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CIRCULAR ELECTRONICS: A LIFE-CYCLE FRAMEWORK WITH EVIDENCE FROM KAZAKHSTAN

Digital transformation, the rapid development of artificial intelligence (AI), and the diffusion of smart-home practices are currently the principal drivers of increasing use of electrical and electronic equipment (EEE). While research on circular electronics has predominantly focused on manufacturing economies, limited attention has been paid to import-dependent countries where circularity is constrained by weak domestic production and fragmented governance. This study develops a life-cycle framework for circular electronics and examines its application in Kazakhstan as a representative case of an import-dependent economy in Central Asia.

The research employs a qualitative multi-method approach combining a comprehensive literature review, analysis of national and regional legislation, policy and institutional documents, administrative records, and firm-level case studies. Building on existing circular economy literature, the study proposes a three-layer Circular Electronics Framework that integrates product life-cycle stages, governance instruments, and digital enablement technologies.

The findings demonstrate that Kazakhstan's circular electronics system is characterized by significant institutional gaps between upstream stages (eco-design, manufacturing, repair) and downstream stages (collection and recycling), resulting in a predominantly end-of-life policy orientation. The study further identifies a structural imbalance between the country's negligible domestic EEE production and its dependence on imported electronics, which weakens the effectiveness of Extended Producer Responsibility (EPR).

Keywords: *e-waste, electrical and electronic equipment (EEE), circular electronics, circular economy, digital transformation, life cycle approach, Central Asia*

Кілт сөздер*: электронды қалдықтар, электрлік және электрондық жабдықтар (ЭЖЖ), айналмалы электроника, айналмалы экономика, цифрлық трансформация, өмірлік цикл тәсілі, Орталық Азия*

Ключевые слова: *электронные отходы, электротехническое и электронное оборудование (ЭЭО), циркулярная электроника, циркулярная экономика, цифровая трансформация, подход, основанный на жизненном цикле, Центральная Азия*

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Introduction. Annual software and chip upgrades associated with AI requirements effectively compel consumers to replace devices as older hardware loses compatibility with newer software, thereby steadily shortening product lifespans. The digitalisation of the economy stimulates not only EEE consumption but also production, increasing pressure on natural resources and the volume of electronic waste generated.

According to The Global E-waste Monitor 2024, approximately 62 million tonnes of e-waste were generated worldwide in 2022, of which only 22.3% was documented as formally collected and recycled [1]. The corresponding rate was 11.8% in Asia and no more than 3.7% in Central Asia. Kazakhstan, with a formally managed share of 8.7%, is the regional leader but remains below the wider Asian average [1]. From a baseline of 136.1 thousand tonnes in 2019 (7 kg per capita), Kazakhstan's annual e-waste generation is projected to reach 18 kg per capita, or 432 thousand tonnes, by 2050. Under a business-as-usual trajectory, cumulative unmanaged e-waste over 2020–2050 could reach 8 billion kg, compared with 4 billion kg under a circular-economy pathway. The latter could additionally return 3 billion kg of valuable materials to productive use, reduce associated greenhouse-gas emissions by almost 95%, and yield a positive economic effect of USD 276 million, compared with USD 791 million in costs under the current trajectory.

These figures demonstrate the declining viability of the linear take–make–dispose model as a basis for resource security. Within a circular economy, e-waste is not treated as the primary point of regulatory intervention but as the final and least-preferred stage of the product life cycle. System performance is

therefore largely determined by decisions made at the stages of eco-design, manufacturing, use, repair, and reuse.

The literature on e-waste mainly oriented to manufacturing countries where circularity can be addressed through product design, consumption, repair, reuse, collection, and recycling [2]. While less attention paid to import oriented countries, where domestic EEE manufacturing is limited and the effectiveness of conventional circular economy instruments—particularly EPR—may be constrained by dependence on foreign producers and fragmented institutional arrangements.

To fill these gaps, this study utilized qualitative approaches to investigate e-waste life cycle regulation by literature review, analysis of documents and firm-level case-studies in order to develop framework that integrates product life cycle stages, governance instruments, and digital enablers.

Literature Review. A recurring weakness in the empirical circular economy (CE) literature is the conflation of "circularity" with recycling and secondary-material recovery, leaving the upper tiers of the R-hierarchy like reduce-reuse-repair-refurbish- remanufacture comparatively underexplored. Leipold and Petit-Boix (2018), in a qualitative content analysis of 15 EU and German bio-based stakeholders, show that recycling and secondary raw materials are referenced by almost all actors, whereas reduce appears in only a third of documents and reuse, sufficiency and cradle-to-cradle principles in fewer than a quarter. Their business-model mapping indicates that established recycling-oriented models are heavily overrepresented relative to less established approaches such as sharing or leasing, which are almost absent [2]. This asymmetry motivates an operational definition of circular electronics that treats recycling as the residual, least-preferred loop rather than as a synonym for circularity.

