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Circular Recovery of Retired Electronics: A Critical Review and Environmental Scenario Modeling of the S25 Framework

Arushi Guleria[1], Ravinder Guleria[2]
[1]Department of Mathematics and Computing, National Institute of Technology Hamirpur, Himachal Pradesh, India
[2] Department of Physics, SCVB Government College Palampur, Himachal Pradesh, India

Abstract: Electronic waste (e-waste) presents a triple systemic threat: severe environmental contamination, critical-material demand, and premature loss of potentially useful electronic equipment [1], [2]. In 2022, global e-waste generation reached 62 million tonnes, while only 22.3% was formally documented as collected and recycled [1]. A substantial proportion of retired electronic equipment may retain whole-device, module-level, or component-level value beyond administrative retirement, creating opportunities for reuse, repair, refurbishment, and controlled component recovery [7], [8], [11], [12]. In developing economies such as India, historical studies indicate that a substantial proportion of e-waste has been handled through informal channels, although estimates vary according to period and analytical boundary [31]. Inadequate collection and storage conditions can further reduce the fraction of equipment suitable for preparation for reuse [16]. Evidence from an empirical study of 61 collection points in Bavaria further indicates that collection conditions can affect the preservation of reuse potential: 86% of identifiable damage causes of WEEE in that investigated system were attributed to insufficient weatherproof roofing [16]. International evidence also demonstrates measurable functional potential in used equipment; approximately 81% of tested used electrical and electronic equipment entering Lagos was found to be functional [24], while a Delphi-based expert assessment estimated that 63% of imported UEEE was functioning and reused, refurbished, or resold [5]. These figures describe different populations and methodologies and are therefore used only as contextual evidence rather than as universal recovery rates.

This paper proposes the S25 scenario as a bounded analytical framework in which 25% of technically eligible retired computing-equipment intake is assumed to achieve successful secondary use through qualified whole-device reuse or refurbishment, qualified module reuse, or qualified component reuse. S25 is therefore a study-specific scenario target and is not presented as an empirically established universal recovery rate or as a 25% whole-device reuse rate. The framework integrates environmental impact, component viability, reliability screening, institutional deployment, economic feasibility, behavioural participation, worker safeguards, and policy requirements. Life-cycle accounting principles are used to distinguish published environmental evidence from scenario assumptions and derived outputs [19]. For environmental quantification, the combined S25 recovery fraction is not treated as equivalent to whole-device displacement; instead, whole-device climate benefit is calculated from the Path-A fraction (P_A), the whole-device displacement factor (d_A), and the product-specific climate-impact reduction (I_A). A separate normalized laptop illustration assumes 25% whole-device reuse with one-for-one functional displacement. Using the approximately 40% climate-change reduction reported for the assessed second-hand laptop case by André et al. [21], this hypothetical whole-device case gives an illustrative portfolio-level reduction of approximately 10%. This 10% value is a scenario illustration rather than the environmental outcome of the combined S25 framework. The proposed framework therefore provides a basis for field validation of whether protected collection, qualification, reuse, and component recovery can preserve functional value while reducing dependence on destructive end-of-life processing and supporting affordable secondary computing applications.

Keywords: electronic waste, circular recovery, component recovery, life-cycle assessment, second-life computing.

I. INTRODUCTION AND PROBLEM STATEMENT

Electronic waste (e-waste) presents an escalating global environmental and public-health challenge driven by increasing generation, inadequate collection, environmentally unsound processing, and premature loss of product and component value [1], [2], [15]. The Global E-waste Monitor reports that 62 million tonnes of e-waste were generated in 2022, with only 22.3% formally documented as collected and recycled [1].

This formal recycling indicator does not capture all flows of used electrical and electronic equipment and e-waste. Global monitoring also identifies substantial transboundary movement of used equipment and e-waste, including flows through uncontrolled channels into middle- and low-income regions [1], [28].

In developing nations such as India, historical studies indicate that a substantial proportion of e-waste has been handled through informal channels, although estimates vary according to the period, geographical boundary, and analytical method [29], [31]. Informal processing may involve manual dismantling, open burning, uncontrolled thermal treatment, acid leaching, and open dumping, creating exposure pathways for workers, communities, and the surrounding environment [2], [3]. Such practices can also favour rudimentary material-recovery routes and may reduce opportunities for controlled assessment of equipment and components for reuse or refurbishment [29]. Improving the conditions under which retired equipment is collected, stored, assessed, and routed is therefore important not only for pollution control but also for preserving equipment that may remain suitable for preparation for reuse [16]. The condition of equipment before technical assessment is therefore an important part of the reuse pathway. Messmann et al. [16] found that 86% of identifiable damage causes of WEEE in the investigated Bavarian collection-point system were associated with insufficient weatherproof roofing. This finding is specific to the investigated system and does not imply that 86% of all WEEE damage is weather-related; rather, it provides evidence that avoidable deterioration during collection and storage can affect the pool of equipment available for preparation for reuse.

Electronic devices are frequently retired for administrative, economic, technological, or procurement reasons before all of their potential functional value has been exhausted [6], [7]. This creates a distinction between the end of a device's first ownership or service cycle and the end of the useful life of its components. A retired computer, for example, may remain suitable for secondary deployment after appropriate diagnostic assessment, while equipment that is unsuitable for whole-device reuse may still contain recoverable modules or individual components [7], [8], [11], [12]. International functionality studies provide further evidence that technical retirement does not necessarily correspond to complete loss of functional value. Physical inspection of used electrical and electronic equipment entering Lagos found approximately 81% of tested equipment to be functional [24]. A separate Delphi-based study reported an expert guesstimate that 63% of imported UEEE was functioning and directed toward reuse, refurbishment, or resale [5]. These values should not be transferred directly to India or treated as recovery coefficients because they were obtained from different populations and through different assessment methods. The appropriate circular strategy is therefore not to assume that all discarded equipment should be reused, but to establish a qualification process that identifies technically, economically, and operationally suitable assets before material recovery is undertaken.

This distinction is particularly important for printed circuit boards (PCBs), which contain both valuable materials and complex assemblies of potentially reusable components [11], [12]. Controlled component recovery can provide an alternative pathway for selected boards that are unsuitable for whole-device deployment. However, component-level recovery requires appropriate disassembly, testing, traceability, reliability assessment, and end-use qualification rather than simple physical extraction [17], [18], [25].

The environmental rationale for retaining functional value is complementary to conventional recycling. Material recovery remains necessary for exhausted, damaged, contaminated, or otherwise non-reusable equipment [1], [11]. However, when a product, module, or component can safely perform a useful secondary function, avoiding the manufacture of an equivalent new item may preserve a greater proportion of the original manufacturing investment than immediately reducing the equipment to constituent materials [7], [8], [13].

Affordable second-life computing may also contribute to digital inclusion where the required workloads can be met by appropriately qualified equipment. Second-life systems can potentially support educational, public-administration, community-access, and other institutional applications when hardware capability, software support, security, maintenance, and reliability are adequately assessed [22].

A. Research Proposition and Analytical Approach

The central research question is whether a bounded proportion of technically eligible retired computing equipment can be routed through whole-device reuse, refurbishment, and verified component recovery in a manner that simultaneously preserves functional value, reduces dependence on destructive end-of-life processing, and supports affordable institutional computing [7], [13].

The study defines an evaluation band of 15%-25% for technically eligible intake, with the upper case designated as the S25 scenario. Across this paper, S25 is established strictly as a bounded analytical evaluation scenario and modeling framework, not as an empirically established universal recovery rate. It does not represent 25% of all global e-waste, all discarded PCBs, or all retired electronics.

