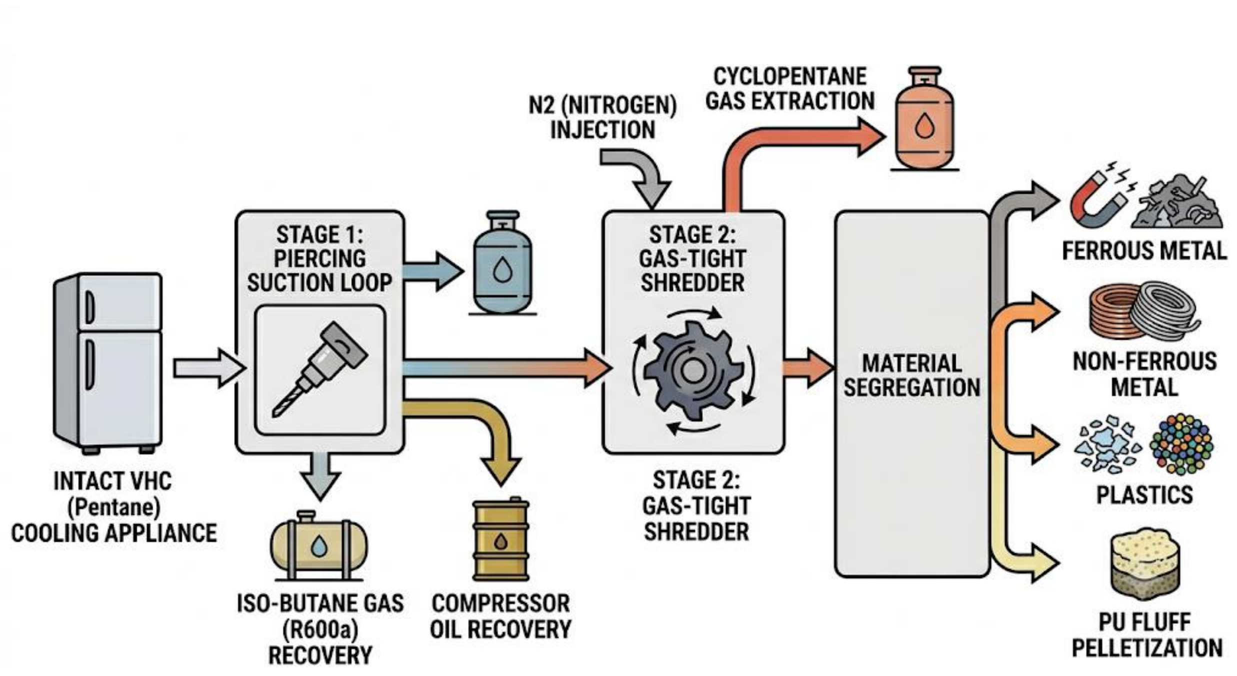


Figure 3.4: Material and gas separation flowchart for the current Transistor S.r.l. VHC processing line

Source: Adapted from internal factory process engineering operations documentation

After moving through the setup shown in Figure 3.4, fluid removal and material breakdown happen together inside a closed loop - this keeps everything away from outside air. Instead of opening things up, vacuum-based piercing tools break into the cooling unit without releasing pressure.

Because the seal stays tight, harmful R600a gas cannot escape into the workspace during disassembly. At the same time, used compressor oil gets drawn out and moved into designated storage containers for safe handling.

After removal of the compressor housing, movement shifts straight into Phase 2 for whatever structure remains. Following the path shown in Figure 3.4, inside a sealed grinding unit flushed continuously with nitrogen (N2), trapped cyclopentane used in insulation gets released without risk. Pieces flow onward into a sorting sequence that separates components - iron-based materials emerge here, alongside lightweight metals there, assorted polymers apart from compressed chunks of polyurethane (PU) fiber, all prepped later for resale into building supply chains.

3.4.2 Regulatory & Structural Bottleneck

Even though the automatic sorting units in Figure 3.3 and Figure 3.4 work well mechanically, how things are set up now limits what the site can do. Without modern deep-cooling towers and later-stage filters for acidic gases made with chlorine or bromine, old types of refrigerants - like CFCs - can't be processed safely here. If these outdated chemicals enter the current 780°C thermal oxidizer, they'd produce aggressive fumes such as hydrogen fluoride and hydrogen chloride; over time, those would eat away at the ceramic layers inside the heat recovery system.

Because of its current environmental permit rules, the site must divert old CFC-containing units through a separate pre-sorting belt. As a result, nearly 1 million kilograms each year from local collections cannot enter production lines. That volume translates into lost income close to 283,500 euros every twelve months. Outdated air treatment systems stand directly in the way of fixing this. Upgrading them would remove one major bottleneck holding back full material throughput.

3.5 Phase I: Hermetic Cooling Circuit Depollution & Fluid Recovery

Inside the Leinì site, along Sector R1, operations begin with a controlled cleanup step known as Phase I degassing (Cucchiella et al., 2015). Before any cooling device enters powerful shredding machinery, its working fluids and reactive chemicals need careful removal (Chancerel et al., 2009). Handling this blend of coolant gas and manufactured lubricant marks the initial safeguard - blocking leaks into air or work areas.

3.5.1 Pre-Treatment and Manual Component Demanufacturing

Before advancing to the automated vacuum suction station, incoming cooling appliances are placed on pre-treatment roller conveyors to undergo an initial manual dismantling process . During this preliminary step, operators strip the appliance chassis of external and internal peripheral hazards to maximize downstream material sorting efficiency (Chancerel et al., 2009). This manual sorting involves the isolation and removal of:

- External power cables and loose wiring.
- Internal glass shelving, plastic drawers, and residual food debris .
- Mercury-containing tilt switches and other environmentally hazardous components that require separate specialized disposal streams.

Once these non-fixed fractions are securely uncoupled, the fully stripped refrigerator cabinet is cleared to enter the active circuit depollution area.

3.5.2 Semi-Automated Circuit Puncture and Vacuum Evacuation

Out here, pulling hot liquid from sealed cool systems happens through sharp vacuum tools that stab and suck. This whole thing runs on a strict order - each move locked into place by careful rules

Starting off, the worker places the piercing tool right on the copper pipe tied into the cooling system. Built different, this device uses a tight rubber seal that locks in completely. Inside it hides a sharp metal point meant to poke through. What makes it work well is how the seal stays firm even after puncturing.

Inside the circuit, vacuum strength shows up clearly on a dedicated gauge. This reading connects straight to the main control panel. A steady watch begins even before work kicks off. Changes happen fast, visible at a glance. Control stays sharp throughout each phase. Readings update without delay, right where the user sees them.

Piercing the copper line happens when the needle moves forward, sealed tight to stop vapors from escaping too fast. This stops refrigerants leaking out where people work. A strong vacuum keeps everything locked during circuit tapping. Pressure stays controlled so no gases go loose nearby.

3.5.3 Thermodynamic Fluid Separation and Storage Architecture

The vacuum pump continuously draws the heterogeneous gas-oil matrix out of the appliance and into a closed-loop collection container. Within this container, a precise thermodynamic separation process is carried out by applying localized heating under vacuum conditions . Because the volatile refrigerant exhibits a significantly lower boiling threshold than the heavy compressor oil, the refrigerant instantly vaporizes.

This vacuum heating process strips the lubricating oil matrix until the remaining dissolved refrigerant gas concentration within the oil is successfully reduced below 0.1% . The decontaminated oil is then siphoned off into external containment vessels for specialized hazardous waste disposal.

As illustrated in the technical engineering layout of Figure 3.5, the liberated gaseous refrigerant vapors are subsequently managed via a specialized multi-stage condensation loop

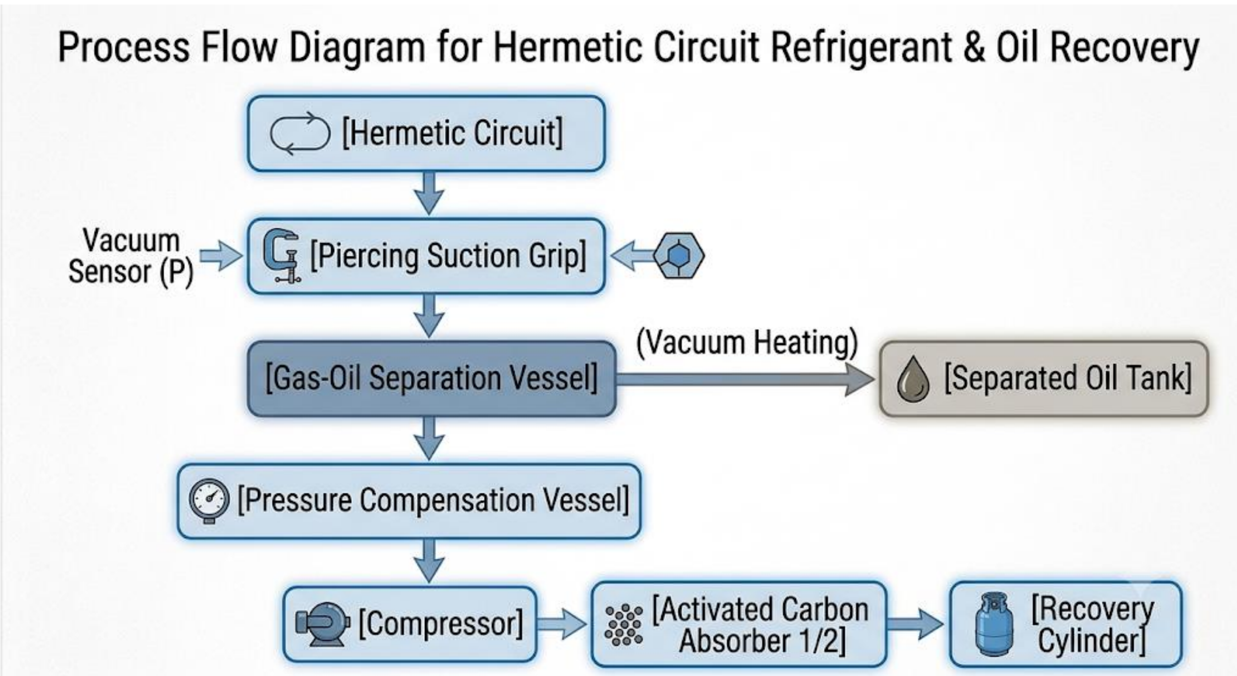


Figure 3.5: Processing flowchart and chemical recovery loop of Phase I circuit depollution.

Source: Figure is extracted from factory documents and illustrated by author

According to the directional processing streams detailed in **Figure 3.5**, a vacuum pump transports the gaseous refrigerant from the separation vessel into a dedicated pressure compensation tank. A downstream mechanical compressor then sucks the vapors from the tank, raising the local pressure to condense the gas into a stable liquid state before transferring it into specialized pressurized cylinders for final off-site recovery.

To capture trace emissions and prevent process slips, the atmospheric vents of the gas compression system are directed through two downstream activated carbon absorbers . These columns operate in automated alternating cycles. Once a single column approaches chemical saturation, the flow is siphoned into the secondary column while the first undergoes thermal regeneration; the liberated regeneration flow is pumped directly back into the recovery cylinders to maximize total capture efficiency.

3.5.4 Logistical Gate Triage and Material Routing

After evacuation confirms cleanliness inside, workers remove the compressor casing by loosening fasteners at the unit's bottom. Built to handle old CFCs along with modern hydrocarbon coolants, the first-stage cleanup system improves structural efficiency when clearing contaminated cooling loops.

Now comes the moment when fridges reach a key spot on the belt - here, sorting happens fast, guided by what's inside their foam walls. Depending on that mix, each unit takes a different path forward. Not every cooling box moves alike once it hits this split. The material deep within decides next steps without delay. Where one ends up ties directly to its internal makeup

Old fridges filled with CFC-11 foam bypass the main assembly track. Instead of moving straight ahead, they get routed sideways by a backup roller system. This separate path keeps harmful chemicals out of sensitive machinery later on. Protection happens without stopping the flow. The detour avoids contamination risks entirely.

Out past the prep area, cooling units built with greenish pentane gas tucked into their foam walls move straight into row two - there, machines take a second pass to pull out leftover fumes before breaking things down further.

3.6 Phase II Degassing: Polyurethane Foam Matrix Shredding & Inertization

After sorting through the logistics checkpoint late in Phase I, fridge units stripped of harmful residues move on their own into Phase II. From there, machines break apart the foam carefully, freeing trapped pentane forms like cyclopentane, isopentane, and L-pentane caught inside tiny bubbles of stiff PU insulation. Only then does air-powered recovery begin pulling out those gases.