At the policy level, Li, Wang, Salleh and Chen (2026) offer a definition broad enough to travel from construction waste to electronics: the circular economy expands beyond waste reduction to strategies for designing out waste, extending product life, and regenerating natural systems, and is explicitly framed as a matter of policy design rather than technology alone [3]. The same study supplies a governance typology that maps cleanly onto the electronics sector: command-and-control policy instruments (CACPIs) that enforce compliance through sanctions, market-driven instruments (MDPIs) that harness economic incentives, and information instruments (IPIs) that operate through voluntary compliance secured via information provision [3]. This CACPI/MDPI/IPI framework is adopted in the current study to classify governance tools at each life-cycle stage.

At the product level, the functional-reuse literature demonstrates that the design-for-repair tier is not merely aspirational. Docu, Tabarani and Naher (2026) build ReVolt, a modular laptop assembled from salvaged keyboards, LCD panels, touchpads and lithium cells, motivated explicitly by the observation that conventional recycling destroys functional subsystems while refurbishment depends on preserving the original device architecture a gap between material recovery and functional reuse that their design is intended to close. Their prototype achieves a cradle-to-grave carbon footprint of approximately 91.5 kg CO2-eq, roughly 3.6 times lower than a typical laptop [4], providing quantitative evidence that reuse-tier strategies outperform recycling-tier strategies on environmental grounds when technically feasible.

At the opposite end of the R-hierarchy, two material-science studies illustrate the ceiling and the constraints of recycling-tier valorisation. Robert, Kumar, Thomas and Kalpathy (2026) show that the polymeric fraction of e-waste (up to 30% of e-waste by weight), is disproportionately landfilled or incinerated despite being reusable as sensor-grade material, and that recovery is chemically constrained: thermoset epoxy-glass laminates account for roughly 60–70% of the non-metallic fraction of PCBs, and their highly cross-linked structure makes conventional recycling both technically demanding and cost-intensive [5]. Gonçalves, Yao and Rocco (2026) test an alternative valorisation pathway incorporating ground waste printed circuit boards (WPCBs) into Portland cement and find a narrow performance window: 10 wt.% substitution optimises hydration kinetics and C–S–H network density, while 15 wt.% measurably slows cement hydration through inert-filler and bromine-related effects, underscoring that even end-of-pipe recycling routes require compositional thresholds to remain safe and effective [6].

The demand side of the reuse/refurbishment tier has received comparatively little attention relative to the supply-side engineering and materials literature reviewed above. Ho, Haaker and Kularatne (2026), surveying Generation Z consumers in the Netherlands, find that environmental awareness, social acceptance, and seller/brand reputation are the significant positive drivers of willingness to buy refurbished electronics, whereas perceived risk and affordability are not decisive [7]. This finding is consequential for circular electronics research: it suggests that scaling the reuse/refurbishment tier is less a pricing problem

than a trust- and legitimacy-building problem, which again points back to the certification and quality-assurance gap identified on the supply side by Das et al. (2026) [8].

On the institutional demand side, Pisipati and Mishra (2026) extend this picture beyond individual consumers to bulk institutional generators. Surveying 17 Information Technology companies and two authorised recyclers in Hyderabad, India, they find that repair or refurbishment, rather than outright replacement, is the first course of action reported by the large majority of respondent organisations when equipment becomes dysfunctional, and that most respondents judge replacing parts more cost-effective than purchasing new equipment [9]. This corporate preference ordering mirrors the reuse-over-replacement logic documented for individual consumers by Ho et al. (2026), suggesting that the viability of the reuse tier is not confined to the household level but extends to bulk consumers whose purchasing volume gives them disproportionate influence over downstream material flows provided, as their survey also shows, that a dedicated e-waste management function and regular collection drives are in place, which only about half and roughly a third of surveyed companies, respectively, reported having [7].

A separate strand of the literature approaches circular electronics not from the product-tier or governance-tier perspective adopted above, but from the digital infrastructure that connects this two. Fernandes and Sousa (2026) study Digital Product Passports (DPPs), the data-sharing tool mandated under the EU's Ecodesign for Sustainable Products Regulation, and situate them as an information-based policy instrument (IPI) in the sense of Li et al. (2026): DPPs are designed to store lifecycle, component and compliance data accessible to actors across the value chain [3,10]. Interview evidence from a technology provider and a recycling operator indicates that the anticipated benefits are asymmetric: life cycle transparency gains are concentrated upstream, where manufacturers can use passport data for eco-design and compliance, while downstream recyclers report that DPPs could become largely ineffective without automated bulk-scanning infrastructure once devices are shredded or arrive mixed at high volume [10]. This finding qualifies the more optimistic reading of digital traceability found elsewhere in the literature: an information instrument's usefulness is conditional on complementary technological capacity at each life-cycle stage, not a uniform property of the instrument itself.