Rather, S25 represents a scenario assumption in which 25% of a defined pool of technically eligible retired computing-equipment intake achieves a verified secondary-use outcome through a combination of whole-device reuse or refurbishment, qualified module reuse, and qualified component reuse. These pathways are combined within the same S25 numerator and expressed against the common denominator of technically eligible intake; therefore, S25 is a combined secondary-use recovery target across mutually assigned pathways rather than a 25% whole-device reuse rate. The target does not imply equivalence of functional value between whole-device, module, and component outcomes. The S25 pathway therefore begins before technical qualification: preserving the condition of eligible equipment during collection and storage may influence whether it remains suitable for subsequent testing and reuse [16]. The effect of such preservation measures is treated as an intervention to be evaluated empirically, rather than as a predetermined increase in the S25 recovery fraction.

The analysis distinguishes four circular pathways:

1) *Whole-device reuse or refurbishment (Path A):* the complete device is qualified and redeployed where technically and operationally appropriate.
2) *Module reuse (Path B):* equipment unsuitable for whole-device reuse but containing potentially reusable modules is selectively disassembled, and qualified modules are redeployed where technically appropriate.
3) *Component harvesting/recovery (Path C)*: equipment unsuitable for whole-device or module reuse may be selectively disassembled, and individual components are tested and qualified for secondary applications.
4) *Material recovery (Path D):* non-reusable residuals are transferred to authorized recycling processes.

Whole-device reuse is prioritized where the complete asset can satisfy the required workload, software-security, electrical-safety, and reliability conditions. Component recovery is considered when whole-device reuse is not technically or economically justified. Material recycling remains necessary for non-recoverable residuals [1], [7], [8], [11].

The environmental analysis uses published life-cycle evidence to estimate avoided manufacturing impacts where secondary use displaces production of an equivalent new product [13], [27]. The S25 results are then presented separately as illustrative scenario outputs. Where a published per-unit environmental benefit is scaled to the S25 case, the calculation assumes one-for-one functional displacement and is explicitly identified as a modelling assumption rather than an empirical universal constant. The scenario is evaluated across environmental impact, material demand, technical qualification, reliability, institutional deployment, economic feasibility, behavioural participation, implementation requirements, and end-of-second-life recovery. This structure allows the proposed S25 framework to be assessed as an integrated circular-recovery pathway rather than as a simple PCB-recycling rate.

B. Literature and Evidence Selection

This article follows a critical evidence-synthesis approach rather than a formal systematic-review protocol. Evidence was selected to address five linked dimensions of circular electronics recovery: (i) global e-waste generation, flows, and hazards; (ii) product life extension, preparation for reuse, and component recovery; (iii) environmental consequences and life-cycle impacts; (iv) reliability, qualification, and data-security requirements; and (v) economic, behavioural, infrastructure, and policy conditions for implementation. Peer-reviewed studies were prioritized for empirical, technical, behavioural, and environmental claims, while international organizations, government agencies, and technical standards were used where they provide authoritative monitoring data, regulatory requirements, or technical frameworks [1], [17], [19], [20].

The evidence base is interpreted according to the strength and function of the underlying source. Accordingly, the international functionality estimates used in this study are interpreted according to their underlying methodology. The approximately 81% figure reported by Odeyingbo et al. [24] is based on physical inspection of tested UEEE, whereas the 63% estimate reported by Thapa et al. [5] is an expert guesstimate derived through a Delphi process. The 86% value reported by Messmann et al. [16] refers specifically to identifiable WEEE damage causes associated with insufficient weatherproof roofing. These measures describe different stages or dimensions of the recovery pathway and are not combined into a single recovery rate. Published experimental, field, and life-cycle results are treated as empirical evidence; standards and institutional reports are treated as technical or policy evidence; and values introduced specifically for S25, including the recovery fraction, displacement factor, incentive assumptions, and selected economic parameters, are treated as scenario assumptions. Derived S25 environmental and economic values are therefore presented separately from published measurements and are not interpreted as universal empirical recovery rates.

Life-cycle interpretation follows the principles and framework of ISO 14040 [19]. Where published per-unit environmental evidence is applied to the S25 scenario, the mathematical scaling is shown explicitly, allowing the reader to distinguish the source evidence from the assumptions and calculations introduced by the present study.

II. ENVIRONMENTAL HAZARDS AND QUANTITATIVE POLLUTION MITIGATION

A. *Informal Processing, Transboundary Risk, and Exposure Pathways*

Informal e-waste processing can create hazardous exposures across multiple stages of material recovery. Open burning of wires and plastics can release hazardous combustion products; uncontrolled thermal treatment can expose workers to metal-containing emissions; acid leaching can generate corrosive and metal-containing effluents and hazardous fumes; mechanical processing can generate contaminated dust; and uncontrolled dumping can contribute to soil and water contamination [2], [3]. Printed circuit board (PCB) assemblies are an important intervention point because they combine valuable metals with complex electronic assemblies and hazardous substances [3], [11].

Electronic devices are frequently retired before the end of their technically useful life, leaving residual potential for reuse, repair, or component recovery [6]-[8]. A verified reuse-first gate can therefore divert technically eligible equipment from immediate destructive processing. Where whole-device reuse is technically and functionally feasible, the original product can retain a greater proportion of its embodied manufacturing value and may avoid some impacts associated with production of an equivalent new device [7], [8], [21]. Where whole-device reuse is not feasible, selected modules and components may be recovered subject to diagnostic, reliability, and compatibility requirements [17], [18], [25]. Non-reusable residuals remain subject to appropriate end-of-life recycling or disposal pathways [1], [11].

B. *Environmental Mitigation Pathways and the S25 Scenario*

Life-cycle evidence indicates that extending the useful life of electronic equipment can reduce environmental burdens because production of electronic products contains substantial material and manufacturing impacts [7], [8], [27], [21]. However, the magnitude of the benefit depends on product type, remaining useful life, refurbishment requirements, functional equivalence, displacement of new-device demand, transport, and the subsequent end-of-life pathway [19], [21]. The preservation of equipment before qualification is also an environmental intervention because deterioration during collection can shift potentially reusable equipment toward repair, component recovery, or material treatment. The Bavaria evidence indicates that collection and storage conditions can influence this pathway, although the magnitude of the effect must be determined for each operating context [16].

Table I therefore distinguishes between published evidence, qualitative mitigation pathways, and S25 scenario outputs. Numerical S25 reductions are reported only where a directly relevant per-unit environmental factor is available. The absence of a numerical value for an impact category does not imply an absence of environmental benefit; it indicates that a defensible percentage cannot be calculated from the evidence and assumptions used in the present scenario.

TABLE I
ENVIRONMENTAL MITIGATION PATHWAYS AND TREATMENT OF THE S25 SCENARIO

Impact vector	Principal pressure addressed	Evidence for reuse/recovery	Treatment in S25
Primary material extraction and resource depletion	Demand for virgin metals and other primary materials associated with production of new electronic equipment	Product life extension can reduce the need for production of replacement equipment, while reuse and controlled recycling can retain material value [7], [8], [21]	Qualitative in the present S25 model. No independent percentage reduction is assigned without a product-specific material inventory and displacement model.
Soil toxicity and heavy-metal contamination	Uncontrolled dumping, dismantling, and other environmentally unsound treatment pathways	Informal e-waste handling can expose soils and surrounding environments to hazardous substances [2], [3]. Reuse-first routing can divert eligible equipment from immediate destructive processing [1], [2], [11]	Qualitative in the present S25 model. No numerical percentage is assigned because the fraction of avoided uncontrolled processing is not independently quantified.

