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Systems Perspectives on Circular Energy Supply Chains: Diversification, Supply-Risk Reduction, and Self-Limiting Recovery Paths in Istanbul's Waste-to-Energy Transition (2020–2024)

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Highlights

Please indicate how your work links to systems science via your contributions to systems practice, theory, and or methodology.

- This study applies systems thinking to an urban circular energy supply chain by combining portfolio decomposition, concentration metrics (HHI, effective source count, Theil index), and a qualitative stock–flow interpretation informed by system-dynamics principles to analyze how recovery-pathway interactions drive diversification.
- The notion of a self-limiting recovery path is proposed as a systems-theoretic concept that extends path-dependency theory by identifying endogenous, policy-mediated resource depletion as a plausible mechanism generating structural diversification pressure in circular energy systems.

What are the main findings and/or the implications of the main findings?

- Istanbul's municipal waste-to-energy generation nearly tripled (457–1332 GWh, 2020–2024), driven not by landfill-gas expansion but by diversification into energy-from-waste and biomethanization; source concentration fell from HHI 1.00 to 0.47, indicating a structural shift from single-source dependence to a diversified recovery portfolio.
- Cities relying on landfill gas should treat it as a transitional bridge technology and plan capacity diversification before resource constraints become binding; the self-limiting recovery path concept offers a transferable lens for anticipating endogenous diversification pressure in renewable energy and circular economy transitions.

Abstract

Municipal waste management is conceptualized as a circular energy supply chain in which waste flows through parallel recovery pathways. This study examines Istanbul's waste-to-energy transition between 2020 and 2024 using portfolio decomposition, concentration indices (Herfindahl–Hirschman index, effective source count, Theil index), and a qualitative stock–flow interpretation of İSTAÇ facility-level data. Electricity generation rose from 457 GWh in 2020 to 1332 GWh in 2024; the Herfindahl–Hirschman index fell from 1.00 to 0.47, and the effective source count rose from 1.0 to 2.1. Energy-from-waste and biomethanization accounted for 73% of the increase, while landfill-gas recovery plateaued at 690–698 GWh, contributing the remaining 27%. The study introduces the concept of a self-limiting recovery path: a technology whose resource base is depleted jointly by physical decay and a policy-mediated reduction in its replenishment. Plant-level evidence

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at the largely closed Odayeri site is consistent with this mechanism, though it cannot rule out ordinary gas decay kinetics or a capacity ceiling as alternatives; the reading is offered as plausible rather than demonstrated. Unlike conventional lock-in pathways, a self-limiting pathway generates self-eroding feedback, suggesting landfill gas is best treated as a transitional bridge technology. The study contributes to path-dependency theory and circular energy supply-chain research.

Keywords: sustainable supply chain; circular energy supply chain; waste-to-energy; renewable energy transition; energy systems integration; supply-chain resilience; source diversification; systems perspective; landfill gas; self-limiting recovery path; system-dynamics-informed framework; circular economy

1. Introduction

1.1. Municipal Waste as a Circular Energy Supply Chain

Municipal solid waste (MSW) is increasingly viewed not merely as a disposal problem but as a strategic resource within circular economy and sustainable-energy frameworks. Across many countries, waste-to-energy (WtE) systems have become important components of urban sustainability strategies, simultaneously supporting waste diversion, renewable energy generation, and greenhouse-gas mitigation [1,2]. This renewable framing, however, applies unevenly across recovery pathways: landfill gas and biomethanization derive from the biogenic fraction of waste and are conventionally counted as renewable, whereas EfW incinerates mixed municipal waste that includes a fossil-derived fraction—plastics and synthetic materials prominent among them—so only part of its output qualifies as renewable under standard accounting conventions. This study accordingly treats "waste-to-energy transition" and "diversification" as the operative terms throughout, rather than characterizing the system's aggregate generation growth as a renewable energy transition in the narrower sense. Within this framing, municipal waste management can be conceptualized as a circular energy supply chain: waste functions as a secondary feedstock that flows through multiple recovery pathways and is transformed into electricity, recovered materials, compost, and avoided emissions. The defining feature of such a supply chain is not a single conversion technology but the configuration of several pathways that together determine how much energy is recovered, at what efficiency, and with what environmental burden. Adopting a systems perspective, this study treats a city's recovery facilities not as isolated installations but as interacting components of an evolving portfolio whose composition can shift markedly over time.