3.6.1 Closed-Loop Grinding Mechanics and Multi-Point Extraction

Inside a vacuum-sealed chamber, the structural cabinet enters a heavy-duty shredder designed to stop volatile organic compounds from escaping. As soon as the polyurethane foam breaks apart mechanically, the captured blowing agents turn immediately into vapor. A system of tightly enclosed conveyors - either screw-type or chain-driven - links straight to the shredder's outlet, maintaining full atmospheric control. Because the entire setup remains physically shut off, released gases cannot spread into the work area. At the same time, outside air stays out, avoiding any contact with the internal process stream.

From start to finish, airflow pulls everything through a special pipe built just for moving ground stuff - five thousand cubic meters every hour. Right where particles break free, fumes get sucked into that stream without delay. Those gases travel straight toward intense heat treatment meant to dismantle them completely. Capture stays total because suction spots appear exactly where needed inside the second stage setup - not scattered, but placed with purpose

Inside the sealed shredder feed opening, a single exhaust unit is built into the cover. Hood placement stays fixed at the center point of the enclosure roof.

Air-powered channels run beside the auger after the shredder compartment.

Pipes pull vacuum right where the robotic foam-sealing units run. Air channels sync up precisely beside them.

Inside the pelletizing press, high-pressure extraction loops pull out tiny pockets of gas. These get stuck in crushed polyurethane when it's pressed tight. The system works while the material is being compacted. Pressure forces most trapped air to escape before pellets form. Extraction happens right where compression takes place. No separate step needed - everything runs together. Gas removal improves density. Material comes out more uniform. Microscopic bubbles weaken output if left behind. This method reduces that risk. Direct integration makes the process efficient. Residual gases have nowhere to hide.

3.6.2 Nitrogen Inertization and ATEX Safety Thresholds

Because pentane vapors exhibit high volatility and a severe explosive profile when mixed with ambient air, maintaining strict chemical safety controls inside the shredder environment is required. The Leinì plant manages this acute risk through continuous process inertization driven by an in-house nitrogen generation system. This utility generates nitrogen compressed to a certified chemical purity of **97%** and maintains a constant injection rate of **165 m³/h** directly into the processing line. This inert gas barrier is blown continuously upstream and downstream of the grinder rotor and into the internal chamber of the pellet press to displace oxygen.

To verify the safety of this environment, automated monitoring instruments track the Lower Explosive Limit (LEL) and volumetric oxygen (O_2) concentrations within the inerted atmosphere. The machine operates using a single internal electronic brain governed by predefined rules.. One alert kicks in when levels rise too high, another if they drop too low. These checkpoints operate without human input. Each trigger follows a strict digital rulebook stored in memory

When levels hit a quarter of what could ignite, machines cut off fresh fridge deliveries to the crusher. That pause kicks in fast - no delay. Instead of shutting everything down, airflow systems keep pulling fumes out, pumping nitrogen steadily through chambers. All activity inside stays alive just long enough to clear the air completely. Only after readings drop beneath danger zones does anything reset.

When gas hits 40% of the danger level, alarms sound. A sudden rise like that sets off automatic shutdowns across machinery. Grinding stops. Movement of materials halts. Yet ventilation keeps pulling air at 5,000 cubic meters per hour. Nitrogen continues flowing without pause. The space gets stabilized from within, even as systems lock down outside.

Right where the grinder dumps material, speed-sensitive spark sensors plus light-based flame monitors stand guard. Should one of these catch a flicker, the system kills refrigerant feed without delay. That snap decision triggers targeted water sprays to douse heat risks early. All this happens before gases ever reach the burner chamber.

CHAPTER 4: EMISSION CONTROL & COMPARATIVE PERFORMANCE (PENTANE VS. CFC)

4.1 Industrial Baseline: Volatile Hydrocarbon (VHC) Processing

Right now, machines at Transistor S.r.l.'s factory in Leinì handle old fridges that use non-fluorinated coolants. These appliances carry volatile hydrocarbons - flammable stuff, yet mild on air quality when released. Instead of manual handling, robots guide each unit through a system built for about 45 to 50 units every hour. Inside them, you find stiff foam made with cyclopentane or similar blends, while cooling parts run on isobutane gas. On average, each item tips the scale at 39.2 kilograms before removing the gassy components. From that standard weight, nearly half goes to steel frames totaling 17.0 kg per machine. Compressors take up another 9.0 kg by themselves. Non-iron metals show up next, weighing in at 2.0 kg across various housing sections. Wiring adds just 0.15 kg; different plastic types outside the inner layer bring it up by 6.2 kg more. Leftover bits split the difference: glass uses 0.25 kg space, water traces fill another 0.25 kg slot, motor oil occupies 0.20 kg volume, and whatever doesn't fit categories rounds out 0.17 kg behind. Inside the setup, a 4.0 kg structure made of polyurethane acts as the base material. This foam type carries about 55 grams of cyclopentane for every kilogram. When added up across the whole block, that amounts to 0.22 kg of cyclopentane in each unit. Running alongside it, a cooling system operates using roughly 0.060 kg of isobutane. Charge levels stay consistent within the loop. Because cyclopentane exhibits an ozone depletion potential (ODP) of zero and a minor 100-year global warming potential (GWP) of approximately 11, the primary design objective of the emission control loop shifts entirely away from halogenated acid vapor capture toward the mitigation of explosive hydrocarbon-air mixtures (Dehoust and Schüler, 2007).

To isolate and control these highly flammable hydrocarbons, the size reduction sequence is executed inside an encapsulated primary shredding chamber operating under a continuous nitrogen (N_2) process inertization framework (Dehoust and Schüler, 2007). The thermal and structural risks of volatile hydrocarbon processing dictate stringent utility inputs. Step 1 fluid evacuation requires low initial utility overheads, consuming approximately 0.03 liters of diesel and 0.1 kWh of electricity per appliance. Conversely, the mechanical breakdown in Step 2 demands approximately 5 kWh of electrical energy per unit within a joint processing plant setup. To sustain a safe, oxygen-depleted grinding envelope, an on-site generation system injects a continuous stream of approximately 165 m^3/h of nitrogen at 97% purity directly into the grinding envelope. This high-volume displacement loop is structurally designed to keep oxygen concentrations safely below the lower explosive limit (LEL) of the outgassed pentane isomers.

Vapor safety metrics are governed by an automated dual-threshold monitoring loop linked to the plant's programmable logic controller. Reaching 25% of the LEL triggers a primary alarm that halts automated conveyor appliance loading, which prevents the introduction of new refrigerators into the shredder hopper while leaving internal extraction and nitrogen purging loops fully active to draw down the hydrocarbon accumulation. Alternatively, reaching a secondary threshold of 40% of the LEL activates a high-pressure fire suppression loop and commands an immediate mechanical shutdown of the shredding rotor to eliminate friction-induced ignition risks. Physical outgassing dynamics during size reduction show that a simple mechanical crushing into large chunks releases roughly 30% of the micro-encapsulated cyclopentane from the closed cells of the PU matrix. The remaining 70% stays trapped within the foam cells unless the material is subjected to intensive mechanical milling down to a fine powder, which fully destroys the cellular structure to force complete degassing.

Volatized plant emissions and outgassed pentane vapors are continuously evacuated from multiple nodes across the Stage 2 processing line by a 5,000 m^3/h collection line. This stream is routed directly to a three-chamber regenerative thermal oxidizer (RTO) operating at a baseline destruction temperature of 780°C, which breaks down the hydrocarbon chains into stable carbon dioxide (CO_2) and water vapor (H_2O) prior to atmospheric discharge (Dehoust and Schüler, 2007). RTO units handling this non-fluorinated feedstock operate in a highly efficient, self-sustaining thermal mode whenever the incoming hydrocarbon concentration exceeds 1.5 g/Nm^3, minimizing the need for auxiliary fuel support. This specialized thermal configuration is highly sensitive to the structural purity of the processing stream. If legacy fluorinated compounds were to slip into this 780°C combustion chamber because of sorting errors, the thermal cracking of chlorofluorocarbons would generate highly corrosive hydrogen fluoride (HF) and hydrogen chloride (HCl) gases. Without specialized downstream chemical scrubbing columns or acid neutralizers, these volatile mineral acids would cause severe, irreversible corrosion to the internal ceramic regenerator beds and structural linings of the RTO.

4.2 Technical Requirements for Chlorofluorocarbon (CFC) Expansion

Expanding the engineering infrastructure to handle legacy volatile fluorinated carbons (VFCs), such as trichlorofluoromethane (CCl_3F, designated as R11) and dichlorodifluoromethane (CCl_2F_2, designated as R12), introduces a more demanding chemical and regulatory profile(Dehoust and Schüler, 2007) . Legacy CFC compounds present high stratospheric ozone-depleting characteristics and extreme 100-year global warming potentials, with R11 exhibiting an ozone depletion potential (ODP) of 1.0 and a GWP of 4,680, and R12 exhibiting an ODP of 0.82 and a GWP of 10,720. The historical necessity for a global phase-out of these compounds is governed by the Montreal Protocol, an international treaty whose regulatory success was deeply entrenched in the economic and competitive opportunities made available to large chemical producers—such as DuPont and ICI—to market alternative chemical substitutes like hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) under high commercial margins. Under this global regime, essential use exemptions were strictly limited to applications deemed necessary for health, safety, or the general functioning of society, creating a rigid legal baseline for modern decommissioning frameworks.

Meeting official environmental rules means any upgraded recovery setup has to pull at least 90 percent of harmful gases out during two stages - yet top-tier high heat methods often shoot for destroying nearly every last bit, aiming at 99.99 percent just to stay safe. Starting with the first phase, where cooling systems get cleaned up, the machine pulls leaking coolant away from the oil that keeps compressors running smoothly, using intense suction. That physical process needs to leave behind less than 0.2 percent halogens in the collected oil; surprisingly close to the stricter 0.1 percent cap on leftover R12 set by niche inspection groups watching fridge lubricants.

During step two of foam handling, breaking down the sealed-cell polyurethane structure has to happen inside a fully sealed chamber - this stops tiny trapped R11 gases from escaping into the air (Dehoust and Schüler, 2007; Kjeldsen and Jensen, 2001). The hard insulation material holds quite a bit of CCl3F, about one tenth to an eighth of its weight. Research shows close to two out of every five parts of this gas mix directly into the plastic framework, stuck there by molecular attraction. Meanwhile, nearly three fifths stay locked as gas bubbles inside countless minuscule pockets formed during manufacturing.

Mechanical size reduction significantly alters these retention dynamics. Grinding the appliance insulation down to 2-cm fragments instantly opens the cell boundaries along the fracture lines, inducing a rapid desorptive flash that discharges up to 10% of the total encapsulated CFC mass into the chamber atmosphere within a few weeks. Long-term behavior is dictated by Fickian molecular diffusion through the intact cell walls. This continuous outgassing operates under an effective diffusion coefficient ($D_{eff,c}$) ranging between $0.5 \times 10^{-14} m^2 s^{-1}$ and $1.7 \times 10^{-14} m^2 s^{-1}$. This structural parameter dictates that the remaining structural chemical content exhibits an atmospheric half-life stretching from 9 to 300 years for 2-cm particles, emphasizing the necessity for long-term gas-tight process boundaries.

Routing these fluorinated gas streams directly into the facility's existing thermal loop presents a severe material and environmental barrier(Dehoust and Schüler, 2007; Wuebbles and Calm, 1997) . The high-temperature combustion of chlorofluorocarbons releases hazardous, highly corrosive secondary byproducts, specifically hydrofluoric acid (HF) and hydrochloric acid (HCl)(Wuebbles and Calm, 1997) . The operational challenges of managing municipal solid waste combustion lines under model predictive control (MPC) architectures demonstrate that these acid gases drastically increase the risk of high-temperature corrosion on the flue gas side of processing systems, aggressively attacking the metal surfaces of steam tubes and boiler components whenever temperatures scale toward intensive operational thresholds.

Concurrently, if these volatile halogens escape unmitigated into industrial processing environments, they accumulate in concentrations mimicking standard landfill gas profiles of 20 to 220 mg/m^3, precipitating intense mechanical wear and tear due to acid corrosion within the disposal and extraction infrastructures(Kjeldsen and Jensen, 2001) . Because the existing RTO configuration at Transistor S.r.l. lacks the advanced chemical lining and downstream air pollution control systems needed to neutralize acidic effluents, direct processing would cause catastrophic acid corrosion of the steel stacks and rapid failure of the ceramic regenerator beds(Dehoust and Schüler, 2007) .

Because industry grows, systems that clean waste gas become necessary - either a wet scrubber using sodium hydroxide or a super-cooled condenser that traps CFCs before burning occurs (Dehoust and Schüler, 2007). When scrubbers handle the cleanup, exact amounts of NaOH must match incoming levels of chlorine and fluorine to maintain balance.