Impact vector	Principal pressure addressed	Evidence for reuse/recovery	Treatment in S25
Water and effluent contamination	Acid leaching, contaminated runoff, and uncontrolled treatment residues	Informal processing can generate contaminated effluents and contribute to environmental releases [2], [3], [11]	Qualitative in the present S25 model. No numerical percentage is assigned without a defined avoided-processing inventory and fate model.
Air pollution and greenhouse-gas emissions	Emissions from uncontrolled processing and environmental burdens associated with manufacture of replacement equipment	ICT manufacturing has substantial embodied GHG impacts [27]. A commercial second-hand laptop LCA reported approximately 39-50% lower environmental impacts across assessed categories, with approximately 40% reduction for climate change in the baseline comparison [21]	Applies only to qualified whole-device reuse/refurbishment (Path A); the climate benefit depends on qualified whole-device displacement and the product-specific displacement factor. The combined S25 target also includes module and component recovery and therefore is not equivalent to 25% whole-device displacement. The separate laptop illustration in Section II-D is hypothetical and does not represent the combined S25 environmental outcome.

The S25 scenario therefore does not assume that 25% reuse automatically produces a 25% reduction in every environmental impact category. The environmental effect depends on the impact avoided per reused unit and on whether the reused equipment actually displaces production of an equivalent new product [19], [21].

C. Establishing the 15-25% Evaluation Band and the S25 Scenario

Published preparation-for-reuse evidence provides a basis for evaluating the feasibility of a bounded reuse scenario, but it does not establish a universal recovery rate for all electronic equipment. This emphasis on preparation for reuse is also consistent with European waste-prevention policy, where reuse and preparation-for-reuse are recognized as important elements of waste-prevention and circular-economy strategies [9]. Messmann et al. [16], based on assessments at 61 collection points in Bavaria, reported approximately 13-16% immediate preparation-for-reuse potential across the assessed waste streams, with an additional 13-29% potential depending on waste type and improvements in collection, storage, and treatment conditions. These findings demonstrate that a measurable fraction of collected WEEE can be suitable for preparation for reuse, while also showing that the attainable rate is sensitive to handling and system conditions. The same study provides a further rationale for treating collection and storage as part of the recovery system. Messmann et al. [16] found that 86% of identifiable damage causes of WEEE at the investigated collection points were attributed to insufficient weatherproof roofing. This result supports the proposition that preservation of equipment condition can be an upstream determinant of preparation-for-reuse potential. However, the 86% value is not used as a recovery multiplier in the present study and is not interpreted as a universal proportion of WEEE damage.

On this basis, the present study uses 15-25% as an analytical evaluation band for technically eligible intake, with the upper value defining the principal S25 scenario. The 15-25% range is therefore a scenario assumption informed by published preparation-for-reuse evidence, rather than a universal empirical recovery rate. The scenario concerns only the defined pool that has passed the initial eligibility boundary. For clarity, the S25 recovery fraction represents the combined proportion of technically eligible intake that achieves a verified secondary-use outcome through whole-device reuse/refurbishment, qualified module reuse, or qualified component reuse. These recovery pathways are evaluated against the same denominator of technically eligible retired computing-equipment intake. Accordingly, S25 is defined as:

$$S_{25} = \frac{N_{WD/R} + N_{MR} + N_{CR}}{N_{eligible}} = 0.25$$

where $N_{WD/R}$represents eligible source units achieving whole-device reuse, with refurbishment where required; N_{MR}represents eligible source units achieving qualified module reuse; N_{CR}represents eligible source units achieving qualified component reuse; and $N_{eligible}$represents the total technically eligible retired computing-equipment intake.

S25 accounting is defined as:

$$S_{25} = P_A + P_B + P_C = 0.25$$

where , , and represent the respective fractions of technically eligible intake achieving whole-device reuse or refurbishment, module reuse, and component reuse. For S25 accounting, each eligible source unit is assigned to only one primary successful secondary-use pathway to avoid double counting. A source unit is counted as a successful Path-C outcome only when recovered components pass qualification and achieve verified secondary use; simple physical removal or recovery for scrap does not count toward the S25 numerator.

Further international evidence indicates that a measurable proportion of used equipment may remain functional at the point of assessment. Odeyingbo et al. [24] reported approximately 81% functionality among tested UEEE entering Lagos, based on physical inspection, while Thapa et al. [5] reported a 63% functioning estimate based on expert Delphi assessment. The difference between these values illustrates the influence of population definition and assessment methodology rather than establishing a single universal recovery rate. Neither value is used as the S25 recovery fraction.

The pathway hierarchy is also maintained explicitly:

1) *Whole-device reuse or refurbishment (Path A)*: the complete device is qualified and redeployed where technically and operationally appropriate.
2) *Module reuse (Path B)*: equipment unsuitable for whole-device reuse but containing potentially reusable modules is selectively disassembled, and qualified modules are redeployed where technically appropriate.
3) *Component harvesting/recovery (Path C)*: equipment unsuitable for whole-device or module reuse may be selectively disassembled, and individual components are tested and qualified for secondary applications.
4) *Material recovery (Path D):* non-reusable residuals are transferred to authorized recycling processes.

These international findings therefore support the feasibility question underlying S25 but do not resolve it for India. An India-specific end-to-end study should measure the pathway from collection and functionality testing through refurbishment, verified second-life deployment, component recovery, and final disposition. Actual recovery yields may differ from the S25 assumption because of device condition, storage history, repairability, diagnostic capability, data-security requirements, compatibility, remaining useful life, secondary-use requirements, and the ability of a recovered device or component to displace a new product.

D. S25 Scenario Calculation Methodology

The following equations are a study-specific scenario formulation derived from standard life-cycle accounting and functional-displacement principles [19]. The notation is defined for the present S25 analysis and is not intended to represent a previously established universal S25 equation. The S25 recovery fraction should be understood as an outcome of the complete managed system, including collection, condition preservation, qualification, refurbishment, and pathway routing. The S25 accounting and environmental-displacement calculations are treated as related but distinct quantities. The combined S25 recovery target is:

$$S_{25} = P_A + P_B + P_C = 0.25$$

where P_A, P_B, and P_C are the fractions of technically eligible intake achieving, respectively, whole-device reuse or refurbishment, qualified module reuse, and qualified component reuse. Because these pathways do not provide equivalent levels of functional displacement, the combined S25 fraction cannot be directly multiplied by a whole-device environmental-displacement factor. A source device from which only a module or individual component is recovered does not necessarily displace manufacture of an equivalent new laptop or computing device. For whole-device environmental displacement, the relevant fraction is therefore the Path-A share:

$$R_{GHG,A} = P_A \times d_A \times I_A$$

where P_A is the proportion of technically eligible intake achieving qualified whole-device reuse or refurbishment, d_A is the fraction of those reused devices that actually displace an equivalent new device, and I_A is the product-specific net climate-impact reduction per displaced whole-device reuse relative to production of an equivalent new device. The value of I_A should be derived from an appropriate product-specific life-cycle assessment and should account for the relevant preparation-for-reuse, refurbishment, transport, use, and end-of-life assumptions [19], [21].

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Module and component recovery remain important circular-recovery pathways within S25, but they are not assigned full-device climate-displacement credits in the present calculation. Such credits could be incorporated in future analyses only where defensible pathway-specific functional-equivalence and displacement factors are established.

Accordingly, the present study does not assign a numerical whole-device climate reduction to the combined S25 target because an independently established value of P_A is not available. This avoids treating the full 25% combined recovery target as if it represented 25% whole-device reuse. For comparison and methodological illustration only, a separate normalized laptop case may assume $P_A=0.25$, $d_A=1$, and $I_A=0.40$, based on the second-hand laptop LCA reported by André et al. [21]. Under that separate hypothetical whole-device case:

$$R_{GHG,A} = 0.25 \times 1 \times 0.40 = 0.10$$

or an illustrative 10% portfolio-level climate-change reduction.

This 10% value is therefore not presented as the climate result of the combined S25 scenario. It represents only a normalized hypothetical case in which 25% of the eligible laptop population achieves whole-device reuse and each reused laptop displaces an equivalent new laptop on a one-for-one basis. For the actual S25 framework, the climate result should instead be calculated from the measured or independently estimated P_A and d_A values, together with the product-specific I_A factor.