Framed in supply-chain terms, the urban recovery system is a feedstock-to-energy supply chain: municipal waste is the upstream feedstock, the recovery facilities (LFG, EfW, and biomethanization) are parallel conversion nodes, and electricity is the downstream output. Read this way, the concentration metrics used below double as supply-risk indicators—an electricity portfolio dominated by a single, resource-constrained pathway is more exposed to supply risk than a diversified one—while the qualitative stock–flow interpretation of how the pathways co-evolve supplies the system-dynamics-informed conceptual lens. The study therefore links waste-to-energy planning to the broader questions of energy systems integration and supply-chain resilience that recur across renewable energy transitions.

1.2. Renewable Energy Transitions and Diversification Challenges

The transition from landfill-dependent disposal toward diversified recovery portfolios mirrors broader renewable energy transitions: municipal waste systems increasingly

combine landfill-gas recovery (LFG), energy-from-waste incineration (EfW), anaerobic digestion and biomethanization, and material recovery in order to raise resource efficiency and reduce environmental and operational risk [3]. Because LFG and biomethanization rest on the biogenic fraction of waste, these pathways are at least partly renewable, and their expansion is frequently presented as a contribution to renewable energy and climate targets. EfW is treated differently here: because it incinerates mixed municipal waste containing a substantial fossil-derived fraction—plastics and other synthetic materials—its output is not classified as renewable in this paper, and the diversification documented below should accordingly be read as a shift in portfolio composition and supply risk rather than as a proportional increase in renewable generation. The supply-risk rationale for diversification, and its formal measurement, are developed in Section 2.2.

1.3. Research Gap

A substantial body of research has examined individual WtE technologies, including landfill-gas utilization, incineration, anaerobic digestion, and their life-cycle environmental performance [2]. Yet, this literature remains largely technology-centered: it concentrates on the technical efficiency or environmental impact of single technologies, often assessed cross-sectionally at a single point in time. Comparatively little is known about how an urban recovery portfolio evolves over time—how the relative roles of competing pathways shift, and how those shifts reshape the structure of a municipal energy supply chain. As a consequence, the dynamics of diversification itself—its drivers, its measurement, and whether it is a voluntary strategy or a constrained outcome—remain under-researched. The present study addresses this gap by analyzing portfolio evolution longitudinally rather than examining technologies in isolation.

1.4. Theoretical Motivation

The evolution of recovery portfolios may not be entirely voluntary, which makes it a productive site for engaging several theoretical traditions—most directly, path-dependency theory and its energy-domain application as carbon lock-in, developed fully in Section 2.3 [4–7].

Some recovery pathways appear to follow a fundamentally different trajectory. Landfill-gas recovery depends on a finite, decomposing stock of previously deposited biodegradable waste, and successful diversion policies reduce the future inputs that would otherwise replenish that stock. In such systems the very success of sustainability policy can contribute to the depletion of the resource base on which the technology depends; Section 2.4 develops this dynamic formally and contrasts it with conventional lock-in.

To capture this phenomenon, this paper introduces the notion of a self-limiting recovery path—a recovery technology whose resource base is eroded jointly by physical decay and by policy-driven diversion—as an analytical lens developed formally in Section 2.4.

This notion is analytically distinct from three adjacent bodies of work—the economics of exhaustible resources, path-dependency and carbon lock-in theory, and accounts of regime destabilization—compared directly in Section 2.4. The contribution is therefore not the observation that landfill-gas output declines, nor a claim to an entirely new depletion mechanism, but the joint conceptualization—within a path-dependency framework—of physical resource depletion and a policy-mediated reduction in that resource's future replenishment, and of the diversification pressure their combination creates, pressure whose actual translation into portfolio change is mediated by strategic investment, institutional capacity, and technology choice, rather than a deterministic structural necessity.