Because real-world measurements come from large urban and factory burn sites, the design of this cleaning system must weigh how much acid it removes against how many extra materials get used - around 5.01 kilograms of activated lignite alongside 4.6 kilograms of ammonia mix for every metric ton of garbage processed. Thanks to this added filtration stage, emissions exiting the stack stay within tight legal thresholds: no more than 1.97 milligrams per cubic meter of hydrogen chloride, just 0.11 for hydrogen fluoride, fine particles under 1.11, sulfur dioxide capped at 6.19, nitrogen oxides held below 94.09 - all measured in milligrams per cubic meter. With such thorough cleanup steps active, buildings near the site avoid long-term corrosion damage even as rules remain satisfied.

4.3 Life Cycle Assessment and Environmental Impacts

The environmental rationale for retrofitting the Leinì facility is deeply supported by global life cycle assessment data comparing joint multi-stream processing against fragmented disposal routes. Baseline environmental modeling demonstrates that joint processing of CFC and hydrocarbon appliances in a single plant yields the lowest overall environmental burden, saving approximately 193,000 tons of $CO2$ equivalent per year (Dehoust and Schüler, 2007) compared to baseline alternatives. Bypassing specialized degassing loops by diverting unworkable streams to conventional auto shredder facilities degrades environmental performance significantly. Mechanical processing of appliances in a standard auto shredder results in the instantaneous volatilization of up to 70% of the micro-encapsulated R11 or cyclopentane blowing agent directly into the atmosphere, causing severe fugitive greenhouse gas emissions (Dehoust and Schüler, 2007).

Mechanical shredding down to small particle sizes drastically accelerates the long-term diffusional release of trapped gases, whereas larger, non-shredded foam panels retain their gaseous content for much longer periods. Under a standard industrial 5-cm foam panel slab configuration, molecular transport through the closed-cell polymer structure proceeds slowly but reducing this matrix to 2-cm shredded cubes yields a desorptive flash that shifts the physical half-life of the remaining volatile content to an accelerated range of 9 to 300 years. In comparison, larger, non-shredded structural panels maintain longer gaseous retention timelines, rendering un-abated mechanical size reduction a primary driver of acute desorptive emissions (Kjeldsen and Jensen, 2001).

The most critical parameter governing the total environmental impact of a multi-stream plant is the sorting error rate. Approximately 20% to 30% of waste refrigeration appliances suffer from missing or completely illegible labeling, meaning that a sorting error rate of 1% represents the absolute lower limit achievable under rigorous professional training. Sensitivity analyses indicate that a baseline sorting error of 1% restricts the stratospheric ozone depletion potential (ODP) to 1,207 kg R11 equivalent per year, though parallel or auto-shredder routes with the same 1% error rate still cause ODP levels to climb between 4,116 and 8,609 kg R11 equivalent per year. If appliances are misallocated at local collection gates due to a lack of trained staff, sorting error rates escalate to 5% or 10%. At these thresholds, the ODP of the processing network increases dramatically to 38,000 and 75,000 kg R11 equivalent per year—representing a 32-fold to 62-fold increase in stratospheric degradation due entirely to emissions from misallocated CFC units (Dehoust and Schüler, 2007).

Furthermore, a dual stream upgrade satisfies critical requirements for photochemical ozone creation potential (POCP). While the release of uncaptured cyclopentane and isobutane from un-abated shredders dominates plant emissions and creates severe local ground-level summer smog burdens, routing the combined stream through advanced joint containment loops eliminates these photochemically active precursors entirely. Joint processing turns summer smog precursors into a net environmental benefit of 15,032 kg ethylene equivalent per year. Conversely, parallel processing or shredder-based alternatives generate substantial local burdens ranging from 3,828 to 38,035 kg ethylene equivalent per year. Because ground-level ozone formation is a highly localized, temporary process, even minor fractional increases in volatile organic emissions can make a significant contribution to local ground-level ozone spikes, making closed containment loops an immediate public health necessity (Dehoust and Schüler, 2007).

The technical feasibility of optimizing these multi-variable environmental bounds is strongly enhanced by the application of Model Predictive Control (MPC) frameworks. Industrial combustion plants suffer from a continuous influx of heterogeneous, non-uniform waste streams that cause severe process variations. Conventional combustion networks utilize rigid P- or PI-controllers that fail to handle multivariable interactions and process constraints systematically, forcing facilities to operate conservatively and well below their maximum throughput limits. Implementing an LMPC-based control system utilizing a quadratic criterion and linear inequality constraints allows the automation loop to predict process and disturbance trajectories in real time. This mathematical optimization systematically dampens the severe variations induced by volatile hydrocarbon inputs, allowing the facility to operate safely and continuously near its upper operational bounds without risking fire suppression trips or mechanical trips. Actuators and material conveyors endure fewer rapid adjustments, which preserves equipment lifespan, cuts operational maintenance costs, and maximizes structural throughput to close regional processing market gaps (Leskens et al., 2005)

4.4 Tabulated Comparative Performance Matrix

In **Table 4.1**, the operational, chemical, and environmental parameters of the existing hydrocarbon line are compared directly against the proposed chlorofluorocarbon expansion stream below (Dehoust and Schüler, 2007; Kjeldsen and Jensen, 2001; Wuebbles and Calm, 1997):

Table 4.1: Chemical and Environmental Comparison of Processing tecnologies

Parameter / Metric	**Pentane (VHC) Baseline**	**CFC (VFC) Expansion**
Primary Blowing Agent	Cyclopentane / Isopentane	R11 (Trichlorofluoromethane)
Circuit Refrigerant Gas	R600a (Isobutane)	R12 (Dichlorodifluoromethane)
Ozone Depletion Potential (ODP)	0 (Zero Risk)	1.0 (Severe Stratospheric Risk)
Global Warming Potential (GWP)	11 (Negligible Impact)	4,680 – 10,720 (High Climate Risk)
Primary Industrial Risk Profile	High Flammability / ATEX Hazards	Atmospheric Persistence / Acid Corrosion
Required Abatement Technology	Nitrogen Inertization + RTO Core	Cryogenic Condensation or Alkaline Scrubbing
Effluent Combustion Byproducts	Carbon Dioxide (CO_2), Water Vapor (H_2O)	Carbon Dioxide, Water, Hydrofluoric & Hydrochloric Acids

Mandatory Regulatory Threshold	Safe Volatilization / ATEX Safe Limits	≥90% Certified Capture & Destruction Rate

Source: Author's own elaboration based on parameters detailed by baseline regulatory assessments (Dehoust and Schüler, 2007; Kjeldsen and Jensen, 2001; Wuebbles and Calm, 1997).

Despite its complex setup, the system handles pentane-rich devices by sealing them mechanically while flooding the chamber with large amounts of nitrogen - 165 cubic meters per hour - to prevent ignition risks during grinding. A regenerative thermal oxidizer set to 780 degrees Celsius acts as the primary method for breaking down hazardous components thoroughly. This dual-path design connects two distinct chemical environments, each requiring specialized treatment protocols. With non-fluorinated inputs, the outgoing gases show no signs of corrosiveness, since only CO_2 and steam form as byproducts. Because neutralizing additives are unnecessary here, maintenance stays minimal under standard operational conditions. Dehoust and Schüler noted such outcomes back in 2007.

Yet upgrading the facility layout to handle old chlorofluorocarbons demands full replacement of current air emission controls (Wuebbles and Calm, 1997). Since R11 and R12 linger intensely in the atmosphere while driving climate change - and carry an ozone depletion factor of exactly 1.0 - laws mandate verified removal rates no lower than 90% during each treatment phase (Dehoust and Schüler, 2007). Sending such halogen-rich substances straight into the present RTO incinerator breaks apart C–Cl and C–F linkages, forming light, unstable vapors like HCl and HF (Wuebbles and Calm, 1997). Absent high-performance follow-up cleaning units using caustic soda baths or sealed low-temperature recovery modules, those sharp inorganic acids eat through metal exhaust ducts quickly, harming also the layered ceramic components inside thermal chambers (Dehoust and Schüler, 2007).

The material balance of these alternative processing routes also highlights unique physical behavior inside the closed shredding chamber. While pentane processing focuses heavily on immediate gas capture from the shredded foam flakes, mechanical reduction of legacy CFC polyurethane insulation triggers a complex, long-term desorptive release mechanism. Roughly 40% of the micro-encapsulated R11 is chemically dissolved within the solid polyurethane polymer matrix itself, leaving 60% suspended as a gas within the closed cellular voids. High-velocity mechanical size reduction instantly breaks these cell boundaries along the fracture lines, causing an immediate desorptive flash of up to 10% of the total CFC mass directly into the process atmosphere (Kjeldsen and Jensen, 2001). The remaining 90% stays bound within the matrix, outgassing slowly over decades via Fickian molecular diffusion through the intact cell walls, with an effective diffusion coefficient ($D_{eff,c}$) ranging between $0.5 \times 10^{-14} m^2 s^{-1}$ and $1.7 \times 10^{-14} m^2 s^{-1}$. This slow, structural release behavior requires the installation of robust, gas-tight mechanical boundaries and precise automation control loops to prevent fugitive emissions throughout the decommissioning lifecycle (Kjeldsen and Jensen, 2001).

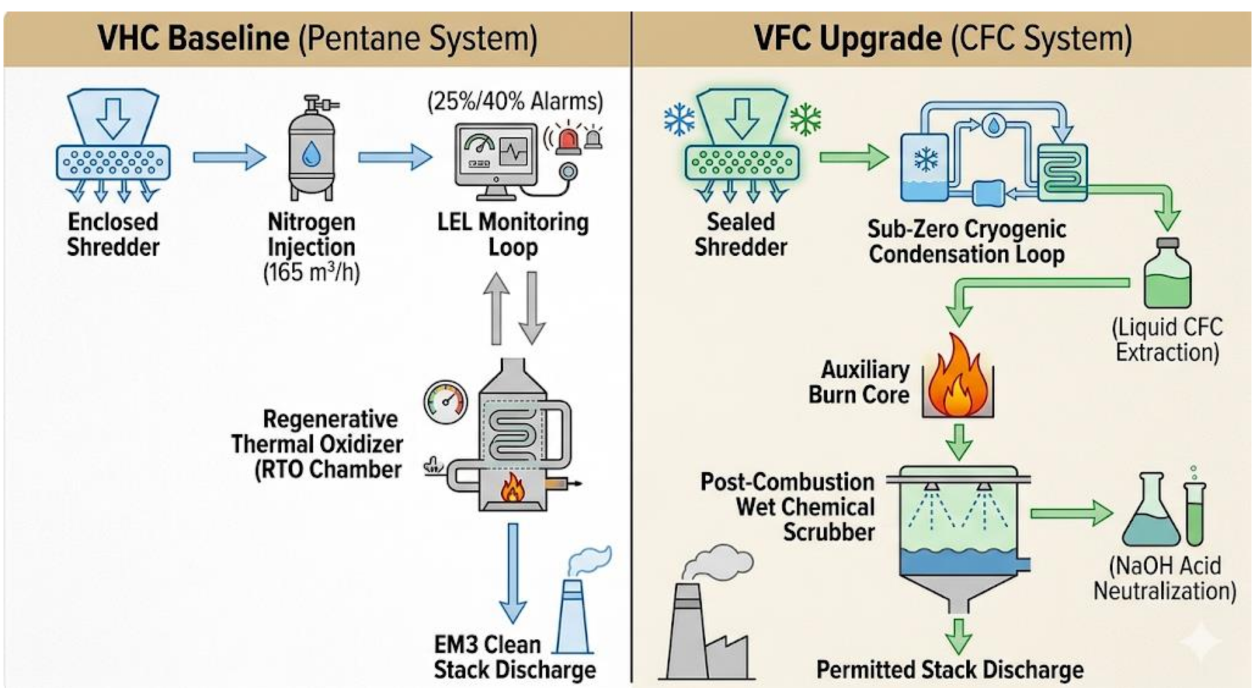
4.5 Emission Monitoring and Compliance Metrics

What happens at the Leinì plant depends on strict rules laid out in its current environmental license. From chimney EM3, dust levels cannot go beyond 5 mg/Nm³ under any condition. Carbon Monoxide stays within legal range only if it measures less than 100 mg/Nm³. Organic vapors without methane hit a hard stop at 30 mg/Nm³. As operations shift toward handling two material streams at once, live emission tracking stays switched on. This constant watch ensures rerouting fuels won't cause sudden jumps in harmful fumes.

Running industrial heat systems this precisely demands close handling of fuel shifts. Instead of standard PI controls, using an LMPC setup improves burn efficiency. Shredded fridge waste burns unevenly - sudden bursts of cyclopentane or isobutane throw off flame stability. Old-style regulators often miss dangerous rises in carbon monoxide and organic vapors (Leskens et al., 2005). With LMPC, the system forecasts chamber behavior through math bounds and forward-looking models (Leskens et al., 2005). It tweaks how fast trash feeds in while modulating extra air supply on the fly. Swings in burning smooth out. Emissions at the stack stay under 100 mg/Nm³ for CO and 30 mg/Nm³ for C.O.T.N.M. - all without pouring in expensive backup gas (Leskens et al., 2005).