Mohsin, Rovetta, Masulli and Cabri (2026) supply the complementary technological half of this picture. Their four-layer Digital Circular Economy Architecture (DCEA-4) proposes that artificial intelligence, layered on IoT sensing and connectivity infrastructure, can operationalise circular decision-making at each product-level step: computer-vision systems for automated disassembly and sorting of mixed waste streams, machine-learning models for predictive maintenance that extend the use phase, and reinforcement learning for reverse-logistics and remanufacturing scheduling [11]. Reported performance gains include sorting accuracy above 99% for plastics and metals, and up to a 40% extension of equipment lifespan through predictive maintenance, which addresses precisely the automated bulk-scanning gap that Fernandes and Sousa (2026) identify as the binding constraint on DPP usefulness for recyclers [10,11]. Read together, the two studies suggest that governance-level information instruments (DPPs) and technology-level intelligence layers (AI-enabled computer vision) are complementary rather than substitute enablers of the product-tier framework: one supplies the data, the other supplies the capacity to act on it at the scale and speed that sorting and recycling operations require. Mohsin et al. (2026) caution, however, that this technological capacity carries its own resource cost, since training and operating large-scale AI models consumes energy that must be netted against the material and energy savings the models enable an efficiency-rebound tension that mirrors, at the digital layer, the same trade-offs documented for physical recycling routes earlier in this section [11].

Main part. This study adopts an exploratory, multi-method qualitative design combining (a) deductive document analysis of regional, national and primary-legal policy documents, (b) comprehensive literature review relating to EEE and circular electronics and based on these (c) development of a novel framework of circular electronics life cycle. The four components are triangulated against the two-tier Circular Electronics Framework and the eight-stage life-cycle table developed in Section 1 of this review, allowing document-level, firm-level and sector-level evidence to be cross-validated against a common analytical structure, a design consistent with recommended practice for institutional case research in the circular-economy literature

Taken together, the studies considered above, motivate a two-tier Circular Electronics Framework, extended here with an explicit digital-enablement layer, used throughout this paper (Figure 1). The product-level tier runs eco-design → modularity/design-for-repair → durability/life-extension → reuse → refurbishment → remanufacturing → material recycling, with each successive step representing a lower-

value, higher-loss fallback rather than an equivalent alternative. The governance-level tier consists of the CACPI/MDPI/IPI instrument mix that determines which product-level step actors are incentivized to pursue, of which DPPs are an emerging IPI case. A third, cross-cutting digital-enablement layer — comprising information instruments such as DPPs and technological capabilities such as AI-enabled sorting and predictive maintenance — determines whether governance intent at a given stage translates into operational capacity, and whether it does so uniformly or asymmetrically across upstream and downstream actors. Later in this study we applied this extended framework stage-by-stage across the electronics life cycle.



Figure – 1. **Circular Electronics Framework**
*compiled by the authors based on [10]

Reframing circular electronics as a multi-tier system requires tracing how actors, regulatory instruments and risks are distributed across the full life cycle, not only at the recycling stage where most existing literature concentrates. Table 1 synthesises this distribution across eight stages, drawing on the case evidence assembled above and extended with institutional and digital-infrastructure evidence from Pisipati and Mishra (2026), Fernandes and Sousa (2026), and Mohsin et al. (2026)[9–11].

Table – 1

Actors, regulatory instruments and risks across the electronics life cycle.

Life-cycle stage	Key actors	Regulatory instruments	Risks / evidence
Design	OEM designers, IC/chip suppliers	Eco-design directives, modularity/repairability standards Emerging DPP data-capture requirements under the EU ESPR, an IPI case [10]	Software–hardware lock-in and AI-driven compatibility cycles shorten device lifespans, reinforcing the linear take-make-dispose model [4] DPP compliance costs are expected to be passed downstream to consumers, raising affordability questions at the design-to-market transition [10]
Manufacturing	PCB fabricators, component OEMs	Material-content standards (RoHS-type), CACPI/MDPI/IPI instrument mix [3]	Thermoset epoxy–glass laminates (60–70% of PCB non-metallic fraction) are technically demanding and cost-intensive to recycle; brominated flame retardants complicate safe processing [5] Even within the EU's harmonised regulatory bloc, innovation and circular-economy indicators for EEE cluster into structurally distinct territorial patterns — an eastern/southern low-circularity cluster, a northern/central innovation-oriented cluster, and an energy-intensive France–Germany cluster — showing that manufacturing-stage outcomes remain uneven under a common directive [4]
Import / Distribution	Importers, distributors, retailers	EPR schemes, import tariffs/bans, eco-labelling	Design-incentive loop crosses jurisdictional boundaries in import-dependent economies, weakening EPR's circular function Empirical confirmation from an import-dependent developing economy: despite India's E-waste