1.5. Research Questions

Istanbul offers a particularly relevant setting for examining these dynamics. As one of Europe's largest metropolitan regions, with approximately 15.7 million inhabitants [8], it operates one of the largest municipal waste management systems in the broader European region and, during the study period, expanded its WtE infrastructure across landfill-gas recovery, energy-from-waste incineration, and biomethanization. It thus provides an instructive example of a large-scale urban transition occurring outside the EU and the Western-European and North-American contexts that dominate much of the existing literature. Against this background, the study investigates how Istanbul's municipal waste-to-energy portfolio evolved between 2020 and 2024 and what this evolution reveals about resource constraints, diversification, and renewable energy transitions. It addresses three research questions:

RQ1. How did the structure of Istanbul's waste-to-energy portfolio evolve between 2020 and 2024, and to what extent did diversification across recovery pathways—rather than the expansion of landfill-gas recovery—account for the growth in total generation?

RQ2. Does landfill-gas recovery display the empirical signature of a self-limiting recovery path—that is, a plateauing, resource-constrained output even as the overall recovery portfolio expands?

RQ3. To what extent are the observed patterns consistent with a policy-coupled depletion mechanism, and at what spatial scale—city-wide or plant-level—is that consistency supported by the available evidence?

Source-concentration co-evolution is addressed within RQ1 and RQ2 through the Herfindahl–Hirschman index, effective source count, and Theil index, which are reported across the full study period. Energy recovery efficiency and emission intensity are also examined, but as secondary, exploratory indicators reported for completeness rather than as an independent research question: the energy recovery rate is available only as a single cross-sectional figure with no year-by-year series, and per-ton emission intensity is comparable across only two years, an insufficient basis to support a formal co-evolution claim. These indicators are presented in Section 4.4 and discussed as suggestive rather than firm evidence in Section 5.7.

1.6. Contribution Statement

The study makes three contributions. Empirically, it provides one of the first longitudinal, portfolio-level accounts of a large non-EU, emerging-economy megacity's waste-to-energy transition, showing that the near-tripling of generation between 2020 and 2024 was predominantly driven by diversification into energy-from-waste incineration and biomethanization, with landfill-gas recovery contributing a smaller share of the increase. Methodologically, it combines portfolio decomposition, source-concentration metrics—the Herfindahl–Hirschman index, the effective source count, and the Theil index, adapted from the energy-diversity and supply-risk literature [9–11]—and a qualitative stock–flow interpretation informed by system-dynamics principles, triangulated against Eurostat municipal waste indicators and publicly available EPDK records, in order to quantify diversification and changes in structural concentration exposure within a single urban system. Theoretically, it proposes the self-limiting recovery path as an analytical lens that extends path-dependency and carbon lock-in discussions by jointly conceptualizing physical resource depletion and a policy-mediated reduction in resource replenishment within a single framework, engages the economics of exhaustible resources and transition-destabilization theory, and foregrounds this coupling—rather than extraction-induced depletion alone—as a driver of diversification in circular energy supply chains.

2. Literature Review and Theoretical Framework

2.1. Waste-to-Energy as a Circular Energy Supply Chain

Research on municipal waste-to-energy (WtE) has historically been organized around individual conversion technologies and their technical and environmental performance. Landfill-gas (LFG) recovery, incineration with energy recovery (EfW), and anaerobic digestion have each been studied extensively, typically through engineering performance metrics or life-cycle assessment—Astrup et al.'s comparative review of thermal WtE technologies [12] and Dong et al.'s plant-level case study of pyrolysis, gasification, and incineration [13] are representative of this tradition. Comprehensive global assessments document the rising scale of municipal waste generation and the growing role of energy recovery within waste management [2], and WtE is increasingly framed as a key element of sustainable waste management rather than as a mere disposal endpoint [14]. This technology-specific tradition remains active: recent systematic reviews continue to synthesize the anaerobic-digestion literature on the organic fraction of municipal solid waste [15], to track a growing and increasingly favorable framing of WtE within circular economy discourse—Brunner and Morf's mini-review traced this shift [16] and Boloy et al.'s bibliometric analysis quantified its growth in the published literature [17]—and to reassess landfill-gas management practice under contemporary diversion policy [18], indicating that the individual-technology tradition has continued to develop rather than converge on a settled account of how these pathways relate to one another within a single portfolio.