To bridge these rigorous monitoring parameters with physical equipment modifications, the facility must integrate specialized post-combustion abatement technologies directly into the exhaust infrastructure.

Figure 4.1: Side-by-Side Emission Control Architecture: VHC Baseline vs. VFC Upgrade



Source: Author's own elaboration based on treatment processing variants modeled by engineering design frameworks (Dehoust and Schüler, 2007).

Picture shows how the improved RTO setup shifts from a simple heat-based hydrocarbon device to a layered system that handles acid gases. Coming up from the sealed shredding area, untreated gas flows into the lower section of a three-room thermal burner. It moves step by step through chambers filled with ceramic material - named A, B, and then C - where high-heat breakdown happens steadily at 780 degrees Celsius, according to findings by Leskens and team in 2005.

Figure 4.1 shows how old CFC units are handled. When heat breaks down fluorinated compounds, harsh gases form. Because those can damage equipment and harm air quality, steps follow right away. From the upper manifold, heated fumes get pulled away - directed into a cleaning unit filled with alkali liquid. Rising inside this chamber, sour vapors meet fine mists of sodium hydroxide, sprayed by automatic systems. Reactions lock chlorine and fluorine acids into harmless water-based salts. What exits afterward - the cleaned airflow - moves up and out through the EM3 test vent.

Concurrently, the plant must establish structural sampling protocols to verify that the mechanical separation lines prevent halogen and polymer cross-contamination into solid output streams. As outlined in high-standard industrial processing criteria, the residual polyurethane (PU) foam dust adhering to recovered ferrous and non-ferrous metallic fractions must be kept strictly below 0.3% by weight to ensure high material purity. Within the isolated post-consumer plastic fractions, residual PU foam contamination must not exceed a maximum threshold of 0.5% by weight . Any failure to satisfy these physical purity baselines indicates a drop in degassing liberation efficiency, requiring immediate process optimization to avoid structural non-compliance, production halts, or severe administrative sanctions under national environmental statutes (Dehoust and Schüler, 2007).

Maintaining these low contamination rates is heavily dependent on the mechanical properties of the closed-cell PU structure during size reduction. Rigid insulation foams carry an average initial blowing agent concentration of roughly 10% to 15% by weight, with approximately 40% of this volatile organic fraction dissolved directly into the solid polymer struts and 60% trapped as a gas inside the cell cavities. High-speed mechanical shredding instantly alters this distribution; the initial impact releases roughly 10% of the micro-encapsulated blowing agent due to cell rupture along the fracture planes (Kjeldsen and Jensen, 2001).

If the shredding line fails to reduce the material down to sufficiently small particle sizes, larger foam fragments will continue to outgas slowly over a half-life of several decades via Fickian molecular diffusion, with an effective diffusion coefficient ($D_{eff,c}$) ranging between$0.5 \times 10^{-14} m^2 s^{-1}$ and $1.7 \times 10^{-14} m^2 s^{-1}$ (Kjeldsen and Jensen, 2001). These un-degassed foam fragments degrade the downstream sorting steps by clinging to iron and copper matrices. This increases the total mass of halogenated residues above the 0.3% limit and carries uncaptured blowing agents directly into metal melting furnaces, causing unauthorized point-source emissions. Consequently, the facility must enforce systematic sieve analyses and automated air classification checks to verify that complete cellular collapse is achieved within the inerted shredding envelope before downstream magnetic and density separators discharge the fractions.

CHAPTER 5: CASE STUDY: TRANSISTOR S.R.L.

5.1 Institutional Background and Facility Overview

Born from the Arcobaleno Social Cooperative in 2010, Transistor S.r.l. operates as a targeted arm focused on handling electronic scrap. Though launched later than its parent body, it follows the same core aim: offering lasting jobs to people excluded from standard work paths. Arcobaleno began in 1992, built around the idea that employment can help overcome deep-rooted disadvantages. Now employing about 300 workers, nearly one-third hold roles reserved for those rejoining society after hardship - such as leaving addiction behind or returning post-incarceration. Instead of working alone, the cooperative links several waste-focused teams throughout northern regions. In Turin, Cartesio gathers paper and cardboard directly from homes, while Ingombranti handles large discarded items in the same city. Further east, Soeko collects recyclable materials like glass, plastic, and printed matter near Chivasso. With no overlap into these streams, Transistor manages only electrical and electronic waste. Its reach extends through more than 380 drop-off sites using a coordinated transport layout across three areas: Piedmont, Liguria, and Valle d’Aosta.

North of Torino, at Via Paolo Veronese 202, an inter-municipal ecocentre manages incoming logistics alongside local waste drop-offs. This center organizes delivery routes either directly to recipients or to disposal points, working under contract with over 100 towns across the Turin region. Instead of being processed in central Torino, certain items take a different path: refrigeration units requiring temperature control (R1 category), along with compact electronic gadgets (R4), move toward dedicated facilities in Leinì (TO). Washing machines, stoves, hobs, and dishwashers - classified as R2 - are handled entirely at the primary city-based plant. At Leinì, around seventy workers form the core team responsible for reclaiming intricate e-waste types. Because of its role in integrating disadvantaged groups into employment, preserving staff numbers matters greatly. Hence, plans to modernize the R1 processing system - which would allow safe handling of older coolers containing CFCs - have been shaped specifically to retain all current positions. Even as machinery improves, human continuity stays fixed.

Working with the national waste management authority, the Leinì site handles old fridges using sealed systems that cut down size, sort materials mechanically, then trap gases - keeping risks low and meeting tough ecological rules. Its main recycling track runs on machines built to handle around 45 to 50 used cooling units each hour. During normal shifts, the system deals carefully with fridge bodies containing non-CFC foams expanded with light fuels like cyclopentane, isobutane, or L-pentane. At stage one, vacuum-powered suction pulls out working R600a gas; pressure packs it into storage tanks, whereas heat applied in empty space frees oil from parts till less than 0.1% gas remains. After cleaning ends and motors come off, phase two breaks shells apart via grinding inside tight chambers where airflow stays locked at 5,000 cubic meters hourly. Inside, a tight seal stops pentane gas from escaping while keeping air out. Connected straight to the shredder's exit, either a screw or chain conveyor moves material without breaking containment. Nitrogen flows constantly through the loop, supplied at 165 cubic meters per hour. The gas comes from an on-site generator, running at ninety-seven percent purity. Levels stay under the point where fire could ignite. Protection holds steady because fresh nitrogen replaces any possible leaks. No spark finds fuel when conditions remain this controlled. After capture, hydrocarbon vapors move into a three-chamber thermal oxidizer running at 780 °C. This unit eliminates the gas completely using continuous internal burning. Heat from the process keeps the reaction going without extra fuel.

Still, the machine setup struggles with how it was first built. Without strong chemical filters or modern freezing-based separators to handle corrosive outputs, the site breaks rules if it tries cleaning cooling gear filled with old CFC gases. Early in sorting, fridges with outdated foam inside get pulled off the main line by a side belt, stopping damage further down. That design flaw slows everything. Of nearly four million kilograms of discarded coolers arriving, only about three million make it through - those using safer pentane. Just over one million fail entry, blocked for being too risky. At a typical cost of 280 euros per ton for fridge recycling, income stays capped at 862,349 euros due to current technical constraints. Though handling runs at 45 units hourly, full potential remains out of reach without better equipment. An improved RTO system built to resist acidic conditions could remove that barrier completely. Once installed, the plant would manage every portion of the 4,092,228 kilograms delivered each year. Revenue from treatment then climbs up to 1,145,824 euros annually under identical operational speed. This multi-tiered engineering and social layout, supported by a consistent staff of 70 personnel, offers an ideal baseline for testing advanced diagnostic audit frameworks designed to assess structural compliance in complex solid waste architectures (Larsen, 2004).

5.1.1 Structural and Workforce Specifications

The Leinì industrial site functions as a centralized Category 1 treatment facility housed within a purpose-built industrial structure, featuring partitioned operational cells designed to isolate the R1 and R4 processing lines. The facility layout incorporates heavy-duty concrete flooring to support high-throughput mechanical shredding machinery and is equipped with advanced pneumatic extraction systems required for ATEX compliance.

The plant maintains a steady, specialized workforce of **70 employees** which work in two shifts dedicated to the Leinì site operations. This staff is responsible for the manual dismantling, active circuit depollution, and supervised mechanical sorting of incoming WEEE. Following the proposed technological upgrade—specifically the integration of the acid-resistant RTO unit and downstream scrubbing columns—the facility's operational architecture is designed to maintain this exact labor headcount of 70 personnel. This consistency in staffing levels during the expansion ensures that the facility's social integration mission is preserved, confirming that the throughput increases associated with CFC processing are achieved through technological optimization rather than labor force restructuring.

5.2 Existing Operating Throughput and Production Audit

Inside the Leinì site, motion begins fast - a single R1 recovery chain moves at full stretch, handling close to fifty used fridges each hour. When matched with real-world data on weight - roughly 39.2 kilograms per unit - the math shows steady material flow: just under two metric tonnes every sixty minutes while running. Downstream tasks like shredding and heat extraction only accept devices without fluorine-based gases; instead, they rely on systems tuned for cyclopentane, isopentane, or L-pentane locked inside stiff PU foam, along with working parts using isobutane (R600a). Because of this setup, older models loaded with CFCs cannot enter the process, blocked by both law and machine limits. That restriction pinches hard - about twenty-five percent of incoming junk still carries those outdated compounds, according to Vehlow and Gloël in 2020.

Hidden risks emerge when old cooling devices reach end-of-life, since standard retired units often contain around 140 grams of compressed coolant in their systems while holding 450 to 780 grams of unstable foaming chemicals within insulated panels (Vehlow and Gloël, 2020). Packed tightly into solid foam layers, these chlorine-based substances become dangerous if treatment lacks emission controls. Crushing such materials without sealed containment triggers sudden breakdowns in plastic cell walls - releasing trapped gases all at once.

Out at Transistor S.r.l., one fixed sorting path means every fluorinated unit gets pushed straight off the main belt by automatic systems, diverted through a side track on rollers before heading out to outside handlers. That reroute leaves tons of usable stock stranded each year - specifically 1,012,410 kilograms missed from the full intake of 4,092,228 brought onsite. Money slips away quietly as these discarded batches pile up, then get hauled off-site at extra cost just to clear space inside the plant.

One step beyond just upgrading means bringing in powerful systems that grab pollutants fast, even when VOC levels swing wildly - all while keeping operations running smoothly. Because these setups must manage two very different types of vapors at once - light hydrocarbons and heavier chlorofluorocarbons - typical burn-and-release methods struggle to keep up. During foam shredding processes, gases erupt unpredictably; sudden surges flood cleanup equipment built for steady flows. That chaos pushes conventional filter beds past their limits, often leading to clogs or shutdowns.

Older methods that pull pollutants from air using cold traps or single charcoal beds often fail fast. Heavy contaminants clog them quickly, heat needed to clean the filters runs up expenses, plus strong chemicals push out lighter vapors. At a complex site like Leinì, sticking with these outdated tools won’t meet pollution rules reliably. Instead, layered cleanup steps become necessary. A modern three-part burner running steady at 780 °C links straight into liquid soap-like wash tanks after treatment. Burned remains of oil-based fumes vanish entirely under this setup, meanwhile sharp acid gases made when old fluorine materials break apart get cooled and calmed by the rinse stages right afterward.

5.3 Detailed Engineering Description of the Three-Phase Process

The active R1 recycling architecture at the Leinì industrial site isolates and recovers material fractions by executing a highly automated, three-phase decontamination, grinding, and gas destruction sequence.

Phase 1: Circuit Depollution and Compressor Extraction

Out there on the roller tracks built just for prep work, fridges roll in and get checked over by hand while workers study how they're put together. Those units packed with flammable foams? They either get pulled aside or handled in special runs - depends what makes sense at that moment, since early cleanup steps are made to manage any kind of coolant setup without risk. Getting into the charged cooling lines means a worker fits a custom puncture clamp right onto bare copper tubes tied to the sealed fridge core. Inside that device: stretchy sealing rings hold tight around a sharp metal spike, working along with its own pressure meter to watch - and adjust - the heavy vacuum forming inside the system once it opens up.

A high-vacuum suction pump evacuates the circuit, siphoning the heterogeneous mixture of refrigerant gas and viscous lubricating oil into a sealed collection vessel. Within this thermodynamic separation container, localized heating is applied under strict vacuum conditions to flash off the volatile refrigerant from the liquid matrix, successfully stripping the synthetic lubricating oil until the residual refrigerant concentration embedded within the oil is reduced below a safe threshold of 0.1% . The separated refrigerant vapors are drawn into a pressure compensation vessel to balance thermodynamic fluxes across the pneumatic circuit. An automated gas compressor then draws from the compensation vessel and compresses the vapor stream to its specific condensation threshold, liquefying the chemical fractions into high-pressure cylinders for secure off-site recovery.