			(Management) Rules mandating disposal through authorised channels, most domestic and imported e-waste is still absorbed by unregistered informal operators able to outbid formal recyclers on collection price [9]
Use	Consumers, corporate/institutional users	Right-to-repair legislation, warranty policy	Rapid technological obsolescence driven by digitalisation and AI-linked update cycles AI-enabled predictive maintenance is reported to extend equipment lifespan by up to 40% in industrial settings, illustrating a technological rather than regulatory lever for slowing obsolescence at the use stage [11]
Repair	Independent repairers, authorised service centres, DIY/maker communities	Right-to-repair mandates, spare-parts availability rules	Factory-sealed, glued/soldered assemblies obstruct repair, in contrast with fully user-serviceable modular designs [4] DPP data is intended to give independent repairers brand-agnostic access to repair information currently controlled by producers, though this benefit remains emerging rather than realized [10]
Reuse / Refurbishment	Component-recovery plants, secondary markets, refurbishers, Gen-Z consumers; bulk institutional consumers such as IT companies [9]	Quality-certification schemes for recovered components; techno-economic break-even frameworks [8]	Interoperability barriers across donor devices and absent quality certification [8]; demand-side uptake hinges on environmental awareness, social acceptance and seller/brand reputation rather than price or perceived risk [7] Institutional confirmation: most surveyed IT companies report repair/refurbishment as their first response to dysfunctional equipment, though only about half maintain a dedicated e-waste function and roughly a third run regular collection drives [9]
Collection	Formal/informal collectors, EPR operators	EPR (collection targets), take-back obligations	Persistently low formal collection (only 22.3% of e-waste formally collected/recycled worldwide in 2022; cited in [5,6] informal recycling releases lead and mercury Competitive bidding for bulk e-waste inflates formal recyclers' acquisition costs; one surveyed Indian recycler reported roughly 90% of collected volume passing through informal intermediaries despite formal registration [9]
Recycling / Material recovery	Specialised recyclers, metallurgical/chemical processors, construction-materials industry; AI-enabled sorting operators [11]	CACPI + MDPI policy mix (Li et al., 2026); solvothermal/chemical depolymerisation protocols; DPP-linked automated scanning (aspirational) [10]	Value-chain fragmentation: mechanical recycling recovers metals but discards the polymer-rich fraction (25–30% of e-waste mass) as landfill or incineration feedstock (Robert et al., 2026); valorisation routes remain nascent — WPCB incorporation into cement is beneficial only within a narrow 5–10 wt.% window [6] Computer-vision and hyperspectral sorting systems report classification accuracy above 90–95% for mixed material streams, offering a technical route around the manual bulk-scanning bottleneck, though large-scale deployment carries energy costs that partially offset material-recovery gains [11]

**compiled by the authors*

Two patterns emerge from Table 1 that structure the remainder of this paper. First, regulatory instrumentation is heavily weighted toward the downstream stages (Collection, Recycling) through EPR and CACPI/MDPI mixes, while the upstream stages (Design, Manufacturing) that determine repairability and material recoverability remain governed mainly by voluntary eco-design guidance and by emerging, not-yet-mandatory information instruments such as DPPs which is an instrument-stage mismatch consistent with the IPI-heavy, MDPI-light policy portfolios documented by Li et al. (2026) for construction waste and confirmed empirically for EEE at the EU territorial level by Docu et al. (2026), whose clustering analysis shows that innovation and circular-economy indicators for electrical and electronic equipment co-move unevenly even among EU member states subject to the same directives [3,4].

Second, the risk evidence is geographically asymmetric. The technical and materials-science literature synthesized in Table 1 (based on [4–6,8]) is produced almost entirely from design- and manufacturing-economy perspectives (USA, China, Brazil, India, Singapore), and the one systematic bulk-consumer study available from an import-dependent developing economy ([9], on India) still describes a domestic IT sector that is itself a first-tier importer of components and finished devices rather than a component manufacturer. Evidence on the Import/Distribution stage, where jurisdictional boundaries interrupt the EPR design-incentive loop, therefore remains comparatively thin even after incorporating this case, and peer-reviewed academic evidence from Central Asia specifically is absent from all seven country-level studies reviewed above. This gap is precisely where import-dependent economies such as Kazakhstan and Central Asia are structurally distinct from the cases reviewed here. The literature review shows that, while the academic gap

persists, a small body of programmatic, primary-legal and grey literature has begun to describe this context empirically.

Figure 2 previews the framework that populate with evidence: it maps the same eight life-cycle stages used in Table 1 against the regulatory instruments in force in the EU (WEEE Directive, RoHS, the ESPR, right-to-repair rules) and in the EAEU/Kazakhstan bloc (the 2021 Environmental Code, EPR, EAEU technical regulations), stage by stage. The dashed line separating the two rows is deliberate: it marks the point-by-point institutional gap between the two regulatory regimes that the remainder of this review documents empirically. Two further features of the frame matter for the analysis that follows. First, the actor row shows that Kazakhstan has essentially no domestic-manufacturing actor at the Production stage ("production almost not represented"), which anticipates the import-dependency finding developed in this study. Second, the frame distinguishes two distinct material pathways at the base of the diagram: a circularity loop, in which repair and reuse return devices directly to the Use stage without passing through Collection or Recycling at all, and a leakage pathway, in which scrap is diverted through informal metal collectors and the export of used equipment, bypassing the formal collection and recycling infrastructure entirely. Both pathways are, by construction, invisible to statistics collected at the formal collection point a measurement caveat that qualifies the managed-share figures reported later: Kazakhstan's 8.7% formally managed share is a lower bound on total circularity, not a full account of reuse activity, precisely because informal repair and reuse are, on this framework, structurally excluded from the formal statistic.