This reframing is closely tied to the circular economy agenda, in which materials and embedded energy are kept in productive use for as long as possible rather than discarded, a principle codified in EU circular economy legislation [1], elaborated as a sustainability paradigm by Geissdoerfer et al. [19], and shown by Kirchherr et al.'s review of 114 competing definitions to remain conceptually unsettled even as it has proliferated across the literature [20]. Within this agenda, energy recovery occupies an intermediate position—preferable to landfilling but subordinate to prevention, reuse, and material recycling in the waste hierarchy. A related and older tradition, urban metabolism, conceptualizes the city as a system that ingests resources and discharges waste and emissions, and analyses the flows that pass through it—a tradition inaugurated by Wolman's foundational metabolism model [21] and since extended by Kennedy, Pincetl, and Bunje to urban planning and design applications [22]. Read together, these studies imply that a city's WtE facilities are best understood not as standalone plants but as nodes in a circular energy supply chain linking waste sources, conversion pathways, and energy and material outputs. What remains comparatively underdeveloped is an account of how the composition of that supply chain changes over time—the emphasis this study adopts. A recent comprehensive review confirms that this tradition remains active and increasingly intersects with energy-transition and circular economy research, while noting that integrated frameworks linking material and energy flows to the co-evolution of specific recovery pathways—of the kind this study undertakes for waste-to-energy—remain comparatively rare [23].

2.2. Diversification and Supply Risk in Energy Systems

A second body of work concerns diversity and supply risk in energy systems. The case for diversifying energy sources rests on a long-standing observation: dependence on a narrow set of supplies exposes a system to price, availability, and disruption risks, whereas diversification spreads these risks across heterogeneous sources [9]. Stirling's framework decomposes diversity into three properties—variety (the number of sources), balance (the evenness of their contributions), and disparity (how different they are)—and links these properties to the resilience and adaptive capacity of energy portfolios [9,10]. The salience of this framework has, if anything, increased since 2022, as the disruption of European gas

supply prompted a wave of scholarship revisiting energy-security and resilience concepts for systems undergoing rapid transition, underscoring that diversification away from single-source dependence remains a live structural concern rather than a settled one [24].

To operationalize the balance dimension, the energy-security literature has widely adopted concentration and diversity indices drawn from industrial economics and information theory, most prominently the Herfindahl–Hirschman index (HHI) and Shannon–Wiener-type measures—cataloged in Kruyt et al.'s review of energy-security indicators [11], operationalized in ECN's supply-security indicator framework by Jansen et al. [25], and applied empirically to UK electricity generation by Grubb, Butler, and Twomey [26]. The HHI, computed as the sum of squared shares, attains its maximum under single-source dependence and falls as supply becomes more evenly distributed; its reciprocal can be interpreted as an effective number of independent sources, an intuitive indicator of how many sources a system effectively relies upon. The Theil index, borrowed from the inequality literature, provides a complementary entropy-based view of how evenly output is distributed across pathways.

This concern with concentration connects directly to the supply-chain literature, in which single-source dependence is treated as a core vulnerability and source diversification as the principal structural mechanism for reducing exposure to disruption: Christopher and Peck frame resilience as a design property engineered into the supply chain [27], Sheffi and Rice operationalize it through redundancy and flexibility in enterprise practice [28], and Tang surveys the broader risk-management literature linking single-sourcing to disruption exposure [29]. Applying these tools to a municipal energy recovery portfolio is therefore well founded: the HHI, the effective source count, and the Theil index offer a transparent way to characterize whether a city is moving from single-source dependence toward a more balanced—and, by extension, less supply-risk-exposed—recovery portfolio. The present study adopts these measures for exactly this purpose, thereby grounding its empirical strategy in an established tradition of energy-diversity and supply-risk measurement.