Atmospheric vents from the gas compression loop are directed through two downstream activated carbon absorbers operating on an alternating cycle to catch trace process slips . Once a single carbon column approaches chemical saturation, the line diverts the stream to the secondary column while the first undergoes automated thermal regeneration, routing the desorbed vapors back into the refrigerant gas recovery cylinders to maintain total containment . Following complete circuit decontamination, operators remove the internal compressor shell, and the structural cabinets advance to a logistical gate triage. At this junction, appliances identified as legacy assets containing fluorinated (CFC) insulation foams are automatically deflected from the primary production flow via a specialized auxiliary roller conveyor to shield the thermal core from corrosive mineral acid vapors (Dehoust and Schüler, 2007). Conversion parameters dictate that appliance cabinets loaded with modern pentane insulation are cleared to advance directly to the primary mechanical size-reduction line.

Phase 2: Airtight Size Reduction and Nitrogen Process Inertization

The cleared pentane-insulated cabinets enter a heavy-duty industrial shredder operating inside an absolute vacuum-sealed, gas-tight, and enclosed environment. Rapid mechanical fragmentation of the rigid insulation cells causes the instantaneous volatilization of micro-encapsulated cyclopentane, isopentane, or L-pentane blowing agents. Because these volatile hydrocarbons pose severe flammability and explosion hazards if mixed with ambient air, the process is fully encapsulated from the grinding stage onward to prevent gas dispersion and block oxygen ingress. Continuous pneumatic suction is maintained across the Stage 2 processing grid by a centralized 5,000 m³/h collection line. This high-volume extraction loop targets four critical operational nodes where liberated gases accumulate :

- Vacuum extraction points integrated within the closed shredder loading hopper canopy .
- Direct suction ducts mounted along the internal material extraction screw downstream of the grinding rotor .
- Pneumatic capture connections aligned with the polyurethane air-density material separation lines.
- Deep extraction loops integrated directly within the mechanical pelletizing press, which squeezes residual microscopic gas fractions out of the isolated polyurethane flakes during structural compaction.

System isolation is reinforced by using hermetic screw or continuous chain conveyor units connected directly to the shredder discharge hopper, establishing an absolute physical barrier against fugitive hydrocarbon migration and atmospheric oxygen infiltration. To complement this suction array, an integrated process inerting framework utilizes an in-house utility generation system that delivers nitrogen N_2at a certified purity of 97% . This system constantly injects approximately 165 m³/h of nitrogen directly into the upstream and downstream zones of the grinding rotor and into the internal compaction chamber of the pellet press to displace oxygen .

Volatile gas metrics and oxygen concentrations within this inerted atmosphere are continuously audited by automated monitoring sensors tied to safety interlocks. Reaching 25% of the Lower Explosive Limit (LEL) activates a primary alarm threshold that automatically locks out the primary feeding mechanism, halting the loading of refrigerators into the shredder hopper while leaving extraction fans and nitrogen injection fully active until vapor concentrations settle safely below the margin. Reaching 40% of the LEL triggers a critical safety override that instantly initiates an emergency plant trip, suspending all mechanical grinding and transport loads while concentrating remaining electrical power on the 5,000 m³/h extraction fans and nitrogen lines to neutralize the chamber. As a final layered safety measure against friction-induced ignitions, high-speed spark and optical flame detectors are aligned across the grinder's discharge hopper . Upon thermal or optical activation, these sensors automatically halt the material conveyors and trigger a high-pressure water deluge extinguishing system directly into the active material stream to quench the threat.

Phase 3: Regenerative Thermal Oxidation

The 5,000 m³/h volatile hydrocarbon stream captured across the Phase 2 size-reduction line is routed directly to a three-chamber regenerative thermal combustor operating at an authorized destruction temperature of 780 °C . A gas load monitoring system located at the combustor inlet quantifies vapor mass metrics to continuously evaluate downstream capture efficiency and establish automated alarm and shutdown thresholds to protect the thermal core from volatile spikes. To protect the internal ceramic regenerator beds from unintended halogen contamination, the inlet line is equipped with an active CFC meter. If any legacy fluorinated molecules are detected in the incoming flow due to upstream triage sorting errors, a safety interlock instantly stops the Phase 2 shredding phase to prevent the generation of corrosive hydrofluoric and hydrochloric acids (Dehoust and Schüler, 2007).

The thermal oxidizer utilizes the high calorific value of the desorbed organic vapors to achieve an autogenous (self-sustaining) operational mode whenever the hydrocarbon gas supply from the grinding line exceeds a mass threshold of 1.5 g/Nm^3, running virtually without external natural gas inputs. At the combustor outlet, an automated monitoring system continuously tracks chimney concentrations to verify complete destruction and guarantee strict compliance with environmental point-source emission limits before final atmospheric discharge.

5.4 Plant Operations Optimization and Combustion Control Analysis

Despite its benefits, expanding into dual-stream processing demands careful handling of unpredictable behavior during mixed-waste treatment at Transistor S.r.l. Instead of relying on traditional P-type or PI systems, which struggle under abrupt shifts in fuel supply because they lack flexibility, more responsive controls are needed. As operations grow to include fluorinated foams together with regular hydrocarbon inputs, instability in heat output and gas flow becomes harder to avoid. Without adaptive regulation, sharp swings may trigger either chilling spots or dangerous surges inside key furnace areas - conditions documented by Leskens et al. in 2005.

Because they act only once an error appears, standard SISO controllers respond too late in fast-changing environments. When cold, heavy CFC fumes mix with sudden pentane vapor spikes in a two-stream setup, delayed reactions trigger wild swings in flow behavior. Gas pulses erupt violently as the polymer foam structure breaks down, flooding the chamber with unpredictable fuel concentrations. Without time to adapt, control units struggle to balance airflow against these abrupt changes, pushing burn conditions into risky zones. As a result, workers must slow incoming material far below peak capability, just to keep mixture levels safely under LEL limits.

Implementing an advanced control strategy, such as Linear Model Predictive Control (LMPC) utilizing an experimentally identified linear process and disturbance model, provides a systematic framework to minimize these process variations . An LMPC-based combustion framework dynamically balances multiple conflicting variables simultaneously. It stabilizes the RTO core temperature at 780 °C, minimizes auxiliary natural gas consumption, and maintains stable extraction suction across the shredder enclosure. This is accomplished by calculating optimal multi-variable adjustments across the waste loading line and secondary air dampers concurrently (Leskens et al., 2005).

The underlying optimization problem is formulated using a quadratic objective criterion executed over a finite prediction horizon N_P, which can be mathematically defined as:

$$\min_{\Delta u} J = \sum_{k=1}^{N_p} \|y(t+k\|t) - r(t+k)\|_Q^2 + \sum_{k=0}^{N_c-1} \|\Delta u(t+k\|t)\|_R^2$$

Where $y(t+k\|t)$ represents the predicted path of critical outputs such as furnace temperature, flue gas oxygen content, and chimney pressure, while $r(t+k)$ denotes the respective reference trajectories. The vectors Q and R represent positive-definite weighting matrices that penalize state deviations and aggressive control moves, respectively, across the control horizon (N_c).

This mathematical framework enables the control loop to enforce explicit linear inequality constraints on both the states and the physical manipulation boundaries, establishing rigid operating limits:

$$u_{min} \leq u(t) \leq u_{max}$$
$$\Delta u_{min} \leq \Delta u(t) \leq \Delta u_{max}$$
$$y_{min} \leq y(t) \leq y_{max}$$

By solving this constrained quadratic program at every sampling interval, the automation matrix anticipates fuel composition variations before they manifest as chimney compliance spikes. If a high-volume pocket of cyclopentane gas enters the extraction line, the model projects the imminent heat release profile and proactively opens the secondary air dampers while dampening the conveyor feeding velocity. This predictive capability allows the system to smoothly manage sudden gas load surges within safe LEL boundaries. It minimizes the aggressive, high-amplitude corrections typical of standard PI loops, reducing structural shocks on mechanical valves and pneumatic actuators. The resulting stabilization of the thermal baseline cuts operational maintenance costs, eliminates premature degradation of internal ceramic regenerator beds, and secures the long-term economic and environmental stability of the recycling facility (Leskens et al., 2005).

Parallel to centralized thermal optimization, maintaining high low-temperature destruction pathways over optimized catalysts provides an alternative or supplementary mechanism to minimize secondary organic byproduct formation and secure high point-source efficiency under strict compliance limits (Kamal et al., 2016). High-temperature thermal oxidation at 780 °C successfully shatters volatile organic compounds but introduces severe penalty bounds. These include high auxiliary fuel inputs during dilute feeding phases and the thermal synthesis of nitrogen oxides (NO_x), alongside highly toxic polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) if halogenated molecules slip past the sorting triage lines.

Shifting the destruction mechanism toward catalytic oxidation allows the gas breakdown to proceed at a lower temperature window, typically between 250 °C and 450 °C, by significantly decreasing the required chemical activation energy (Kamal et al., 2016). The choice of catalytic material dictates the plant's resistance to chemical fouling. Noble metal configurations based on highly dispersed platinum (Pt) or palladium (Pd) supported on $\gamma - AI_2O_3$ or TiO_2 display exceptional specific activity for low-temperature hydrocarbon conversion, but they remain highly vulnerable to volatile halogen poisoning. The introduction of trace chlorine or fluorine species coordinates strongly with the active noble metal sites, blocking reactant adsorption and causing rapid deactivation of the catalyst bed.

To handle a dual-stream stream containing chlorinated compounds, the system must deploy transition metal oxide catalysts, such as mixed cobalt-manganese (Co-Mn) or copper-cerium (Cu-Ce) frameworks, which exhibit robust stability in the presence of acidic exhaust fractions . Mechanistically, this low-temperature conversion operates via the Mars-van Krevelen or Langmuir-Hinshelwood kinetic pathways. The organic molecules adsorb onto the catalyst surface and react directly with lattice oxygen species, which are then continuously replenished by gaseous oxygen from the process stream. This structured surface reaction ensures complete oxidation into CO_2, H_2O, and easily scrubbed acid gases (HCl and HF) without allowing the molecular rearrangements that form complex secondary organic byproducts, maximizing point-source conversion efficiency while fulfilling strict regional emissions thresholds (Kamal et al., 2016).

CHAPTER 6: ECONOMIC EVALUATION & FUNDING CASE

6.1 Baseline Operational Comparison

Right now, the numbers show how much money the current setup makes compared to what it could make if the line were bigger - using real processing records from 2025. At present, around four million kilograms of old cooling appliances arrive each year for handling. Only those fridges with pentane trapped inside their foam layers get worked on, making up roughly three point one million kilos during that time. Because older models carry banned gases like CFCs, about a million kilos must be turned away - they simply won't run through today's system. But once the updated heat-cleaning unit is running, that block disappears entirely. Suddenly, every single incoming appliance fits into the flow, no matter the internal chemistry. That full load? Still just under four point one million kilos - same amount, now fully usable.

Looking at the checked numbers shows just where the one-pipe system falls short. Not every setup handles pressure the same way. What works in theory often bends under real load. Numbers on paper behave differently than those in motion. A clean design can still crack when tested. The whole shape shifts once things start flowing.

Table 6.1: Material Throughput and Bottleneck Analysis

Kilograms of Refrigerators Received in 2025	Kilograms of Refrigerators with Pentane Gas in the Polyurethane Foam Processed by Transistor in 2025	Kilograms of Refrigerators with CFC Gas in the Polyurethane Foam that Transistor Cannot Process at Present (2025)	Kilograms of Refrigerators with Pentane/CFC Gas in the Polyurethane Foam that Transistor Can Process After the Implementation of the New RTO Infrastructure
4,092,228	3,079,818	1,012,410	4,092,228

Source: Author's own elaboration based on audited operational logs and facility intake records provided by Transistor S.r.l.

As compiled within the audited performance inventory of table 6.1, the mass distribution of incoming waste creates a rigid operational boundary. Under the baseline 2025 configuration, processing only the 3,079,818 kilograms of pentane-blown refrigeration units at a market treatment price of 280 € per metric ton yields a realized revenue of exactly 862,349 €. This structural bottleneck forces the facility to reject 1,012,410 kilograms of CFC-bearing appliances annually, which are directed to external disposal networks because the existing thermal core cannot neutralize halogenated off-gases. The data modeled in Figure 6.1 demonstrates that deploying the upgraded, acid-resistant RTO machine allows the plant to safely treat this rejected material, processing the entire inbound volume of 4,092,228 kilograms to achieve an optimized projected revenue of 1,145,824 € while maintaining a constant operational treatment capacity of 45 refrigerators per hour.

Out of all the numbers pulled into view, what stands clear is how shifting the energy mix reshapes profit margins behind the scenes. When scaling up trash handling, money spent upfront has to make peace with ongoing daily and monthly outflows later down the line. Usually, in facilities burning or sorting solids, buying machines and setting them into place eats up most of the starting budget - more than fifty percent lands right there.