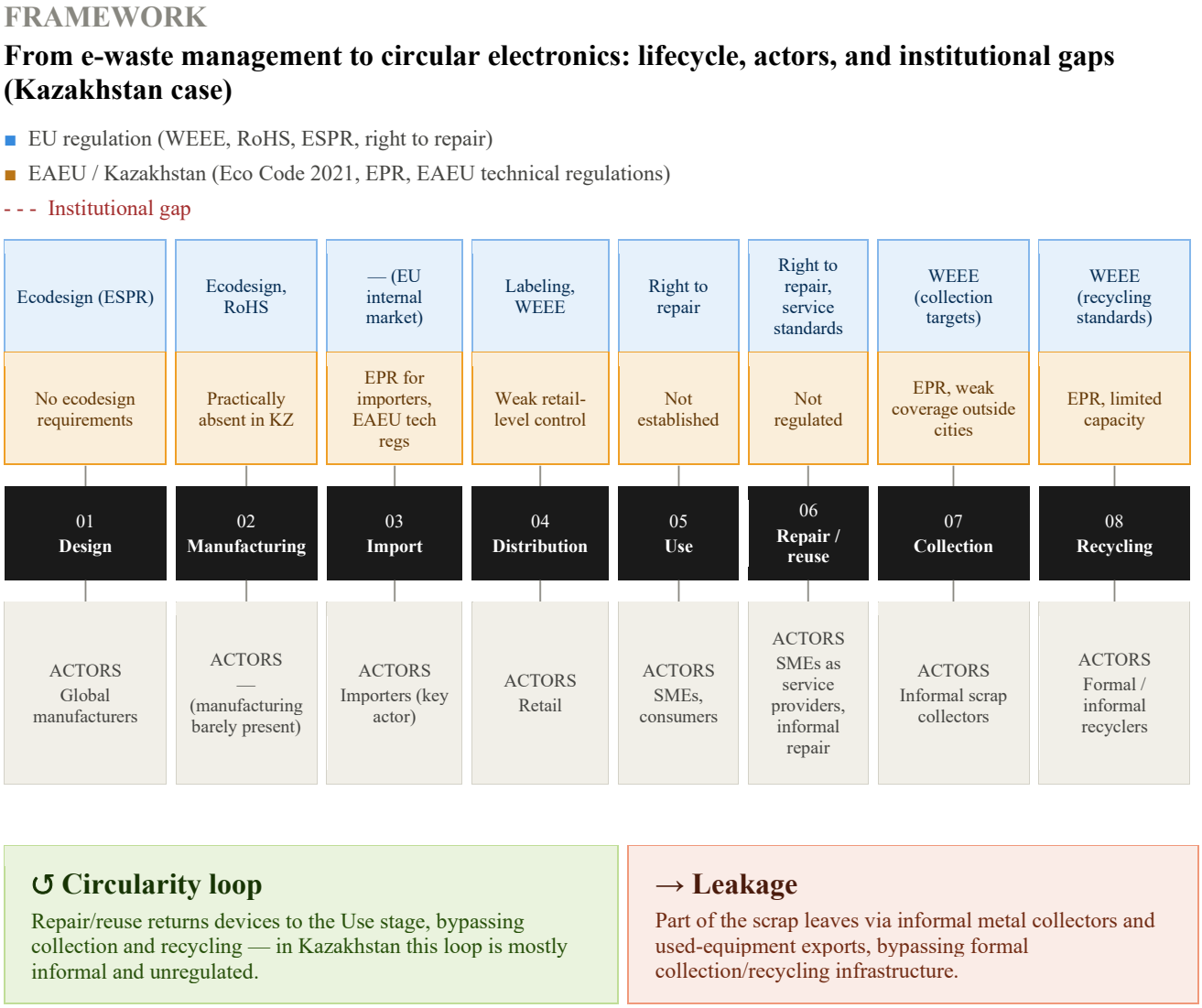


Figure – 2. **Framework: from e-waste management to circular electronics – life cycle, actors and institutional gaps, the Kazakhstan case**

**compiled by the authors based on EU and EAEU/Kazakhstan primary regulatory.*

No peer-reviewed study in the corpus reviewed above examines Central Asia, yet the region is not empirically silent: a recent cluster of programmatic and grey literature, produced by regional and multilateral initiatives rather than academic outlets, offers the first systematic description of Central Asia's electronics and e-waste sector against the life-cycle categories used in Table 1. This literature is reviewed here on its own terms as descriptive, practitioner-generated evidence rather than peer-reviewed research, both because it is currently the only empirical account of the region available at this level of detail, and because it allows the geographic asymmetry identified previously to be characterised rather than merely asserted.