Making this link to resilience explicit, rather than leaving it metaphorical, requires distinguishing the structural diversity that these indices measure from the functional resilience that diversity is presumed to support. In the supply-chain literature, resilience is commonly decomposed into robustness—the capacity to keep functioning when a source is disrupted—and recoverability—the capacity to return to function afterwards—with redundancy and flexibility across multiple sources serving as the structural properties through which both are achieved, a decomposition most closely associated with Sheffi and Rice's enterprise-resilience framework [28] and echoed in Christopher and Peck's and Tang's treatments of the same underlying design properties [27,29]. Stirling's variety, balance, and disparity map onto these properties directly: variety and balance govern how much output can be reallocated if one pathway fails, whereas disparity—the extent to which pathways draw on independent resource bases and are exposed to uncorrelated risks—governs whether that reallocation can actually buffer a given shock [9,10]. The concentration indices used in this study capture variety and balance, and therefore measure a necessary structural precondition for resilience, namely the reduction in single-source exposure; they do not, on their own, measure realized resilience, which would require observing how the system responds to a specific disruption. Several qualifications follow, each identifying a common-mode risk channel that limits how much the observed fall in concentration reduces overall systemic risk. The first is feedstock correlation: because landfill-gas recovery and biomethanization both draw on the biogenic fraction of municipal waste, a shock to biogenic waste generation or collection—for instance, a shift in consumption patterns, or a source-separation and composting policy that diverts organic waste away from recovery pathways generally—would affect both simultaneously, so the three pathways are not fully

independent in the resource-base sense; the disparity dimension, and hence the resilience benefit, is accordingly more limited than the headline fall in concentration alone would suggest. The second is common logistics risk: as described in Section 3.1, all three pathways are embedded within a single integrated collection, transfer-station, and landfilling network operated by İSTAÇ, so a disruption to that shared logistics backbone—a transfer-station closure, a labor action, a fuel-price shock affecting collection vehicles—would propagate to all three pathways together rather than being absorbed by diversification across them. This third is common regulatory shocks: because LFG, EfW, and biomethanization all operate under the same municipal waste management framework and the same national environmental and tariff regulation, a single policy change—an adjustment to feed-in tariffs, a revision of landfill-diversion targets, or a new emissions standard—could affect generation across all three pathways at once, in a way that treating them as independent "suppliers" for HHI purposes does not capture. Taken together, these channels mean that the fall in HHI documented in Section 4.3 should not be read as evidence that overall systemic risk fell by a proportionate amount: it measures a reduction in the concentration of output across nominally distinct pathways, not a reduction in exposure to shocks capable of affecting several or all of those pathways simultaneously. The present analysis is therefore best read as demonstrating a structural shift toward a configuration that supply-chain theory associates with greater resilience, and as treating the measured decline in concentration as an indicator of reduced supply risk, rather than as a direct test of the system's response to disruption.

2.3. Path Dependency and Carbon Lock-In

A third tradition explains why energy and infrastructure systems are so often difficult to change. Path-dependency theory holds that early choices, reinforced by increasing returns, can become self-perpetuating: as a technology accumulates adopters, complementary investments, and institutional support, switching costs rise and the incumbent becomes entrenched. David's account of the QWERTY keyboard layout supplies the canonical illustration of a historically contingent design becoming locked in through accumulated adoption [4], and Arthur formalizes the underlying increasing-return mechanism [5] through which competing technologies can lock a system onto a particular trajectory irrespective of the relative merits of alternatives.

In the energy and climate domain, Unruh [6,7] synthesized these mechanisms in the concept of carbon lock-in, arguing that co-evolving technological and institutional structures—a "techno-institutional complex"—entrench fossil-energy systems and create persistent barriers to low-carbon alternatives. The dominant message of this literature is one of stability and inertia: feedback is reinforcing, resource and infrastructure bases persist, and escaping the path typically requires external shocks or deliberate policy disruption. Almost without exception, the framework is mobilized to explain why incumbent systems endure. Powerful as it is, this emphasis leaves a blind spot for pathways whose internal dynamics push in the opposite direction—toward decline and diversification rather than entrenchment. It is this blind spot that the following section addresses.

2.4. Self-Limiting Recovery Paths: A Conceptual Extension

The waste-to-energy pathways examined in this study display dynamics that the lock-in framework does not anticipate. Landfill-gas recovery depends on a finite stock of biodegradable waste already deposited in landfills. As that stock decomposes, gas generation follows a declining trajectory well described by first-order decay models [30–32]; as diversion policies succeed in routing waste away from landfill, the future stock—and hence future gas potential—is reduced still further. The pathway therefore faces not increasing but

decreasing returns, and not reinforcing but self-eroding feedback. We term such a pathway a self-limiting recovery path: a recovery technology whose resource base is progressively depleted both by physical processes and by the success of the transition policies within which it operates. Table 1 contrasts the two ideal types along four dimensions.

Table 1. Conventional lock-in paths versus self-limiting recovery paths.