Running a costly machine like a high-end thermal oxidizer makes sense only when it runs close to full power, spreading out steady bills such as upkeep, skilled staff pay, and site charges across more output. Since those daily costs stay the same whether the machines run hard or slow, keeping the Leinì plant stuck on one limited flow means the big equipment sits partly idle, pushing up the price for each ton handled. Adding back 1,012,410 kilograms of CFC material once turned away brings in an extra 283,475 euros, all while using the current team size. More throughput lifts the project's internal profit level and ensures future gains outweigh today's spend, showing that upgrading the line technically pays off by pulling more value from waste.

Shifting to a healthier money flow fits naturally with how the circular economy works at its root. Moving away from straight-line methods - grab, make, toss - means making loops where materials keep cycling back, especially inside local trash handling setups; that only sticks if recycling actually pays off. Rules and public programs may force basic eco-behavior, yet industries won't stay engaged unless steady profits back the effort, giving real reason for businesses, nonprofit ventures, and funders to jump in.

Every time the RTO core gets updated to handle new heat-transfer gear, Transistor S.r.l. moves further away from just sorting scraps without purpose. Instead of leaving value behind, it now pulls more worth out of every ton of local e-waste. Efficiency climbs when systems adapt like this, turning what was once seen as trash into usable assets. With stronger returns comes less worry about swings in material availability across markets. Growth no longer has to mean heavier tolls on nature within that area's economy.

Right now, clearing the site's physical limits cuts shipping costs significantly - thanks to smarter local trash pickup routes. How much it costs to handle city and factory garbage depends largely on how routes are mapped, how far trucks drive, and how bins are placed. If a nearby treatment center can't process certain materials, problems ripple outward: haulers make extra runs, spend more hours collecting, burn more fuel, then send those leftover loads far away to outside plants just to get them handled.

Eliminating the forced rejection of the 1,012,410 kilograms of CFC-bearing appliances streamlines this collection infrastructure. It allows regional municipal collection routes to consolidate their drops at a single, centralized ecocentre. This logistical optimization cuts unnecessary vehicle mileage, minimizes long-term truck maintenance, and significantly reduces fuel consumption. This directly lowers greenhouse gas emissions across the transport lifecycle and reinforces the regional optimization bounds of the facility.

6.2 Revenue Scaling and Mathematical Validation

Gross income from state-controlled WEEE systems climbs steadily with each additional kilogram handled, thanks to fixed local gate fees. For every metric ton treated, operators receive exactly 280 euros - no more, no less - a rate set across the region (Cucchiella et al., 2015). Back when only one type of stream was used, running 3,079,818 kilograms of pentane-laced waste through brought in precisely 862,349 euros. That upper limit exists simply because old chlorofluorocarbon materials never made it into current processing runs.

Now comes the part where old waste gets another chance. Thanks to fresh RTO systems paired with chemical scrubbers below, what once got tossed now counts toward usable volume - pushing totals up to 4,092,228 kilograms. That shift alone brings earnings near 1,145,824 €. Hidden inside those numbers sits an extra gain: exactly 283,475 € more profit drawn from identical delivery patterns. Growth shows up not by rushing trucks or cranking machines faster - but simply using every bit that arrives. Speed stays locked, steady as ever, handling 45 fridges each hour without change.

The exact percentage growth in structural treatment revenue (ϕ_{growth}) is mathematically validated using the baseline operating revenue (R_{base}) and the expanded multi-stream operating revenue ($R_{expanded}$) as follows:

$$R_{\text{base}} = 3,079.818 \text{ Mg} \times 280 \text{ €/Mg} = 862,349 \text{ €}$$
$$R_{\text{expanded}} = 4,092.228 \text{ Mg} \times 280 \text{ €/Mg} = 1,145,824 \text{ €}$$
$$\Delta R = R_{\text{expanded}} - R_{\text{base}} = 1,145,824 \text{ €} - 862,349 \text{ €} = 283,475 \text{ €}$$
$$\Phi_{\text{growth}} = \left(\frac{\Delta R}{R_{\text{base}}}\right) \times 100\%$$
$$\Phi_{\text{growth}} = \left(\frac{283,475 \text{ €}}{862,349 \text{ €}}\right) \times 100\% = 32.87\%$$

A rise of 32.87% in vertical capacity shows how removing technical limits at site entrances improves cost performance. Because the mechanical system runs steadily at 45 units hourly, stress on core shredder parts stays low - according to Zhao and team (2016). Pushing speeds beyond that limit creates problems: blade degradation worsens sharply while heat buildup raises chances of accidental combustion inside the reduction zone.

Because processing stays consistent, returns on new equipment rise even as safety remains strong beneath pentane's explosion threshold. Treating more material each hour helps justify the steep price tag of corrosion-proof burner systems, research shows. High hourly throughput softens the financial impact of expensive heat-cleaning technology purchases.

Because industrial setups need balance, fine-tuning how waste is gathered locally helps cities manage costs. A region's ability to process electronic trash rests largely upon where pickup points are placed, their size, and how routes link them together. Erratic flows of old devices arrive when city drop-off sites skip clear sorting rules or suffer poor placement - sparking irregular work rhythms downstream. Processing plants then run in fits and bursts, wasting time and energy each time they halt and restart (Zamorano et al., 2009).

With spatial analysis tools linked to GIS, city waste teams adjust pickup routes more efficiently. Fuel needs drop when travel paths shrink. Container sizes align better with how much trash neighborhoods produce. Because of these changes, the flow of materials into the Leinì facility stays consistent. Sudden spikes or dips in delivery volumes fade out. Emissions tied to hauling decline across each trip's full span. Even under tight environmental rules, recycling gains stay high. Evidence shows such coordination sharpens overall system performance (Zamorano et al., 2009).

6.3 Tabulated Techno-Economic Comparison

The mass throughput balance and financial changes between the current operational baseline and the upgraded system are summarized below:

Table 6.2: Economic Comparison of Upgrading the RTO

Operational Parameter	Current Pentane Baseline	Upgraded Dual-Stream Line	Net Change	Growth Rate (%)
Workable Mass (kg)	3,079,818	4,092,228	+1,012,410	32.87%
Gross Revenue (€)	862,349	1,145,824	+283,475	32.87%
Treatment Capacity	45 fridges / hour	45 fridges / hour	0	0.00%

Source: Author's own elaboration based on audited operational data and financial logs provided by Transistor S.r.l. (2025).

The total fixed capital expenditure (CAPEX) required to execute the dual-stream environmental integration at the Leinì facility amounts to **798,000 €**. To ensure high budgetary transparency, this initial asset outlay is strictly categorized into two primary cost centers. The first and largest component is the direct procurement of the specialized, acid-resistant three-chamber regenerative thermal oxidizer (RTO) machine, which requires a fixed capital outlay of **748,000 €**. The second component involves the execution of necessary ancillary engineering works, including civil retrofitting, gas-tight ductwork integration, and automated system synchronization, which is budgeted at approximately **50,000 €**.

Of course, the numbers in Table 6.2 aren't just placeholders - they sketch out what happens when RTO systems grow. Take the volume stats: they show how bringing back 1,012,410 kilograms of once-discarded coolers pushes usable material up by exactly 32.87 percent. That same rise appears straightaway in local income, dollar for dollar. Such even growth points to one clear outcome - the site earns more yet keeps operations running at the old pace, locked in at handling 45 fridges every hour.

One way to look at it: separating income growth from faster physical processing makes operations run smoother. When industrial shredders push beyond their intended speed limits, they wear down fast - not slowly, but sharply worse over time (Zhao et al., 2016). Instead of cranking up conveyor belts or spinning rotors quicker, which burns more power per ton and dulls tough steel cutters faster, holding steady matters. Running exactly 45 fridges each hour cuts stress on machines. That stability means the extra 283,475 € gained isn't wiped out by surprise repairs or gear breaking too soon.

Despite steady operations, the way costs are spread shifts across the site. Within intricate recycling systems, buying equipment and setting up plants takes most of the upfront money (Deng et al., 2024). Costs like skilled staff wages and office management stay unchanged - no matter if machines run fully or face frequent material rejections. Because the Leinì plant operated under past single-stream limits, its permanent investments - structures, belts, sorting zones - were split over less processed weight (3,079,818 kg). As a result, each metric ton handled carried higher operational expense. Handling all 4,092,228 kilograms received boosts how fully the site operates. Because of this adjustment, equipment delivers stronger financial returns, while overall project worth grows under standard valuation models. Higher internal rates follow - offering justification for recent tech investments cited by Deng and team in 2024, along with earlier support from Zhao's group six years prior.

On a macro-level, this technological update addresses a major bottleneck in regional circular economy performance. Closing industrial material loops requires that waste treatment facilities operate with high material recovery efficiency across all incoming waste fractions, rather than cherry-picking easily treatable sub-streams. Ejecting a quarter of regional temperature-exchange assets due to technical deficiencies breaks the continuity of the recovery chain, forcing a reliance on linear disposal patterns or fragmented third-party shipping loops. Integrating an acid-resistant thermal oxidizer allows Transistor S.r.l. to establish a balanced system where environmental preservation matches corporate economic sustainability (Ghisellini et al., 2016). This configuration provides a resilient industrial blueprint for urban mining operations, proving that proper waste management can achieve high environmental targets while remaining financially independent from external operational subsidies.

6.4 Strategic Funding Justification

Looking into costs and benefits through clear numerical methods like NPV and IRR help determine whether a project makes sense over time. Moving toward reuse-based systems in local e-waste loops often stumbles due to high spending needs for cleaner tech. Equipment such as ceramic-coated thermal burners resistant to acid, paired with liquid-neutralizing filters down the line, demands large early investment outlays. Because these setups require extensive design, purchase, and startup efforts, their price tags stretch beyond typical company return timelines. For mission-driven ventures, this weight falls harder than it does elsewhere. Because margins are narrow, their operations need to manage both recycling efforts and job placement rules for disadvantaged groups. Showing that money is well spent means growth has to produce steady income over time - enough to beat what else could be done with those funds (Ghisellini et al., 2016).

Because of how tightly finances depend on initial spending, even small cost increases during building or buying materials push repayment periods too far out. When infrastructure budgets shift—especially regarding core machinery procurement or site adaptations, the return rate drops sharply under current policy pricing models. For the Leinì facility, this initial fixed capital expenditure (CAPEX) is strictly defined: the direct procurement of the specialized, acid-resistant three-chamber regenerative thermal oxidizer (RTO) machine requires a fixed capital outlay of 748,000 €, while the execution of necessary ancillary engineering works, including civil retrofitting and automated ductwork integration, is budgeted at approximately 50,000 €. Funding from national or supranational sources ends up required under baseline assumptions just to keep projects viable long enough to break even, drawing support from EU mechanisms like the LIFE initiative focused on circular systems and urban well-being. Without outside grants covering major setup expenses, many upgrades fail traditional economic feasibility tests. However, to ensure long-term structural resilience and prove that the social enterprise's business model does not collapse without non-repayable public capital injections, a secondary private financing pathway is fully viable. In the event that public co-funding is unavailable, Transistor S.r.l. can leverage traditional capital markets by securing a long-term credit facility or a specialized green mortgage from a commercial bank. This private financing option structures the total 798,000 € investment over a 10-year amortization schedule at a competitive, low interest rate. Financial sensitivity analyses confirm that the expanded post-upgrade gross revenue comfortably absorbs this annual debt servicing obligation, demonstrating that the project remains fundamentally self-sustaining, bankable, and economically viable even under an exclusive private debt framework.

The granular distribution of the required fixed capital asset investment, alongside the operational parameters of the alternative 10-year private debt financing structure, is systematically detailed in **Table 6.3**. This breakdown illustrates both the immediate allocation of capital and the long-term bankability of the commercial upgrade.

Table 6.3: Fixed Capital Expenditure Breakdown

Investment Component / Debt Metric	Financial Value (€)	Operational Specification / Credit Terms
Primary RTO Equipment Procurement	748,000 €	Direct acquisition of a specialized, acid-resistant three-chamber regenerative thermal oxidizer.
Ancillary Engineering & Civil Works	50,000 €	Structural factory retrofitting, gas-tight ductwork integration, and automated sorting line synchronization.
Total Project Capital Expenditure (CAPEX)	798,000 €	Total fixed capital asset outlay required for full dual-stream site deployment.
Private Loan Amortization Period	10 Years	Structured commercial credit facility / green mortgage from a private credit institution.
Estimated Annual Interest Rate	3.5% – 4.5%	Standard market rate applied to sustainable regional development and social enterprise assets.
Estimated Annual Debt Service	~98,500 € / year	Combined principal and interest obligation over the 120-month maturity window.
Projected Annual Revenue Expansion	+283,475 € / year	Incremental gross income generated by processing the rejected 1,012,410 kg CFC stream.
Net Operational Surplus Ratio	2.87 : 1	Debt Service Coverage Ratio (DSCR) indicating that new revenues cover annual bank payments nearly three times over.