Reference [27] provides independent embodied-GHG estimates for ICT products, including desktop and laptop computers, but is not used as the source of the approximately 39-50% reuse reduction reported for the second-hand laptop comparison [21]. All derived environmental reductions and life-cycle scaling factors in this study represent scenario outputs that require application-specific empirical field validation. For a mixed computing fleet, the appropriate I_A value should be determined from product-specific LCA evidence and weighted according to the actual device mix, refurbishment requirements, and functional displacement achieved [19], [21].

III. COMPONENT VIABILITY, RELIABILITY, AND CIRCULAR ROUTING

A. How Much Functional Value May Remain?

Inventory and diagnostic studies indicate that administrative retirement does not necessarily coincide with complete physical or functional failure. Retired electronic equipment may therefore contain residual value suitable for whole-device reuse, repair, module recovery, component recovery, or material recycling, depending on condition and application requirements [6], [7], [12].

At the printed circuit board (PCB) level, the presence of recoverable components does not by itself establish that those components are suitable for direct reuse. Their suitability depends on electrical condition, package integrity, traceability, compatibility, remaining service life, and the results of post-removal testing [11], [17], [18]. Consequently, component recovery should be treated as a qualified downstream pathway rather than as an automatic outcome for all discarded PCBs.

International functionality studies indicate that a proportion of used or retired equipment may remain functional at the point of assessment [5], [24]. Such findings support the use of an initial qualification stage before material recovery is undertaken. This qualification-first principle is also supported by international functionality evidence. Odeyingbo et al. [24] found approximately 81% of tested UEEE entering Lagos to be functional, whereas Thapa et al. [5] reported a 63% functioning estimate based on expert assessment. These figures demonstrate measurable functional potential but should be regarded as context-specific evidence rather than directly transferable recovery rates. However, reported percentages are context-specific and should not be interpreted as universal recovery rates for all WEEE streams.

Whole-device reuse generally retains more of the original product functionality and embodied production effort than component harvesting or material recycling [7], [8]. Where whole-device redeployment is not technically or economically appropriate, module- and component-level recovery may provide additional circularity opportunities, provided that recovered parts pass defined diagnostic and dependability requirements [17], [18], [25], [26].

Jiang et al. [25] demonstrated a 98% disassembly rate for the investigated surface-mounted components and metal shielding under their specified experimental disassembly conditions. This result demonstrates the technical potential of controlled disassembly, but it should not be interpreted as a 98% functional-reuse rate. Functional reuse requires additional inspection, electrical testing, grading, compatibility assessment, and remaining-life evaluation. The distinction between functionality, recoverability, and verified reuse is therefore central to the S25 framework: equipment may be physically present and potentially functional, but only a subset can ultimately satisfy the technical, safety, compatibility, and remaining-life requirements for secondary deployment.

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B. *Dependability and Remaining-Life Screening*

Functional status at the time of collection is not sufficient to establish suitability for secondary deployment. Reused products and recovered components require application-specific qualification addressing electrical performance, physical integrity, compatibility, safety, software support, and expected remaining service life. IEC 62309:2024 provides a framework for products containing used parts and supports the assessment of dependability when reused components are incorporated into products [17]. EN 45554 provides general methods for assessing characteristics relevant to repairability, reusability, and upgradeability [18]. These standards provide assessment frameworks; they do not imply that every recovered component will satisfy the requirements for secondary deployment.

Accordingly, the S25 pathway should apply a staged qualification process. Whole devices should first be evaluated for direct redeployment or refurbishment. Devices unsuitable for whole-unit reuse may then be assessed for module or component recovery. Components selected for secondary use should undergo appropriate electrical and physical testing before release. Components failing qualification should be directed to controlled material recovery rather than forced into secondary service. This hierarchy preserves the distinction between technical recoverability and verified functional reuse, which is important when interpreting the S25 scenario.

C. *Circular E-Waste Routing and Qualification Workflow*

To operationalize the reuse-first approach, retired computing assets should pass through a structured intake and disposition process. The proposed workflow begins with collection, identification, condition assessment, and chain-of-custody documentation [36], [37]. These stages establish the information required for subsequent technical qualification and responsible final disposition. Condition preservation should be incorporated into this initial stage because deterioration before assessment can unnecessarily reduce reuse potential. Evidence from the Bavarian collection-point study indicates that insufficient weatherproof roofing was associated with 86% of identifiable WEEE damage causes in that investigated system [16].

Following intake, equipment should be assigned to one of the following principal pathways:

1) *Path A - Whole-device reuse or refurbishment*: Equipment that passes functional, safety, software-support, and data-sanitization requirements is refurbished and redeployed where technically appropriate.
2) *Path B - Module reuse*: Equipment unsuitable for whole-device deployment but containing potentially reusable modules is subjected to controlled disassembly, compatibility verification, inspection, and diagnostic testing. Qualified modules may then be released for upgrades or spare-module use where technically appropriate [17], [25], [26].
3) *Path C - Component harvesting/recovery*: Equipment unsuitable for whole-device or module reuse but containing potentially reusable components is subjected to controlled component removal, identification, provenance logging, electrical screening, and application-specific qualification before secondary use [17], [25], [26].
4) *Path D - Material recycling*: Residual fractions that fail reuse, repair, or component qualification are transferred to authorized recycling facilities for material recovery and environmentally controlled treatment [1], [30].

The routing hierarchy therefore prioritizes preservation of functional value while ensuring that non-qualifying material is not unnecessarily retained in the reuse stream. Fig. 1 should be interpreted as a proposed operational workflow, rather than as a validated field-performance model.

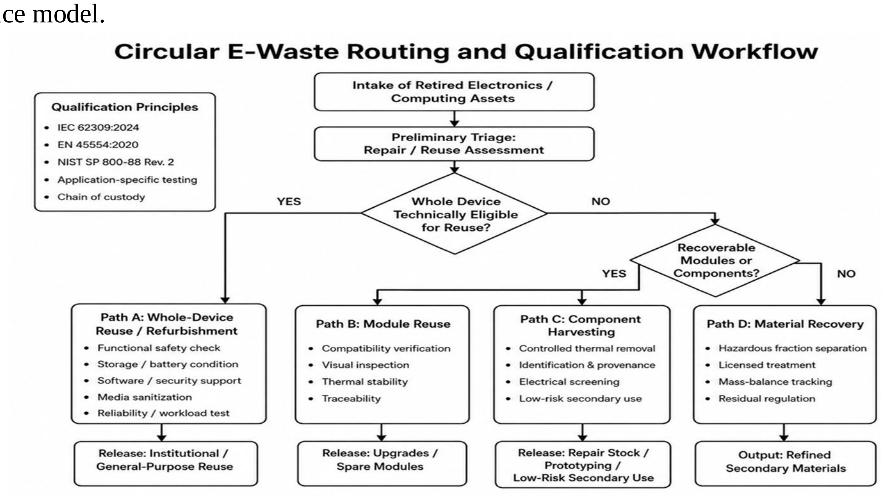

Fig. 1 Circular E-Waste Routing and Qualification Workflow

IV. DEPLOYMENT IN AFFORDABLE INSTITUTIONAL COMPUTING

The environmental and digital-access potential of circular hardware depends on matching qualified second-life equipment with applications for which its performance, reliability, security, and remaining useful life are adequate. Refurbished systems should therefore be deployed according to workload requirements and qualification results rather than chronological age alone [13], [17].

Institutional applications such as document processing, web-based learning, digital libraries, administrative systems, introductory programming, and other moderate computing workloads may be suitable candidates for qualified refurbished equipment. More demanding applications require additional performance and reliability screening.

The deployment decision should consider at least four dimensions: workload compatibility, software and security support, hardware condition, and expected remaining service life. The acceptance criteria in Table II are therefore proposed pilot criteria rather than universal thresholds.