Dimension	Conventional Lock-In Path	Self-Limiting Recovery Path
Returns over time	Increasing returns	Decreasing (declining marginal) returns
Feedback structure	Reinforcing feedback	Self-eroding feedback
Resource base	Resource persistence	Progressive resource depletion
System tendency	Stability and entrenchment	Diversification pressure

The contrast is more than descriptive. Whereas a lock-in path is stabilized by the very mechanisms that sustain it, a self-limiting path is destabilized by them: the more effectively diversion policy works, the faster the resource base on which landfill-gas recovery depends contracts. This differs from the classical economics of exhaustible resources, in which a fixed natural stock is depleted through extraction [33]; here depletion is policy-induced rather than extraction-induced. It also differs from accounts of regime destabilization that locate the source of decline in external landscape pressures or niche competition, as in Geels' multi-level perspective on technological transitions [34] and Turnheim and Geels' application of that framework to the decline of the British coal industry [35]. In a self-limiting path, by contrast, the decline is endogenous, arising from the pathway's own coupling of resource base and policy success. The consequence is that self-limiting dynamics create diversification pressure on the incumbent pathway; whether and how that pressure is translated into an actual diversification response is mediated by strategic investment, institutional capacity, and technology choice, rather than following as a deterministic structural necessity imposed by the pathway's own dynamics.

This distinction is best made precise against the landfill-gas engineering literature, which offers a well-developed account of ordinary decay unrelated to policy. Standard first-order decay (FOD) models—including the IPCC's waste-sector methodology and the US EPA's LandGEM tool—represent methane generation from a fixed mass of already-deposited waste as an exponential decline governed by a generation-rate constant k and an ultimate methane potential L0, so that gas output from any single waste deposit falls over time purely as a function of its age, independent of any diversion policy [30,31]. Field-calibrated parameter estimates for these kinetics, including the lag phase and rate constants reported for wet landfill cells, describe how a site's output declines once waste placement ceases—that is, during post-closure operation [32]; a further, independent source of decline is imposed by the physical capacity of the gas-collection infrastructure itself, since collection efficiency is bounded by wellfield and blower capacity regardless of the gas actually generated below ground [36]. All three of these mechanisms—kinetic decay of already-placed waste, post-closure decline, and collection-capacity limits—would produce a plateauing or falling landfill-gas trajectory even in the complete absence of any policy-coupled depletion mechanism, and this is precisely the observational problem addressed in Section 5.4: a self-limiting recovery path, as defined here, is distinguished from ordinary engineering decay not by the shape of the output trajectory, which the two can share, but by the channel through which the depletion operates. Ordinary FOD depletes the stock of gas remaining in waste already placed; the policy-coupled mechanism proposed here instead depletes the future stock of waste available to be placed, by diverting it away from landfill before it arrives. The two operate on different objects—already-deposited waste

versus future waste inputs—and are not mutually exclusive: a real landfill-gas trajectory reflects both simultaneously, which is why the plant-level Odayeri evidence, closed to new inputs and hence isolated from future-diversion effects, carries more diagnostic weight in this paper than the system-wide plateau alone (Sections 3.1 and 5.4). Table 2 summarizes this comparison across the four adjacent bodies of theory just discussed.

Table 2. Self-limiting recovery paths compared with four adjacent theoretical frameworks.

Concept	Core Depletion/Change Mechanism	Object That Changes	Role of Policy Success	Distinguishing Empirical Signature
First-order landfill-gas decay (engineering)	Exponential kinetic decomposition of waste already deposited, governed by a generation-rate constant k [30–32]	Gas remaining in waste already placed	None; decay proceeds independently of diversion policy	Smooth decline dated to waste age, present even in the complete absence of any diversion policy
Exhaustible-resource depletion (economics)	Extraction of a fixed natural stock [33]	The physical resource stock itself	None; driven by extraction rates and market dynamics	Depletion tracks cumulative extraction; scarcity rents rise as reserves fall
Path dependency/carbon lock-in	Increasing returns to adoption; reinforcing techno-institutional feedback [4–7]	Not depletion; the incumbent's own dominance	Typically reinforces the incumbent rather than eroding it	Persistence and entrenchment absent an external shock or deliberate policy disruption
Regime destabilization/multi-level transitions	External landscape pressure or niche competition [34,35]	The incumbent regime's relative dominance	Exogenous to the pathway; policy may act as a landscape pressure but originates outside the pathway itself	Regime shift following landscape pressure or niche breakthrough, not tied to any single pathway's own resource base
Self-limiting recovery path (this study)	Diversion-policy success reduces future waste inputs, depleting the pathway's own future resource base	Future waste inputs not yet deposited	Central and endogenous: the same policy pursued for sustainability erodes the pathway that generates it	Plateau or step-decline concentrated at the point diversion becomes binding, followed by a stable, diversified portfolio (Proposition 1)