Source: Author's own elaboration based on technical vendor quotes and standard commercial banking credit structures (2026).

Capital grant assistance functions as a non-repayable equity injection, lowering the facility's weighted average cost of capital (WACC) by dampening the risk premiums demanded by traditional banking institutions. By de-risking the industrial upgrade for Transistor S.r.l., these public-private capital arrangements bridge the gap between strict regulatory environmental enforcement and the fiscal constraints of specialized solid waste facilities (Deng et al., 2024; Ghisellini et al., 2016).

This funding synergy supports the socio-economic dual dividend targeted by modern circular infrastructure policies. When public grants cover a portion of the fixed capital expenditure, the facility can avoid passing the cost on through higher municipal treatment gate tariffs, ensuring local waste networks remain stable and cost-effective (Deng et al., 2024). Lower initial private capital exposure also protects the social enterprise's operational cash reserves, enabling it to maintain its core staffing headcounts of disadvantaged personnel without sacrificing financial liquidity. This structural combination turns a capital-intensive regulatory requirement into a resilient economic baseline, confirming that targeted policy instruments and advanced environmental engineering are co-dependent drivers of regional sustainability (Ghisellini et al., 2016).

CHAPTER 7: CONCLUSIONS & STRATEGIC RECOMMENDATIONS

7.1 Synthesis of Technical and Environmental Findings

The engineering, environmental, and economic evaluation conducted throughout this research validates the multi-stream technical expansion of the Sector R1 processing line at Transistor S.r.l. as an effective industrial response to regional waste bottlenecks. Audited operational metrics from the 2025 reference period show that while the facility successfully stabilized 3,079,818 kilograms of pure volatile hydrocarbon appliances, its single-stream design forced the automated rejection of 1,012,410 kilograms of legacy chlorofluorocarbon (CFC) units, resulting in a direct lost revenue opportunity of 283,475 € under the standard 280 €/t regional processing tariff. By implementing the new regenerative thermal oxidizer (RTO) infrastructure, the plant scales its workable capacity to the full incoming volume of 4,092,228 kilograms per year without modifying its baseline line velocity of 45 refrigerators per hour, driving a precise gross treatment revenue expansion of 32.87% to 1,145,824 €.

The technical feasibility of this expansion is deeply bound to the stabilization of the thermodynamic and chemical parameters inside the size-reduction chamber. The processing of heterogeneous electronic waste streams introducing variable gas loads can easily disrupt traditional proportional-integral feedback systems, inducing thermal instability and increasing the risk of explosive atmosphere generation. Incorporating a Linear Model Predictive Control (LMPC) architecture utilizing linear inequality constraints optimizes the plant's operational safety by proactively modifying waste-feeding rates and air dampers before volatile organic compound accumulation crosses critical thresholds. This predictive framework allows the line to run continuously at its design capacity of 45 units per hour, eliminating transient mechanical shocks on actuators and ensuring complete thermal cracking of volatile hydrocarbons at 780 °C without requiring excessive auxiliary natural gas additions (Leskens et al., 2005).

From an environmental standpoint, baseline life cycle assessment (LCA) data confirms that joint multi-stream processing yields a lower environmental load than fragmented disposal models, saving approximately 193,000 tonnes of CO_2equivalent per year (Dehoust and Schüler, 2007). Conversely, diverting unworkable streams to conventional auto shredder facilities causes severe environmental damage, as mechanical shredding open to the atmosphere results in the instantaneous volatilization of up to 70% of micro-encapsulated insulation blowing agents. Because particle size reduction down to small fragments accelerates the long-term diffusional release of trapped gases, executing complete cell destruction under tight containment is a prerequisite to prevent the fugitive release of pollutants into the biosphere (Kjeldsen and Jensen, 2001).

Physical behavior characterization demonstrates that approximately 40% of the trichlorofluoromethane (CCl_3F or R11) load remains chemically dissolved or sorbed within the solid polyurethane struts, while the remaining 60% rests as a free gas within the cell cavities (Kjeldsen and Jensen, 2001). Mechanical grinding down to 2-cm segments shatters the cell boundaries, initiating an immediate desorptive flash followed by long-term Fickian molecular diffusion through the remaining polymer matrix governed by an effective diffusion coefficient ($D_{eff,c}$) spanning $0.5 \times 10^{-14} m^2 s^{-1}$ and $1.7 \times 10^{-14} m^2 s^{-1}$. Closed, gas-tight mechanical handling systems are required to capture these slow, continuous emissions, transforming an acute atmospheric liability into a structured recovery path (Kjeldsen and Jensen, 2001).

Routing the combined streams through advanced joint containment loops satisfies strict photochemical ozone creation potential (POCP) requirements by destroying volatile cyclopentane and isobutane precursors that would otherwise generate severe local ground-level summer smog burdens (Dehoust and Schüler, 2007). Joint processing changes these reactive precursors into a net environmental benefit of 15,032 kg ethylene equivalent per year, whereas un-abated auto-shredding cascades into localized ground-level ozone formation ranging between 3,828 and 38,035 kg ethylene equivalent per year (Dehoust and Schüler, 2007). This transition highlights the multi-variable environmental improvements achieved by integrating specialized chemical scrubbing towers downstream of the primary RTO core. Stoichiometric injection of sodium hydroxide (NaOH) targets the volatile hydrogen chloride (HCl) and hydrogen fluoride (HF) molecules synthesized during the thermal cracking of legacy chlorofluorocarbons, reducing point-source emissions below the active permit cap of 5 $mg/Nm^3$for total particulate matter and 30 mg/Nm^3 for total non-methane organic carbon at stack EM3.

Because it runs in a loop, the system tackles deep-rooted issues blocking reuse of plastics and mixed material wastes. Market studies show second-life raw materials often fail to circulate due to scattered demand, uneven knowledge about specs, and impurities lowering output grade. Instead of clean splits, standard e-waste methods leave behind stubborn bits of polyurethane dust stuck on metal and plastic outputs - this drags down resale worth and blocks premium recycling paths. With precision air sorting added into the sealed grinding stage two process, leftover foam drops under 0.3% for metals, just 0.5% for separated plastics. Purity like that hits exacting industry thresholds, weakening old supply chain roadblocks that held back uptake of recycled consumer inputs - now Transistor S.r.l. functions as a reliable hub meeting tight circular economy benchmarks (Dehoust and Schüler, 2007; Milios et al., 2018).

7.2 Strategic Roadmap for Transistor S.r.l.

To achieve full dual-stream operational status at the Leinì industrial site, a structured engineering and regulatory roadmap must be executed across three sequential phases based directly on verified plant operating parameters.

- **Phase 1: Circuit Depollution Optimization**
  The facility must maintain its high-vacuum piercing clamps equipped with elastomeric hermetic seals and integrated pressure gauges to decontaminate incoming cooling circuits safely. The vacuum extraction loop must continue to separate gaseous refrigerants from compressor lubricating oils under heated vacuum conditions to keep the residual refrigerant concentration embedded within the oil below 0.1% by weight. Achieving this thermodynamic threshold requires precise control over the localized stripping temperature and vacuum depth within the separation vessel. Because volatile refrigerants exhibit a substantially lower boiling point than heavy synthetic compressor lubricants, applying low-temperature thermal energy under a deep vacuum shifts the phase equilibrium, forcing the dissolved gas fraction to rapidly flash out of the liquid phase.

  Vents from the gas compression system must route through parallel activated carbon absorbers operating on an alternating cycle to ensure complete recovery and eliminate process slips. While one carbon column actively intercepts trace gaseous emissions from the compression circuit, the secondary column undergoes automated thermal regeneration. The desorbed refrigerant vapors are siphoned back into high-pressure collection cylinders, ensuring zero-loss containment across the Step 1 depollution grid. This optimization prevents the atmospheric flashing of legacy dichlorodifluoromethane (R12) or modern isobutane (R600a), satisfying initial decontamination thresholds before the appliance chassis enters mechanical size-reduction cells (Dehoust and Schüler, 2007).

- **Phase 2: Sealed Sizing and Process Inertization**
  Mechanical size reduction must take place within an encapsulated shredder operating under an airtight, vacuum-sealed closed environment to manage volatilized insulation gases. The continuous 5,000 m^3/h air collection line must actively draw gases from the loading hopper, downstream extraction screws, air separation lines, and the pelletizing press to prevent fugitive dispersion. Physical characterization studies show that high-velocity milling breaks open the closed cells of the rigid polyurethane matrix, generating an immediate desorptive flash of micro-encapsulated blowing agents (Kjeldsen and Jensen, 2001).

In legacy units, roughly 40% of the trichlorofluoromethane (R11) load is chemically dissolved within the solid polymer struts, leaving 60% suspended as a gas within the cellular voids (Kjeldsen and Jensen, 2001). Mechanical reduction down to 2-cm segments shatters these boundaries, accelerating long-term Fickian molecular diffusion governed by an effective diffusion coefficient ($D_{eff,c}$) spanning $0.5 \times 10^{-14} m^2 s^{-1}$ and $1.7 \times 10^{-14} m^2 s^{-1}$ (Kjeldsen and Jensen, 2001). This continuous outgassing behavior makes complete mechanical encapsulation an absolute necessity.

Process safety must be maintained by an in-house nitrogen generation system constantly injecting 165 m³/h of nitrogen at 97% purity to keep oxygen levels safely below the lower explosive limit (LEL) of the outgassed hydrocarbon isomers.Should vapor levels hit 25% of the LEL, the automatic safety circuits will lock out the loading conveyors, stopping fresh appliances from entering - yet airflow extraction continues without delay. At 40%, a hardwired signal cuts power to the grinding rotor instantly, removing any chance of heat-triggered sparks; meanwhile, sensor arrays monitor continuously, prepared to release pressurized water into the discharge chute should flames appear. Detection relies on both spark scanners and visual flame units, each operating in parallel.

Strict physical barriers keep volatile cyclopentane or pentane mixtures securely separated. At the same time, precise mechanical isolation stops polyurethane particles from attaching to reclaimed substances, limiting contamination to less than 0.3% by mass in iron portions and under 0.5% in purified plastics (Dehoust and Schüler, 2007). Through this cleaning stage, obstacles across supply networks are reduced, producing refined recycled inputs that overcome gaps in market knowledge while meeting demanding industry benchmarks (Milios et al., 2018).

- **Phase 3: Thermal Loop Integration and Permitting**
  Despite its high capacity, the 5,000 m³/h extraction system feeds straight into a three-chamber regenerative thermal oxidizer designed for sustained operation at 780 °C. Should fluorinated compounds appear during transitions between production batches, an inline CFC sensor triggers immediate shutdown of material handling conveyors - this prevents exposure. When older types of chlorofluorocarbons break down within furnaces built for hydrocarbons, they form aggressive acids: hydrogen fluoride and hydrogen chloride. These gases eat through ceramic heat exchange modules and corrode metal flues fast. Evidence shows such reactions severely degrade infrastructure over time (Dehoust and Schüler, 2007; Wuebbles and Calm, 1997).

  Although the combustor runs on its own when organic gas levels rise past 1.5 g/Nm³, it still needs careful balancing to cut down extra natural gas use by tapping into the heat from released vapors. Instead of standard response systems, sudden shifts in fuel demand call for Linear Model Predictive Control setups that adapt ahead of time. While adjusting waste input and airflow together across a set forecast window, the LMPC structure smooths out burn spikes effectively. Because emissions must stay under tight thresholds - no more than 100 mg/Nm³ of CO and only up to 30 mg/Nm³ of C.O.T.N.M. -

the method keeps exhaust outputs within legal bounds, as shown earlier (Leskens et al., 2005).

One way to meet environmental rules involves sending updated technical files to renew the current AIA license, which permits extended handling and retention of dangerous fluorine-based materials. Sending untreated streams directly into regular car crushers - instead of using dedicated multi-stage degas systems - leads to immediate release of nearly three-fifths of trapped gases, sharply increasing local climate-warming pollutants. To cross the required legal line, facilities can install a wet scrubber after combustion, where a caustic soda circulation process ensures at least nine-tenths of harmful emissions are captured and broken down (Dehoust and Schüler, 2007).

With this unified improvement, regional delays in handling drop off entirely - enabling throughput to rise from 3,079,818 kg annually up to the total incoming load of 4,092,228 kg. Because every bit now gets processed, income climbs by 283,475 €, even though speed stays fixed at 45 fridges each hour. Performance shows tighter ecological standards go together with lasting financial balance in reuse-based systems (Dehoust and Schüler, 2007; Ghisellini et al., 2016).