At the regional level, Mustafina (2025), writing for the Regional Alliance for Circular Electronics in Central Asia with support from the United Nations Environment Programme, profiles Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan as occupying the final, consumption-side stage of the global electronics value chain [12]. Regional domestic EEE production is reported at approximately USD 2.4 billion in 2024, overwhelmingly concentrated in Uzbekistan (about USD 2.0 billion), with Kazakhstan's own production valued at only USD 637,000 in the same year, which is several orders of magnitude below the region's annual EEE import bill of USD 6 billion, of which Kazakhstan and Uzbekistan jointly account for over 80%. The brief estimates regional e-waste generation at 337 thousand tons in 2019, with a formally managed share below 4% region-wide, and reports that buyback schemes, trade-in programmes and household reverse-logistics infrastructure are “virtually nonexistent” across all five countries. Its stage-by-stage regulatory assessment, covering pre-production/design, production, and post-production/consumption, finds no mandatory eco-design, durability, energy-efficiency or green-procurement requirements at the design stage in any of the five countries; technical-safety-only regulation with no sustainability or reuse provisions at the production stage; and Extended Producer Responsibility implemented in only two of the five countries (Kazakhstan and, partially, Kyrgyzstan) at the post-production stage, alongside an acknowledged absence of separate collection infrastructure and cross-border waste-flow monitoring region-wide. This distribution reproduces, at the scale of an entire economic region, the same downstream-weighted governance pattern that Table 1 documents for construction waste in China [3] and for EEE across the EU[4], and is visualised for Kazakhstan specifically in Figure 2.

A second, complementary source of evidence is the design documentation for the Global Electronics Management (GEM) Kazakhstan project [13], a Global Environment Facility-funded initiative (USD 5,000,000 grant, USD 45,270,189 in-kind co-financing) running from 2026 to 2031 under UNIDO's international GEM programme, implemented by the CSD Center and the United Nations Institute for Training and Research. Its baseline documentation independently estimates Kazakhstan's annual e-waste generation at over 136,000 tonnes, projected to reach a cumulative 8.8 million tonnes by 2050, a figure examined alongside the underlying National E-Waste Monitor data, and reconciled with it, in Section 3.1 and identifies the same upstream regulatory gaps as Mustafina (2025): absence of repairability, resource-efficiency and energy-efficiency standards, and an EPR system not yet linked to repair, reuse or reliable statistics [12]. The project's planned interventions are organised around legislative and economic-instrument development (including EPR, repair and reuse requirements), technical regulation and national standards for repairable electronics, a voluntary certification and eco-labelling pilot, household e-waste collection trials in three pilot cities (Astana, Almaty, Shymkent), technical support to WEEE processors, and system-level monitoring of e-waste flows a programme structure that, read against Table 1, targets essentially every stage of the life-cycle framework simultaneously, from Design through to Recycling.

With a projected national population of 24 million, the National Monitor expects per-capita e-waste generation to rise from 7 kg (136.1 million kg total) in 2019 to 18 kg (432 million kg total) per year by 2050, and its own scenario analysis shows that a Circular Economy pathway could nearly halve cumulative unmanaged e-waste relative to a Business-as-Usual pathway (4 versus 8 billion kg between 2020 and 2050) [14] greenhouse-gas emissions by approximately 95%, and yielding a net positive economic effect of USD 276 million by 2050, against an estimated USD 791 million in costs under Business as Usual. Independent journalistic coverage of the GEM project's official launch adds further, more immediate detail. Reporting on the project's unveiling in Astana on 30 June 2026, Pokidaev (2026) quotes Ruslan Tukenov, director of the Waste Management Department at Kazakhstan's Ministry of Ecology and Natural Resources, framing e-waste management as an issue that “extends far beyond environmental policy alone” into industrial policy and access to critical raw materials, and cites the KazWaste industry association's own estimate that approximately 19 businesses collect or process e-waste nationally, where fewer than the 30 firms identified independently in the licensing registry compiled for this study, a discrepancy that itself illustrates how

unsettled even the basic count of active recyclers remains across data sources [15]. Most consequentially for proposition P1, Pokidaev (2026) reports that company-level disclosures recorded only 1,300 tonnes of e-waste for the same reference year, roughly a hundredfold below the independently estimated total, which treats as the sharpest quantitative evidence available for the measurement gap this review associates with institutional decoupling [15].

At the firm level, a case-study series published by the Regional Alliance for Circular Electronics in Central Asia documents circular practices at two Kazakhstani companies positioned at opposite ends of the value chain [15]. Qazaq Technology Ltd, a small Almaty-based assembler of computer equipment operating since 2014, reports that engaging external plastic recyclers was economically unfeasible once logistics and virgin-material costs were accounted for, that government tenders can be won without mandatory EAEU conformity certification, and that no tax incentives or long-term contracts reward circular producers; its response was to build an in-house plastic-shredding and remoulding line and to accept decommissioned equipment from other manufacturers for component recovery [12]. Aleks-Asu, an ISO 9001/14001/45001/27001-certified IT solutions provider, documents a broader portfolio of practices spanning most of the product-level tier introduced in Section 1.1: print outsourcing and IT-equipment rental as product-as-a-service models; a service centre that repairs and refurbishes equipment using original parts, reselling or donating units at residual value; a documented collection and dismantling chain routed through a dedicated facility in Aktobe; and two upcycling initiatives converting printer toner into road paint and WEEE-derived material into 3D/5D-printing feedstock. The same case study reports persistent constraints that mirror the regional regulatory assessment, a lack of collection venues for e-waste from the general population, the absence of deep recycling plants in Kazakhstan (forcing export of processed WEEE abroad), no regulatory framework for novel processing technologies, unresolved certification requirements for refurbished equipment, and low public awareness of secure data destruction on discarded storage devices [12].