Proposition 1. *Recovery technologies whose resource base is depleted by the success of the transition policies within which they operate—self-limiting recovery paths—generate diversification pressure on the portfolio. This pressure need not resolve as a smooth, continuously increasing trend; it may instead manifest as a discrete or step-like portfolio reconfiguration concentrated around the point at which the resource constraint becomes binding, followed by a comparatively stable configuration thereafter. Empirically, this pressure should be observable as a decline—gradual or discrete—in the output share of the depleting pathway, even as total energy recovery expands. Because portfolio concentration indices such as the HHI are computed directly from the same share vector, a falling HHI accompanies this pattern by construction whenever new pathways scale up while the depleting pathway does not; it therefore documents that diversification occurred rather than providing*

independent evidence of the depletion mechanism itself, which must instead be assessed from the depleting pathway's own output trajectory and plant-level evidence.

This proposition links the theoretical framework to the empirical analysis that follows. If it holds for Istanbul's system, the share of landfill-gas recovery should plateau or decline even as total generation grows; concentration measures (the HHI, the Theil index, and the effective source count) register this outcome mechanically rather than testing it independently, since they are computed from the same share vector. The research questions set out in Section 1.5 are designed to test the underlying mechanism through the landfill-gas trajectory itself and through plant-level evidence, not through the concentration indices alone.

2.5. Theoretical Boundary Conditions

The self-limiting recovery path concept, and Proposition 1's prediction of diversification pressure, do not apply unconditionally: they presuppose a specific configuration of resource, policy, and institutional circumstances. Making these conditions explicit clarifies when the concept should be expected to travel to other settings, and when it should not.

Resource stock dependence is the first and most basic condition: the pathway's output must derive from a finite, decomposable stock rather than a continuously renewed flow. This is what separates Type B (self-limiting) from Type A (persistent-resource) pathways in the typology developed in Section 5.3; a technology drawing on solar, wind, or hydrological flows does not meet this condition, and the mechanism proposed here does not apply to it.

Replenishment rate is the second: even a stock-dependent pathway is self-limiting only if inputs to the stock are not replenished at least as fast as they are drawn down. Where new waste continues to arrive faster than it is diverted away, the stock does not shrink in aggregate, even if individual withdrawal points—a specific landfill cell, a site closed to new inputs—show local decline. This is precisely the pattern documented in this study: city-wide landfilled tonnage continued to rise over 2021–2024 even as the plant-level Odayeri site, closed to new inputs, showed sustained decline (Section 5.4); the mechanism was operative because replenishment had stopped locally, not because it had stopped system-wide.

Diversion intensity is the third: the depletion mechanism requires that diversion policy be strong and sustained enough to meaningfully redirect future waste away from the incumbent pathway within a policy-relevant time horizon. A weak, intermittent, or narrowly targeted diversion policy will not generate a resource constraint that binds soon enough to produce an observable plateau or decline; the self-limiting logic describes what happens once diversion is effective, not a claim that diversion is automatically effective.

Landfill closure—or more generally the cessation of new inputs at a specific site—is the fourth, and the condition under which the mechanism is most cleanly observable. As Section 5.4 discusses, a site closed to new waste isolates the depletion signal from the confounding effect of continued city-wide input growth, which is why the plant-level evidence at Odayeri, rather than the city-wide landfilled tonnage series, carries the paper's causal weight.

Waste composition is the fifth: the resource base's depletion dynamics depend on the proportion of biodegradable material in the deposited waste, since only the biogenic fraction generates landfill gas. A waste stream with a low or declining biogenic share offers less gas potential to begin with, which can either accelerate the apparent plateau, because there is less resource base to exhaust, or make it harder to attribute a given decline specifically to policy-induced depletion rather than to a shift in underlying waste composition unrelated to diversion policy.