TABLE II
TARGET INSTITUTIONAL SETTINGS AND WORKLOAD MATCHING MATRIX FOR QUALIFIED REFURBISHED HARDWARE

Target institutional setting	Representative workloads	Acceptance criteria
Schools / Colleges / Universities	Learning-management systems, document processing, digital libraries, online examinations, video instruction, and foundation-level coding.	Supported operating-system and browser environment; satisfactory storage health; network stability; electrical-safety clearance; and acceptable application-level performance [17], [18].
Libraries / Community Access Centres	Web browsing, digital reading, public application portals, email, and civic or digital-literacy instruction.	Secure multi-user configuration, browser compatibility, accessibility support, reliable storage, and simplified maintenance procedures.
Government / Public Administration	Administrative portals, document management, spreadsheets, citizen-service applications, booking systems, and routine data entry.	Continuing security-patch support, peripheral and driver compatibility, stable thermal performance, data-security compliance, and application-specific testing.
Coding / Foundation Laboratories	Introductory programming environments, basic data analysis, STEM software, and light content creation.	Verified CPU and memory operation, storage health, software compatibility, and stability under representative workloads.
Specialized High-Performance Workstations	Advanced CAD, numerical simulation, machine-learning development, and professional media applications.	Restricted deployment to refurbished workstations that pass application-specific functional testing, extended stability or burn-in testing where appropriate, and dedicated GPU validation where relevant [17].

A. Evidence for Institutional Reuse and Digital Access

Evidence from product-life-extension and circular ICT research supports consideration of secondary-use pathways where the performance and remaining service life of equipment are adequate [7], [8], [13]. However, environmental performance should be evaluated over the complete life cycle because refurbishment, transportation, electricity consumption, additional maintenance, and end-of-life treatment can influence the net outcome [19], [21].

Institutional reuse programmes can additionally contribute to digital-access objectives when equipment is matched to appropriate workloads. Examples of large-scale educational and public-sector reuse initiatives demonstrate the operational feasibility of deploying secondary computing equipment in institutional settings [22]. The availability of functioning used equipment in international settings further supports the need to evaluate, rather than assume, the functional potential of retired equipment. The functionality figures reported by Odeyingbo et al. [24] and Thapa et al. [5] provide contextual evidence for this assessment approach, but neither study establishes the suitability of equipment for a particular institutional workload.

The S25 framework therefore treats digital access as a potential co-benefit of qualified reuse, rather than assuming that every recovered device will automatically provide equivalent service to new equipment.

V. ECONOMIC, BEHAVIORAL, AND SYSTEM FEASIBILITY OF THE S25 TARGET

Economic feasibility of circular electronics should be evaluated using the cost of delivering useful secondary service rather than relying solely on the residual scrap value of discarded equipment. The economic outcome depends on procurement prices, collection and logistics costs, diagnostic and refurbishment requirements, warranty provisions, expected secondary service life, displacement of new purchases, and residual end-of-life value.

The S25 target is therefore treated as a scenario parameter requiring field validation, rather than as a demonstrated universal economic optimum.

A. *Parameter Definitions and Life-Cycle Return Model*

A simplified per-asset economic model can be expressed as:

$$\text{Net Economic Saving} = dC_{\text{new}} - \left(C_{\text{coll}} + C_{\text{diag}} + C_{\text{rework}} + C_{\text{dist}} + C_{\text{warr}}\right) + \left(R_{\text{harv}} + \Delta C_{\text{EOL}}\right)$$

This is a study-specific analytical formulation used to structure the S25 economic sensitivity analysis and is not presented as an established universal cost model.

where:

d= displacement factor, representing the fraction of secondary units that actually replace an otherwise required new purchase;

C_{new}= procurement cost of an equivalent new device;

C_{coll}= collection and intake cost;

C_{diag}= diagnostic testing and data-sanitization cost;

C_{rework}= repair, replacement, and upgrade cost;

C_{dist}= packaging, distribution, and deployment cost;

C_{warr}= expected warranty and post-deployment support cost;

R_{harv} = expected residual value from harvested components or materials, weighted by the proportion of assets routed to harvesting or material-recovery pathways;

ΔC_{EOL}= difference in end-of-life treatment cost attributable to the reuse pathway, expressed as a positive saving.

For the baseline S25 calculation, a one-for-one displacement assumption ($d = 1$) is used to illustrate the maximum direct displacement case; the actual value should be estimated empirically for the intended institutional or consumer pathway and tested through sensitivity analysis. Actual values vary by device class, geography, procurement channel, labour cost, component availability, and programme scale.

A useful economic assessment should therefore report sensitivity to d, refurbishment cost, warranty cost, secondary service life, and procurement price rather than presenting a single deterministic outcome.

B. *Justifying the S25 Target Through Incentive Systems and Awareness Programs*

Achieving a substantial recovery rate requires not only technical capability but also reliable collection, user participation, and appropriate return channels. Behavioural and policy research indicates that perceived value, convenience, awareness, and transaction costs can influence participation in formal e-waste collection systems [33]-[35]. However, increasing collection participation alone does not ensure that returned equipment will remain suitable for reuse. For the S25 framework, behavioral interventions should therefore be accompanied by condition-preserving collection and storage practices so that returned assets can reach the qualification stage in a usable condition [16].

Financial incentives such as buy-back payments or deposit-refund mechanisms may therefore be considered as potential instruments for increasing formal collection participation. Their effectiveness, however, depends on incentive magnitude, programme design, convenience, consumer awareness, and competition with informal collection channels [33]-[35].

For the S25 scenario, incentive values should be presented as pilot assumptions rather than established optimal values. For example, an illustrative incentive range may be evaluated through sensitivity analysis, with the resulting collection response measured empirically rather than assumed in advance.

Public awareness programmes can complement financial incentives by communicating the environmental and social value of responsible return and reuse. The objective should be to increase participation in formal collection and qualification pathways, rather than to assume that awareness alone will produce a specific recovery rate.

TABLE III
ECONOMIC, ENVIRONMENTAL, BEHAVIOURAL, AND DIGITAL-ACCESS INDICATORS FOR AN S25 PILOT

Advantage angle	Published empirical anchor	Illustrative S25 scenario implication	Key target field-pilot metrics
Incentive and awareness feasibility	Financial incentives, convenience, and awareness can influence participation in formal WEEE collection systems [33]-[35].	A pilot may test an illustrative incentive range and compare participation with a non-incentivized or lower-incentive baseline.	Collection participation rate; return rate; return velocity; incentive cost per recovered unit; awareness indicator.
Technical recovery	Reuse and component-recovery pathways can retain value when equipment or components satisfy qualification requirements [7], [17], [25], [26].	Recovered assets are routed through whole-device reuse, repair, component recovery, or material recycling according to qualification results.	Whole-device qualification yield; repair yield; component qualification yield; residual recycling fraction.
Environmental performance	Product life extension can reduce some life-cycle burdens when secondary use displaces new production [7], [8], [21].	Environmental savings are calculated only for pathways for which product-specific life-cycle and displacement data are available.	Avoided new-device purchases; estimated life-cycle impact per secondary device; secondary service life; displacement factor.
Digital-access benefit	Secondary computing programmes can support institutional access where equipment is appropriately matched to workloads [13], [22].	Qualified refurbished equipment is allocated to defined institutional workloads rather than treated as universally equivalent to new equipment.	Devices deployed; operational hours; users served; failure/return rate; service life; workload suitability.

VI. IMPLEMENTATION, WORKER SAFEGUARDS, AND POLICY FRAMEWORKS

A reuse-first e-waste programme requires coordinated collection, qualification, refurbishment, reuse, and residual recycling pathways. The proposed regional hub-and-spoke structure provides an organizational model for separating initial collection from specialized diagnostic and refurbishment activities [32].