Finally, an administrative registry of environmentally licensed WEEE-processing companies in Kazakhstan (compiled from state licensing records; N = 30 firms) provides a first indication of the formal recycling sector's scale and composition. Licences cluster heavily in 2021–2022, are concentrated in a small number of urban centres (Astana, Karaganda and Aktobe together account for 40% of licensed firms), and declared processing capacity is highly skewed: a single lead-acid battery recycler accounts for roughly half of all declared tonnage across the registry, while the median firm reports a capacity in the low hundreds of tonnes per year, and mercury-containing waste and lamps, governed by longer-standing hazardous-substance rules, are the most frequently licensed stream rather than consumer ICT electronics specifically.

Table 2 summarises the quantitative profile reported across these sources for Kazakhstan alongside its four Central Asian neighbours. Read together with Table 1, this evidence base indicates that the geographic gap identified at the previous paragraphs is best characterised, at present, as a gap in peer-reviewed academic coverage specifically rather than in empirical documentation altogether: programmatic and firm-level sources already describe a life-cycle governance profile for Kazakhstan, while adding an import-dependency dimension (a domestic EEE production base worth under one million US dollars against multi-billion-dollar import flows) that has no close analogue among the manufacturing- and design-economy cases reviewed.

Table – 2

Quantitative and regulatory profile of the Central Asian electronics and e-waste sector, 2019–2025.

Country	E-waste generated 2019 (kt)	Formally managed (kt)	Managed share (%)	National EPR for EEE	Mandatory eco-design rules
Kazakhstan	136.1	11.9	8.7	Yes (partial)	No
Uzbekistan	139.7	0.3	0.2	Pending	No
Turkmenistan	38.6	0.0	0.0	No	No
Tajikistan	12.9	0.11	0.9	No (draft)	No
Kyrgyzstan	10.0	0.1	1.0	Yes (partial)	No
Central Asia (region)	**337.3**	**12.4**	**3.7**	**2 of 5 countries**	**0 of 5 countries**

**compiled by the authors based on the source[12]*

Above we noted that, of the seven country-level studies synthesised in Table 1, none originates from Central Asia, and that this gap coincides precisely with the region's structural distinctiveness as an import-dependent bloc in which the EPR design-incentive loop crosses jurisdictional boundaries to foreign producers. The present section operationalises that gap. Newly available primary and grey-literature evidence, where a regional stakeholder brief compiled by the Regional Alliance for Circular Electronics in Central Asia [12], the design document of the GEF-funded Global Electronics Management (GEM) Kazakhstan project (UNEP/UNIDO/CSD Center/UNITAR, 2026–2031), the primary legal instruments governing EPR for EEE in Kazakhstan (Order No. 448, 2021; Order No. 689, 2022; Government Resolution No. 1250, 2023), an original compiled registry of licensed WEEE-processing companies in Kazakhstan, and two firm-level circular-economy case studies, allow the life-cycle framework developed before to be populated with Kazakhstan-specific actors, instruments and risks for the first time in this literature.

Conclusion. This study addressed the question of how a life-cycle approach can reveal the main institutional, regulatory, and operational barriers to circular electronics in an import-dependent economy such as Kazakhstan. The findings show that Kazakhstan’s electronics system remains predominantly linear and focused on end-of-life waste management rather than on preventing waste through eco-design, durability, repair, reuse, and refurbishment. Applying the proposed three-layer Circular Electronics Framework demonstrates that the principal weakness is not the absence of individual recycling initiatives, but the lack of coordination between product life-cycle stages, governance instruments, and digital capabilities.

The analysis identified four interrelated structural problems. First, formal collection and licensing arrangements coexist with a substantially larger informal or unmanaged e-waste stream, creating a significant gap between regulatory intent and actual material flows. Second, governance instruments are concentrated at the collection and recycling stages, while eco-design, repairability, reuse, refurbishment, and green procurement remain weakly regulated. Third, Kazakhstan’s dependence on imported electronics limits the ability of national Extended Producer Responsibility mechanisms to influence product design and manufacturing decisions made outside the country. Fourth, formal processing capacity is geographically concentrated and oriented mainly towards selected high-value or hazardous waste streams rather than the full range of electrical and electronic equipment.

The firm-level cases nevertheless demonstrate that circular practices can emerge despite these institutional gaps. Repair, refurbishment, equipment rental, component recovery, in-house material processing, and upcycling illustrate the potential of firms to act as institutional entrepreneurs. However, these initiatives remain fragmented and difficult to scale without economic incentives, certification standards, accessible collection infrastructure, reliable data, and coordinated public policy.