7.3 Project Implementation Risks and Technical Alternatives

Changing how the Leinì site operates by adding two parallel processing lines reshapes the kinds of dangers present. Because of this engineering change, current rules around quality, health, safety, and environmental protection must be re-examined closely. At the core of concern lies the breakdown of old volatile fluorinated compounds under intense heat - specifically within a 780 °C combustion zone. When substances like trichlorofluoromethane break apart at such temperatures, their strong carbon-halogen links split violently, producing dangerous fumes: hydrogen fluoride and hydrogen chloride (Wuebbles and Calm, 1997). Such acidic gases eat away metal parts and ceramic structures used in heat recycling, especially where hot exhaust passes through - greatly reducing durability over time (Leskens et al., 2005). Should flue gas temperatures approach the acid dew point inside exhaust passages, pockets of vapor may condense into strong acidic liquids. As a result, carbon steel components like ducts and stack linings begin suffering fast surface degradation and material loss. These changes often appear first where moisture gathers most easily.

To reduce this type of wear, engineers must carefully choose one of two distinct cleanup methods located after the main process (Kjeldsen and Jensen, 2001; Wuebbles and Calm, 1997). Following combustion, a wet scrubber can be added beyond the thermal oxidizer as the initial option. Inside this unit, an upward flow of gas meets a downward mist of sodium hydroxide ($NaOH$), arranged in a packed column setup. As the caustic fluid captures airborne halogen compounds, they transform into soluble salts - sodium chloride ($NaCl$) and sodium fluoride (NaF)

- routed later to wastewater streams. Though effective at treating acid gases, it shifts the problem toward managing ongoing reagent supply and water quality oversight instead.

Instead of traditional methods, a highly efficient cryogenic condensation loop operates before the combustion stage. By positioning it ahead of thermal treatment, formation of acid gases does not occur at all. Liquid nitrogen, or multi-stage mechanical cooling, chills the gas flow to less than -60°C. As temperatures drop, CFCs shift from vapor to liquid within the nitrogen stream. Once condensed, these substances separate into sealed containers designed for high-pressure transport. Disposal happens later, handled externally by certified facilities. Unlike wet scrubbers, this method sidesteps equipment corrosion and eliminates wastewater handling demands. However, power consumption rises sharply - driving up daily operational costs across the facility.

Keeping control over these technical processes means enforcing rigid pollution thresholds at the main outlet known as chimney EM3. Real-time tracking of emissions happens through the facility's automatic monitoring setup, called CEMS. Particulates - labeled Polveri totali - must stay under 5 mg/Nm^3 without exception while CO levels must be maintained lower than 100 mg/Nm^3.Meanwhile, non-methane organic carbon (C.O.T.N.M.) faces a hard cap at 30 mg/Nm^3. Holding such narrow limits becomes tough due to unpredictable waste inputs. For instance, sharp releases of uncollected cyclopentane or isobutane from shredding operations may trigger abrupt heat changes. These shifts often drain oxygen inside the combustion chamber. As a result, carbon monoxide might spike without warning. Ahead of time, a predictive control system forecasts how combustion will behave within set limits, tackling issues early on (Leskens et al., 2005). Instead of reacting, it balances several process factors at once - tweaking airflow and fuel delivery through continuous calculations to avoid emissions breaches down the line.

Though modest in profit, Transistor S.r.l. faces distinct upfront financial commitments when upgrading its environmental emissions containment infrastructure. The total fixed capital expenditure (CAPEX) required for full dual-stream site deployment is strictly quantified at 798,000 €, split between the direct procurement of the specialized, acid-resistant three-chamber regenerative thermal oxidizer machine (748,000 €) and necessary ancillary engineering and civil works (50,000 €). Under baseline assumptions, relying exclusively on short-term high-interest financing vehicles can strain localized operational cash flows, particularly within a social enterprise whose financial planning must continuously balance environmental performance with stable job placement rules for disadvantaged groups.

Consequently, while securing non-repayable public capital support through mechanisms such as the European Union's LIFE Programme represents an optimal financial pathway to maximize net present value, it is not a structural single point of failure for the project (Deng et al., 2024; Ghisellini et al., 2016). To ensure long-term business resilience, a secondary private debt scenario is established to validate market feasibility. Financial sensitivity models confirm that Transistor S.r.l. can fully sustain a 10-year commercial bank loan or a low-interest green mortgage from a private credit institution to finance the 798,000 € investment. Driven by the expanded post-upgrade gross revenue framework (reaching 1,145,824 €), the incremental cash flows comfortably absorb the annual debt servicing obligations, demonstrating that the project remains fundamentally self-sustaining, bankable, and commercially viable even in the absence of public grant injections (Deng et al., 2024).

7.4 Policy Implications and Future Research Directions

The operational and structural scaling of Transistor S.r.l. offers a paradigm-shifting model for addressing deep-rooted systemic inefficiencies within the European e-waste framework without compromising socio-economic equity. Rather than decoupling financial viability from social purposes, the enterprise's integrated operational strategy demonstrates that advanced environmental engineering infrastructure can seamlessly absorb an inclusive workforce, with approximately 30% of its site personnel integrated through social cooperative pathways for disadvantaged individuals. Operational efficiency is not compromised by this socio-technical configuration; instead, systemic productivity improves concurrently with heightened social impact. While specialized automation systems execute high-precision mechanical sorting, the structured labor framework provides long-term vocational stability, defying traditional manufacturing paradigms regarding the rigid division of labor within modern automated recycling facilities.

Sorting tasks demanding significant human effort leave overall system efficiency unaffected. Rather than slowing things down, such hands-on checks serve as precise filters - boosting later machine operations by weeding out unwanted elements before automation begins. Seen through a governance lens, the initiative highlights why rigid adherence to CENELEC EN 50625 and WEEELABEX rules must become law everywhere, blocking inferior recycling paths while curbing unlawful cross-border flows of intricate e-waste. When participation stays optional, bargain processors thrive unchecked, passing ecological costs onto communities via escaped halogens and lost raw inputs. Requiring these exacting benchmarks for licensing sets an even playing field, shutting out poor performers so recoverable matter reaches only fully circular recovery networks (Ghisellini et al., 2016).

Even so, getting usable solids out further down the line - especially used plastics sorted mechanically at stage R1 - is held back sharply by a splintered recycling marketplace. Across both Nordic and southern European areas, discarded plastic often goes unused since shifting resin quality and cheap crude rates undermine the cost edge of reprocessed pellets versus new ones (Milios et al., 2018). At play here is an unstable pricing rhythm tied to oil markets. Each time raw petroleum slips lower, production expenses for fresh polymers shrink fast, which makes complex cleaning and separation steps needed for reclaimed plastic too costly unless policies step in.

Because of uneven access to technical knowledge along the supply line, financial strain grows worse. Uncertainty about consistent material performance - like how well recycled plastic stretches, resists heat, or keeps color - troubles processors and makers when tiny pollutants remain, including leftover foam particles or old fire-resistant chemicals. Market obstacles like these call for stronger alignment across sectors - not just hopeful strategies but enforced rules.

Government buying policies need hard targets: minimum percentages of reused plastics in roads, bridges, or buildings help anchor long-term investment. When laws block burning of reusable waste, and require reuse through mandates, demand stabilizes. Without such steps, recycling ventures stay vulnerable when oil prices drop and virgin resin floods back into production channels.

Future research directions should focus on expanding digital network interactions and data-driven material tracking systems, including the exploration of machine learning applications for real-time sorting optimization. Concurrently, a critical path forward begins with rethinking how polymers are structurally combined during primary device assembly. Instead of mixing several kinds - like ABS, PC, and HIPS - products could rely on just one base material per component. When layers differ chemically, machines struggle to pull them apart later. Hidden within many such blends are brominated flame retardants, substances too hazardous for typical recycling setups. Because of health rules, these additives block reuse paths entirely. Safety concerns aside, sorting becomes slower, less accurate, when polymers aren't uniform. A smarter route involves setting clear design limits early in development. Fewer chemicals allowed means fewer conflicts down the line. Uniform materials open doors to cleaner recovery cycles. Devices built with separation in mind reduce pollution risks at dismantling sites. Complete isolation of plastic streams is possible - if planning starts before production. Milios and colleagues showed similar thinking works in practice by 2018.

Because feed conditions shift so dramatically, control strategies need deeper adaptation in unstable combustion environments. When mechanical foam breaks down unevenly, trapped blowing agents escape rapidly - spiking temperature behavior beyond standard response ranges. Though LMPC systems manage steady shifts well, they struggle when sudden chemical flashes disrupt equilibrium states. Instead of relying on fixed models, next-phase solutions might use NMPC designs or self-adjusting estimators combined with responsive optimization routines. By refining prediction accuracy for heat output from erratic cyclopentane-refrigerant blends, these tools could balance multiple operational limits before critical thresholds activate shutdown protocols or flood cooling mechanisms (Leskens et al., 2005).

Low-temperature photo-driven methods could help scale up ways to trap and reuse carbon emissions from industrial sources. Instead of releasing carbon dioxide after burning off harmful vapors at 780 °C in thermal units, that exhaust might become raw material for useful chemicals. Materials like silver-laced titania - crafted using reversed soap-based templates through wet chemistry routes - offer one path forward. When lit locally, such modified surfaces ease the energy barrier for turning CO2 and water into dense fuels including methane or methanol. Small shifts in silver levels or crystal setup may reshape how charges separate and recombine during reaction cycles - a factor demanding closer study. Alongside materials work, smarter flow reactor designs are needed so systems match real-world e-waste treatment speeds and loads (Kamal et al., 2016; Kočí et al., 2010).

REFERENCES

- Arcobaleno Social Cooperative. (2025). *Arcobaleno & Transistor*. Corporate presentation documentation.
- Dehoust, G. and Schüler, D. (2007). *Life cycle assessment of the treatment and recycling of refrigeration equipment containing CFCs and hydrocarbons*. Öko-Institut e.V. Final Report.
- Deng, X., Xie, C., Zhang, J., Wang, Y., Zheng, L., Ding, X., and Wu, L. (2024). Techno-economic analysis of municipal solid waste treatment for poly-generation system. *Science of the Total Environment*, 912, 168869.
- Gareau, B. J. (2010). A critical review of the successful CFC phase-out versus the delayed methyl bromide phase-out in the Montreal Protocol. *International Environmental Agreements: Politics, Law and Economics*, 10(3), 209–231.
- Ghisellini, P., Cialani, C., and Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, 114, 11–32.
- Kamal, M. S., Razzak, S. A., and Hossain, M. M. (2016). Catalytic oxidation of volatile organic compounds (VOCs) – A review. *Atmospheric Environment*, 140, 117–134.
- Khan, F. I. and Ghoshal, A. K. (2000). Removal of Volatile Organic Compounds from polluted air. *Journal of Loss Prevention in the Process Industries*, 13(6), 527–545.
- Kjeldsen, P. and Jensen, M. H. (2001). Release of CFC-11 from disposal of polyurethane foam waste. *Environmental Science & Technology*, 35(14), 3055–3063.
- Kočí, K., Matějů, K., Obalová, L., Krejčíková, S., Lacný, Z., Plachá, D., Čapek, L., Hospodková, A., and Šolcová, O. (2010). Effect of silver doping on the TiO_2 for photocatalytic reduction of CO_2. *Applied Catalysis B: Environmental*, 96(3-4), 239–244.
- Larsen, L. (2004). Methods of multidisciplinary in-depth analyses of road traffic accidents. *Journal of Hazardous Materials*, 111(1-3), 115–122.
- Leskens, M., van Kessel, L. B. M., and Bosgra, O. H. (2005). Model predictive control as a tool for improving the process operation of MSW combustion plants. *Waste Management*, 25(8), 788–798.
- Milios, L., Christensen, L. H., McKinnon, D., Christensen, C., Rasch, M. K., and Eriksen, M. H. (2018). Plastic recycling in the Nordics: A value chain market analysis. *Waste Management*, 76, 180–189.
- Pecchi, G., Reyes, P., Gómez, R., López, T., and Fierro, J. L. G. (1998). Methane combustion on Rh/ZrO_2 catalysts. *Applied Catalysis B: Environmental*, 17(1-2), L7–L13.
- Transistor S.r.l. (2025a). *Presentazione TRANS Inglese R01*. Factory technical presentation registry.

- Transistor S.r.l. (2025b). *R1 Treatment Plant Transistor*. Process engineering operations documentation.
- Vehlow, J. and Gloël, J. (2020). *Thermal destruction of (hydro) chlorofluorocarbons and hydrofluorocarbons*. GIZ Proklima, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.
- Wuebbles, D. J. and Calm, J. M. (1997). An environmental rationale for retention of endangered chemicals. *Science*, 278(5340), 1090–1091.
- Zamorano, M., Molero, E., Grindlay, A., Rodríguez, M. L., Hurtado, A., and Calvo, F. J. (2009). A planning scenario for the application of geographical information systems in municipal waste collection: A case of Churriana de la Vega (Granada, Spain). *Resources, Conservation and Recycling*, 54(2), 123–133.