A. *Collection Points (Spokes)*

1) *Intake and Condition Protection*: Secure, weather-protected intake locations should reduce avoidable deterioration of collected equipment before technical assessment. Messmann et al. [16] found that 86% of identifiable WEEE damage causes in the investigated collection-point system were associated with insufficient weatherproof roofing. This finding is treated here as system-specific evidence supporting condition preservation, rather than as a universal proportion of WEEE damage.
2) *Provenance Logging*: Collection personnel should record available asset identifiers, provenance, condition, and transfer information using documented traceability and chain-of-custody procedures [36].
3) *Condition-Preservation Recording*: Where practicable, collection centers should record visible condition at intake and relevant storage or environmental exposure indicators so that subsequent qualification yields can be compared with collection conditions.

4) *Public Engagement:* Collection points may incorporate awareness activities and, where economically justified, buy-back or incentive mechanisms intended to improve participation in formal return systems [33], [34].

B. Regional Refurbishment and Diagnostic Hubs

1) *Diagnostic Triage:* Centralized facilities should conduct structured testing to determine whether an asset is suitable for whole-device refurbishment, repair, component recovery, or material recycling [17].
2) *Technical Remediation and Data Sanitization*: Qualified personnel should undertake repair, replacement, controlled component removal, and media sanitization using documented procedures appropriate to the equipment and application [25], [37].
3) *Quality Assurance:* Processed devices and recovered components should be graded and tested against defined technical and safety requirements. IEC 62309:2024 may provide a relevant dependability framework for products containing used parts [17].

C. Authorized Recycling Facilities

Residual fractions that are not suitable for reuse or component recovery should be transferred to authorized recycling facilities for controlled treatment and material recovery in accordance with applicable regulatory requirements [1], [30].

D. Protecting Workers and Transforming Livelihoods

1) *Formalization:* Formalization means moving e-waste work from unsafe, informal settings into organized facilities where workers can be provided with proper ventilation, protective equipment, safe chemical handling, electrical safety measures, and controlled work processes [2], [3], [29], [31].
2) *Occupational Safeguards*: Occupational controls should include appropriate local exhaust ventilation where hazardous fumes may be generated, ESD controls for electronic handling, suitable thermal-processing equipment, battery-handling precautions, PPE, and compliant storage of hazardous materials.
3) *Worker Integration and Livelihood Protection*: Where informal collectors are integrated into formal collection and logistics networks, the programme should address worker training, compensation, occupational safety, and continuity of livelihood. Formalization should therefore be treated as a socio-economic transition process, not simply as relocation of existing activities [31], [32].

E. Responsible Transboundary Movement

1) *Distinguishing Reusable Equipment from Waste*: Transboundary movement of used electrical and electronic equipment should distinguish functional second-life products from waste and should incorporate appropriate documentation, regulatory compliance, and functionality verification [1], [10], [28]. International functionality evidence reinforces the importance of this distinction, but functionality should be demonstrated through documented testing rather than inferred from age, appearance, or declared reuse intent [5], [24]. These studies also do not establish eligibility for import into India; they only illustrate why functionality verification is important in any controlled second-life pathway.
2) *Responsible Cross-Border Reuse*: Exports intended for reuse should not be used as a mechanism for transferring non-functional equipment to regions lacking appropriate treatment capacity. Provenance, functionality, receiving-facility capability, and end-of-life responsibility should therefore form part of any responsible cross-border reuse system [1], [28].

F. Actionable Policy Recommendations

To support transition from informal processing toward a more formal circular electronics system, the following measures are proposed:

1) *Establish a pre-disposal assessment requirement*: Require public and enterprise computing assets to undergo documented assessment before final disposal, with routing to whole-device reuse, repair/component recovery, or material recycling according to qualification results [17].
2) *Develop appropriate collection incentives*: Pilot buy-back or deposit-refund mechanisms where evidence indicates that financial incentives can improve formal collection participation [33]-[35].
3) *Implement targeted public-awareness programmes*: Support educational programmes that communicate the environmental and resource implications of inappropriate e-waste disposal and the value of formal return and reuse pathways [34], [35].
4) *Use green public procurement mechanisms*: Incorporate longer operational-life, long-term software support, warranty, energy-efficiency, and take-back considerations into procurement policies where appropriate [13], [20].

5) *Support regional refurbishment infrastructure*: Provide appropriate infrastructure and technical capacity for inspection, diagnostics, repair, data sanitization, and controlled component recovery, accompanied by transparent reporting of qualification yields and secondary service performance [23], [25].
6) *Align EPR with functional-value preservation*: Consider whether producer-responsibility systems can recognize preparation for reuse, repair, and component recovery alongside conventional material-collection metrics [20], [23], [32].
7) *Protect recoverable value during collection and storage*: Establish minimum condition-preservation requirements for formal collection points, including appropriate weather protection and storage practices. The objective should be to reduce avoidable deterioration before technical assessment and to measure whether improved collection conditions increase qualification yield [16].

VII. CONCLUSION

A. *The Global E-Waste Challenge and Circular Recovery Opportunity*

1) *Increasing Generation of E-Waste*: Global e-waste generation continues to increase, while environmentally unsound treatment and inadequate collection remain important concerns [1]-[3]. The increasing volume of discarded electrical and electronic equipment places additional pressure on collection, reuse, recycling, and environmentally sound treatment systems [1].
2) *Toxicological and Environmental Impacts of E-Waste Pollution*: Uncontrolled processing of e-waste can expose workers and nearby communities to hazardous substances through activities such as open burning, uncontrolled dumping, and crude chemical treatment [2], [3]. Such practices can contribute to the release and dispersion of hazardous substances into surrounding environmental media and create occupational and community exposure pathways [2], [3]. These impacts provide an important environmental and health rationale for improving formal collection, controlled treatment, and reuse-oriented management of retired electronics.
3) *Premature Retirement and Loss of Residual Functional Value*: Electronic equipment may be removed from service before complete physical or functional failure because of technological replacement, institutional procurement cycles, software or compatibility requirements, cosmetic considerations, or changes in user requirements [6]-[8]. Consequently, administrative retirement does not necessarily indicate that all functional or recoverable value has been exhausted. This creates an opportunity for continued use through appropriate assessment, refurbishment, preparation for reuse, or qualified recovery of modules and components.
4) *Preserving Recovery Potential:* Evidence from preparation-for-reuse studies indicates that improvements in collection, storage, and treatment can increase the pool of equipment potentially suitable for preparation for reuse [16]. The finding that 86% of identifiable WEEE damage causes in the investigated Bavarian collection-point system were associated with insufficient weatherproof roofing provides a specific example of why condition preservation should be considered part of circular recovery [16]. The result is system-specific and should not be generalized to all WEEE streams.

These observations support a hierarchy in which potentially reusable equipment is assessed before irreversible material-processing routes are selected. However, the proportion that can ultimately be reused depends on equipment type, condition, collection practices, qualification requirements, and programme design.

B. *The S25 Scenario: Reuse-First Framework, Feasibility, and Environmental Benefits*

1) *Evidence-Based Asset Routing*: The S25 scenario follows a reuse-first approach in which technically eligible retired computing equipment is assessed for second-life use before repair, component recovery, or material recycling. Preparation-for-reuse studies show that a proportion of collected equipment can retain sufficient functional value for further use, and that improved collection, storage, and treatment can increase this potential [16]. International evidence provides contextual support for investigating this potential. Approximately 81% of tested UEEE entering Lagos was reported as functional [24], while a Delphi-based expert assessment estimated that 63% of imported UEEE was functioning and reused, refurbished, or resold [5]. These figures demonstrate that measurable functional potential can exist within retired or used equipment and reinforce the need for systematic qualification.
2) *Behavioural Feasibility Through Incentives and Awareness*: Formal collection depends on convenience, awareness, perceived value, and economic incentives [33]-[35]. Buy-back schemes, financial incentives, and targeted awareness programmes can therefore be used to increase participation in an S25 pilot. Their effectiveness should be measured through collection rates, qualification yield, incentive cost, and verified second-life deployment rather than assumed in advance. The S25 pathway therefore depends on more than collection participation: it requires preservation of condition, technical qualification,

appropriate refurbishment, verified secondary deployment, and controlled routing of non-qualifying equipment. Evidence that collection conditions can contribute to avoidable damage further supports treating protected collection and storage as an integral part of the reuse-first system [16].