The findings therefore suggest that Kazakhstan should move from a narrow e-waste management approach towards an integrated circular-electronics policy covering the entire product life cycle. Priority measures include introducing repairability and durability standards; supporting certified repair and refurbishment markets; strengthening importer and retailer take-back obligations; expanding collection infrastructure beyond major cities; improving the traceability of electronic products and waste flows; and using digital product information, AI-enabled sorting, and monitoring systems where adequate operational capacity exists. Because product design occurs largely outside Kazakhstan, national measures should also be coordinated with EAEU technical regulations and international eco-design and product-information standards.

The study contributes to circular-economy research by showing that frameworks developed primarily for manufacturing economies require adaptation when applied to import-dependent countries. In such contexts, circularity depends not only on domestic recycling capacity but also on the ability to govern imports, extend product use, formalize repair and reuse, and reconnect national EPR systems with cross-border product value chains. Although the qualitative design and reliance on a limited number of firm cases and administrative sources restrict broad generalization, the framework provides a basis for comparative research across Central Asia and other import-dependent economies.

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АЙНАЛМАЛЫ ЭЛЕКТРОНИКА: ҚАЗАҚСТАННАН АЛЫНҒАН ДӘЛЕЛДЕРМЕН ӨМІРЛІК ЦИКЛІНІҢ ҚҰРАМЫ

Аңдатпа

Цифрлық трансформация, жасанды интеллекттің (ЖИ) жылдам дамуы және ақылды үй тәжірибелерінің таралуы қазіргі уақытта электрлік және электрондық жабдықтарды (ЭЖЖ) пайдаланудың артуының негізгі қозғаушы күші болып табылады. Айналмалы электроника бойынша зерттеулер негізінен өндірістік экономикаға бағытталғанымен, айналымдылық әлсіз отандық өндіріс пен бөлшектенген басқарумен шектелген импортқа тәуелді елдерге аз көңіл бөлінді. Бұл зерттеу айналмалы электрониканың өмірлік циклінің құрылымын әзірлейді және оны Орталық Азиядағы импортқа тәуелді экономиканың типтік мысалы ретінде Қазақстанды қарастырады.

Зерттеуде жан-жақты әдебиетке шолуды, ұлттық және аймақтық заңнаманы талдауды, саяси және институционалдық құжаттарды, әкімшілік жазбаларды және фирма деңгейіндегі кейс-стадилерді біріктіретін сапалы көп әдісті тәсіл қолданылады. Айналмалы экономиканың қолданыстағы әдебиеттеріне сүйене отырып, зерттеу өнімнің өмірлік циклінің кезеңдерін, басқару құралдарын және цифрлық мүмкіндік технологияларын біріктіретін үш деңгейлі айналмалы электроника құрылымын ұсынады.

Зерттеу нәтижелері Қазақстанның айналмалы электроника жүйесі жоғары сатылар (эко-дизайн, өндіріс, жөндеу) мен төменгі сатылар (жинау және қайта өңдеу) арасындағы айтарлықтай институционалдық алшақтықтармен сипатталатынын көрсетеді, бұл негізінен пайдалану мерзімінің аяқталуына бағытталған саясатқа әкеледі. Зерттеу елдің елеусіз ішкі ЭЭЖ өндірісі мен импорттық электроникаға тәуелділігі арасындағы құрылымдық теңгерімсіздікті одан әрі анықтайды, бұл кеңейтілген өндіруші жауапкершілігінің (ӨӨЖ) тиімділігін әлсіретеді.

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ЦИРКУЛЯРНАЯ ЭЛЕКТРОНИКА: РАМКА ЖИЗНЕННОГО ЦИКЛА НА ПРИМЕРАХ ИЗ КАЗАХСТАНА

Аннотация

Цифровая трансформация, стремительное развитие искусственного интеллекта (ИИ) и распространение практик «умного дома» в настоящее время являются основными факторами, способствующими росту использования электротехнического и электронного оборудования (ЭЭО). Хотя исследования в области циркулярной электроники в основном сосредоточены на производственных экономиках, ограниченное внимание уделяется странам, зависимым от импорта, где циркулярность сдерживается слабым внутренним производством и фрагментированным управлением. В данном исследовании разработана рамочная модель жизненного цикла для циркулярной электроники и рассмотрено ее применение в Казахстане как репрезентативном примере импортозависимой экономики Центральной Азии.

В исследовании используется качественный многометодологический подход, сочетающий всесторонний обзор литературы, анализ национального и регионального законодательства, политических и институциональных документов, административных записей и тематических исследований на уровне предприятий. Основываясь на существующей литературе по циркулярной экономике, исследование предлагает трехуровневую рамочную модель циркулярной электроники, которая интегрирует этапы жизненного цикла продукта, инструменты управления и цифровые технологии.

Результаты исследования показывают, что для казахстанской системы замкнутого цикла в сфере электроники характерны значительные институциональные пробелы между этапами производства (экологическое проектирование, производство, ремонт) и этапами переработки (сбор и переработка), что приводит к преимущественно ориентированной на утилизацию продукции политике. Исследование также выявляет структурный дисбаланс между незначительным внутренним производством электроники и электротехники в стране и ее зависимостью от импорта, что ослабляет эффективность расширенной ответственности производителя (EPR).