3) *Multi-Vector Environmental Benefits*: For the whole-device displacement pathway, environmental benefits arise when a fraction of technically eligible equipment is successfully qualified for whole-device secondary use and each qualifying reused device displaces an equivalent new device. Within the combined S25 framework, this whole-device pathway is only one component of the overall recovery target, so its environmental contribution depends on the Path-A fraction rather than on the full 25% S25 value [7], [8], [21]. The principal benefits are:

- *Air pollution and GHG emissions:* Reuse can avoid part of the embodied energy and greenhouse-gas emissions associated with manufacturing replacement equipment, while diversion from open burning can reduce related air-pollution pathways [1], [4], [21].
- *Primary mining and metal-resource conservation*: Extending equipment life can reduce demand for virgin materials required for replacement devices and thereby reduce associated mineral-resource burdens [7], [21].
- *Soil toxicity and heavy metals:* Diverting equipment from uncontrolled dumping and dismantling can reduce exposure to pathways associated with heavy-metal contamination of soil and surrounding environments [2], [3].
- *Water contamination and toxic effluents*: Reuse-first routing can reduce the amount of e-waste entering uncontrolled processes involving acid treatment, leaching, contaminated wastewater, and runoff [2], [3].

The direction of these environmental benefits is supported by the literature, but their magnitude depends on equipment type, refurbishment requirements, secondary service life, displacement of new production, and the original end-of-life pathway [21]. For an illustrative laptop case, André et al. [21] reported approximately 40% lower climate-change impact for the assessed second-hand laptop scenario. In the present S25 framework, this product-specific factor applies only to the whole-device Path-A fraction. Thus, the whole-device climate-change contribution is expressed as $R_{GHG,A} = P_A \times d_A \times I_A$, where P_A is the fraction of technically eligible intake achieving qualified whole-device reuse, d_A is the fraction of those reused devices that actually displace an equivalent new device, and I_A is the corresponding product-specific climate-impact reduction per displaced whole-device reuse. The combined 25% S25 target is not directly multiplied by the 40% laptop factor because S25 also includes module and component recovery. For methodological illustration only, a separate hypothetical case may assume $P_A = 25\%$ whole-device reuse with one-for-one displacement ($d_A = 1$); under that assumption, $0.25 \times 0.40 = 0.10$, giving an illustrative 10% portfolio-level climate-change reduction. This 10% value is therefore a normalized hypothetical whole-device result and is not the environmental outcome of the combined S25 scenario [21].

C. Bridging the Digital Divide and Circular Deployment

1) *Qualified Second-Life Computing for Digital Inclusion*: Qualified second-life computing equipment can potentially support digital-access programmes where its performance, security support, reliability, and remaining service life are appropriate for the intended workload [22]. The digital divide refers to unequal access to suitable digital devices, internet connectivity, and related ICT facilities, particularly between resource-rich and resource-constrained communities [14]. When appropriately qualified and supported, refurbished equipment could be considered for Gram Panchayat offices, village schools and other educational institutions, community-access centers, libraries, and other local service settings where computing and ICT facilities are limited or unavailable.
2) *Workload-Based Institutional Deployment*: Institutional deployment should prioritize workload compatibility rather than treating refurbished equipment as universally equivalent to new equipment. Preserving equipment condition before qualification is also relevant to digital-access outcomes because avoidable deterioration during collection and storage may reduce the number of devices ultimately suitable for institutional second-life deployment [16]. Educational institutions, community-access centres, and routine administrative environments may provide suitable applications for appropriately qualified equipment, while demanding workloads require more stringent performance and reliability testing.
3) *Reuse and Repair Before Material Recovery*: Future circular-electronics programmes should consequently prioritize direct functional reuse and repair where technically justified, while reserving material recovery for equipment and components that cannot be responsibly maintained in service [7], [17], [20].

VIII. FUTURE SCOPE: ROBOTICS, AUTOMATED QUALIFICATION, AND FIELD VALIDATION

A. *Robotic and Automated Thermal Separation*

1) *Mitigating Occupational Exposure*: Replacing manual heat-gun desoldering with enclosed and automated thermal-separation systems has the potential to reduce worker exposure to hazardous fumes and physical strain associated with manual processing [2], [25].
2) *High-Yield Component Demounting*: Controlled thermal and vibration-assisted separation can improve the consistency and efficiency of component removal. Jiang et al. [25] reported a 98% disassembly/separation rate for investigated surface-mounted components and metal shielding under specified experimental conditions. This demonstrates technical separation potential, but should not be interpreted as a 98% functional-reuse rate.
3) *Preserving Component Health and Recovery Yield:* Precise, localized thermal profiles may reduce unnecessary heating and mechanical damage during component removal, thereby increasing the proportion of components that remain suitable for subsequent electrical, reliability, and compatibility testing and potential reuse [25], [26].

B. *Next-Generation Integrated Recovery Architecture*

1) *Machine Vision and AI Sorting*: Automated optical inspection, machine vision, and AI can identify board layouts, component locations, part numbers, defects, and physical condition before disassembly, enabling more selective recovery [26]. Recent automated-disassembly research demonstrates the feasibility of combining optical sensing, AI and robotic systems for electronics identification and disassembly.
2) *Adaptive Desoldering Profiles*: Future systems could use component-specific process control to optimize temperature, heating rate, dwell time, and removal force for different component types [25], [26].
3) *Automated Testing and Qualification*: Automated electrical and diagnostic testing can help determine whether recovered components remain suitable for secondary use. IEC 62309:2024 provides a framework for assessing the reliability and functionality of products containing reused parts and emphasizes testing and analysis before qualification [17].
4) *Digital Traceability and Data Security*: Future recovery systems can combine component-level traceability with secure media sanitization using NIST SP 800-88 Rev. 2 and IEEE 2883-2022 [37], [38]. Digital records could capture equipment origin, diagnostic results, refurbishment history, operating history where available, and second-life status.

C. *Multi-Institutional Empirical Field Validation*

1) *Pilot Deployment Framework*: Multi-site pilots should test whether the proposed S25 target can be achieved consistently for clearly defined eligible intake while maintaining technical, environmental, economic, and operational performance. Qualified refurbished equipment can be evaluated in schools, universities, libraries, and government offices [22].
2) *End-to-End Metric Tracking*: Field programs should record intake condition, qualification yield, repair and refurbishment outcomes, component recovery, verified component reuse, secondary service life, failure rates, operating performance, final disposition, and cost [17], [19]. For future Indian field programs, the end-to-end dataset should additionally record condition at intake, storage conditions, functionality-test results, refurbishment status, verified second-life deployment, component recovery, and final disposition. International evidence indicates that measurable functional potential exists in some used-equipment streams, but these estimates are population- and method-specific and cannot be treated as recovery coefficients for India.
3) *Validation of the 15-25% Recovery Band:* The proposed 15-25% range should be treated as an evaluation band rather than an established universal recovery rate. Multi-institutional trials can determine whether the target is technically and economically achievable across different equipment streams and operating conditions. A specific field comparison should also test whether protected collection and storage measurably improve qualification yield relative to conventional collection conditions. This would allow the collection-condition mechanism suggested by Messmann et al. [16] to be tested under Indian operating conditions rather than assumed to be transferable.
4) *Environmental and Circularity Validation*: Future pilots should quantify avoided new-device purchases, functional displacement, secondary service life, material recovery, energy use, greenhouse-gas effects, and the fraction diverted from environmentally unsound treatment. These measurements can provide the empirical basis for refining the S25 environmental model.

D. *Limitations and Uncertainty*

The present study is a scenario-based critical evidence synthesis rather than an empirical validation of the S25 target. The international functionality and preparation-for-reuse estimates cited here derive from different populations, definitions, and assessment methods and therefore cannot be directly transferred to India. The environmental results are based on product-specific life-cycle evidence and explicit displacement assumptions, while the S25 recovery fraction, economic parameters, and incentive effects remain scenario inputs requiring field validation. Accordingly, the reported environmental and economic values should be interpreted as illustrative scenario outputs rather than universal performance estimates. Future multi-site Indian studies should quantify qualification yields, functional displacement, secondary service life, costs, and environmental outcomes.

REFERENCES

[1] Baldé, C. P., Kuehr, R., Yamamoto, T., McDonald, R., D'Angelo, E., Althaf, S., et al. (2024). The Global E-waste Monitor 2024. Geneva/Bonn: ITU and UNITAR.
[2] World Health Organization. (2021). Children and Digital Dumpsites: E-waste Exposure and Child Health. Geneva: WHO.
[3] Kiddee, P., Naidu, R., & Wong, M. H. (2013). Electronic waste management approaches: An overview. Waste Management, 33(5), 1237-1250. DOI: 10.1016/j.wasman.2013.01.006.
[4] Robinson, B. H. (2009). E-waste: an assessment of global production and environmental impacts. Science of the Total Environment, 408(2), 183-191.
[5] Thapa, K., Vermeulen, W. J. V., Deutz, P., & Olayide, O. (2023). Ultimate producer responsibility for e-waste management - A proposal for just transition in the circular economy based on the case of used European electronic equipment exported to Nigeria. Business Strategy & Development, 6(1), 33-52. DOI: 10.1002/bsd2.222.
[6] Cooper, T. (Ed.). (2010). Longer Lasting Products: Alternatives to the Throwaway Society. Farnham: Gower.
[7] Wieser, H., & Tröger, N. (2018). Exploring the inner loops of the circular economy: Replacement, repair, and reuse of mobile phones in Austria. Journal of Cleaner Production, 172, 3042-3055. DOI: 10.1016/j.jclepro.2017.11.106.
[8] Bakker, C., Wang, F., Huisman, J., & den Hollander, M. (2014). Products that go round: exploring product life extension through design. Journal of Cleaner Production, 69, 10-16.
[9] European Environment Agency (2018), Waste prevention in Europe: policies, status and trends in reuse in 2017, EEA Report 4/2018.
[10] Huisman, J., et al. (2015). Countering WEEE Illegal Trade (CWIT) Summary Report. INTERPOL, EUROPOL, and WEEE Forum.
[11] Reuter, M. A., & van Schaik, A. (2015). Metallurgy of Recycling: Complexity of E-Waste and Printed Circuit Board Design. CRC Press.
[12] Tesfaye, F., Lindberg, D., Taskinen, P., & Hämäläinen, M. (2017). Recovery of materials from complex electronic waste: A review. Minerals Engineering, 107, 55-67.
[13] Freitag, C., Berners-Lee, M., Widdicks, K., Knowles, B., Blair, G. S., & Friday, A. (2021). The real climate and transformational potential of ICT: A critique of estimates, trends, and regulations. Patterns, 2(9), 100340.
[14] International Telecommunication Union (ITU). (2023). Measuring Digital Development: Facts and Figures 2023. Geneva: ITU.
[15] Kumar, A., Holuszko, M., & Espinosa, D. C. R. (2017). E-waste: An overview on generation, collection, legislation and recycling practices. Resources, Conservation and Recycling, 122, 32-42.
[16] Messmann, L., Boldoczki, S., Thorenz, A., Tuma, A. (2019). Potentials of preparation for reuse: A case study at collection points in the German state of Bavaria. Journal of Cleaner Production, 211, 1534-1546. DOI: 10.1016/j.jclepro.2018.11.264.
[17] International Electrotechnical Commission (IEC). (2024). IEC 62309:2024 - Dependability of new products containing reused parts and life-extended products. Geneva: IEC.
[18] European Committee for Standardization (CEN). (2020). EN 45554:2020 - General methods for the assessment of the ability to repair, reuse and upgrade energy-related products. Brussels: CEN.
[19] International Organization for Standardization (ISO). (2006). ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework. Geneva: ISO.
[20] Ministry of Environment, Forest and Climate Change. (2022). E-Waste (Management) Rules, 2022. Government of India, New Delhi.
[21] André, H., Ljunggren Söderman, M., & Nordelöf, A. (2019). Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse. Waste Management, 88, 268-279. DOI: 10.1016/j.wasman.2019.03.050.
[22] Computadores para Educar. (2017). Servicios de Computadores para Educar. Government of Colombia.
[23] NITI Aayog. (2026). Advancing Circular Economy of Waste Electronic and Electrical Equipment (E-waste) and Lithium-Ion Batteries in India. Government of India, New Delhi.
[24] Odeyingbo, A. O., Nnorom, I. C., & Deubzer, O. K. (2019). Used and waste electronics flows into Nigeria: Assessment of the quantities, types, sources, and functionality status. Science of the Total Environment, 666, 103-113. DOI: 10.1016/j.scitotenv.2019.02.102.
[25] Jiang, Y., Zhao, M., Zhao, L., Chen, Q., Huang, Q., Song, X., Zhang, C., & Wang, J. (2023). Research on the Disassembly Process and Model of Waste Mobile Phone Circuit Board Components. Processes, 11(7), 2052.
[26] Das, P., Leonardi, A., Yan, Q., Peier, K., & Gabriel, J.-C. P. (2026). Techno-economic evaluation of electronic component recovery for reuse from waste PCBs: advancing circular economy practices in automotive electronics. Journal of Industrial Ecology, 30, 405-419.
[27] Teehan, P., & Kandlikar, M. (2013). Comparing embodied greenhouse gas emissions of modern computing and electronics products. Environmental Science & Technology, 47(9), 3997-4003.
[28] Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. (2020). The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential. United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA).
[29] Bhagat-Ganguly, V. (2021). E-Waste Management: Challenges and Opportunities in India. Routledge India.
[30] Central Pollution Control Board (CPCB). (2023). Annual Report 2022-23. Ministry of Environment, Forest and Climate Change, Government of India, New Delhi.
[31] Dutta, D., & Goel, S. (2021). Understanding the gap between formal and informal e-waste recycling facilities in India. Waste Management, 125, 163-171.

[32] NITI Aayog. (2019). Strategy for Secondary Materials Management for Promoting Resource Efficiency (RE) and Circular Economy (CE) in Electrical and Electronic Equipment Sector. Draft for Comments. Government of India, New Delhi.

[33] International Telecommunication Union. (2017). Strategies and Policies for the Proper Disposal or Reuse of Telecommunication/ICT Waste Material: Final Report (Question 8/2). Geneva: ITU.

[34] Stern, P. C. (2000). New Environmental Theories: Toward a Coherent Theory of Environmentally Significant Behavior. Journal of Social Issues, 56(3), 407-424. DOI: 10.1111/0022-4537.00175.

[35] Dhir, A., Koshta, N., Goyal, R. K., Sakashita, M., & Almotairi, M. (2021). Behavioral reasoning theory (BRT) perspectives on e-waste recycling and management. Journal of Cleaner Production, 280, 124269.

[36] CENELEC. (2014). EN 50625-1:2014. Collection, logistics & Treatment requirements for WEEE - Part 1: General treatment requirements. Brussels: European Committee for Electrotechnical Standardization.

[37] National Institute of Standards and Technology (NIST). (2025). NIST Special Publication 800-88 Revision 2: Guidelines for Media Sanitization. U.S. Department of Commerce.

[38] IEEE. (2022). IEEE 2883-2022: IEEE Standard for Sanitizing Storage. IEEE Standards Association.