Alternative technologies are the sixth: self-limiting dynamics generate diversification pressure, not diversification itself (Section 3.6). Whether that pressure is realized as portfolio reconfiguration, as this study documents for Istanbul, depends on whether viable alternative recovery pathways exist and can be scaled within the relevant timeframe. Where no such alternatives are available or affordable, the same resource constraint could instead manifest as a capacity shortfall, rising landfill volumes, or service disruption rather than diversification—an outcome the self-limiting framework treats as a live possibility, not one it rules out.

Regulatory conditions are the seventh: some regulatory driver—a landfill-diversion target, an extended-producer-responsibility scheme, a landfill tax or ban, or an equivalent instrument—is ordinarily what gives diversion policy its intensity in the first place (Section 2.1). In the absence of such a driver, there is no obvious reason for future waste inputs to decline, and the self-limiting mechanism has no policy lever to act through.

Institutional capacity is the eighth and last: as Section 5.5 notes for İSTAÇ's several-thousand-employee operational structure, translating diversification pressure into built capacity—securing sites, financing plants, managing a multi-year commissioning process—requires organizational, financial, and technical capability at a scale not every municipal operator possesses. Where that capacity is absent, diversification pressure may persist unresolved for longer, or be met by external operators, informal recovery, or continued landfilling by default, rather than by the kind of portfolio reconfiguration documented in this study.

Together, these eight conditions define the scope within which Proposition 1 is expected to hold, and outside of which the self-limiting framework, while still conceptually applicable, would not be expected to generate the specific empirical signature—plateau, then diversification—that this paper tests for Istanbul.

2.6. Waste Management in Türkiye and Istanbul: Context and Prior Studies

Placing this study within Türkiye's own waste management literature situates Istanbul's transition within a national trajectory that recent scholarship has only begun to document systematically. A national-level assessment covering 2002–2022 shows that Türkiye's municipal waste system moved decisively away from open burning and uncontrolled dumping toward licensed sanitary landfilling, but that recycling rose only from roughly 5–7% to about 13% of the waste stream over two decades—far below EU levels—while energy recovery showed no consistent upward trend nationally over the same period [37]. This is broadly consistent with the EEA's country profile for Türkiye [38] and its companion cross-country waste generation statistics [39], which together likewise find Türkiye's landfill rate comparatively high and largely stagnant even as national recycling improved further after 2017 under the Zero Waste policy. Read against this backdrop, Istanbul's system-level shift documented in Section 4—a near-tripling of waste-to-energy generation and a fall in source concentration from an HHI of 1.00 to 0.47 over just five years—stands out as considerably faster and more structurally decisive than the national pattern, consistent with the city's exceptional scale, institutional capacity (Section 5.5), and concentrated infrastructure investment rather than with a broader, uniformly diffusing national trend.

Existing Istanbul-specific research has concentrated on discrete technical or social dimensions of the system rather than on the portfolio as a whole. Facility- and site-level studies examine landfill-gas potential, leachate composition, and the local environmental footprint of Istanbul's major disposal sites, but do not track how the pathways' relative contributions have co-evolved over time. Complementary social-science work documents the itinerant, largely informal waste-picking workforce that operates alongside İSTAÇ's

formal infrastructure, and the tensions that recent formalization policy has introduced into that arrangement (Section 5.7) [40]. What remains largely absent from this literature is a longitudinal, portfolio-level account of how Istanbul's landfill-gas, energy-from-waste, and biomethanization pathways have co-evolved as an integrated system—the gap this study addresses.

3. Materials and Methods

3.1. Research Design

The study employs a longitudinal single-case design, tracing the evolution of one municipal waste-to-energy system—that of Istanbul—across the period 2020–2024. A longitudinal design is appropriate because the phenomenon of interest is not the performance of any single technology at a point in time but the change in the composition of a recovery portfolio over time, which can only be observed across successive years. A single-case design is chosen deliberately: the aim is analytical rather than statistical generalization [41]. Istanbul is treated as a revelatory and instrumental case through which the proposed concept of a self-limiting recovery path can be observed, characterized, and assessed; the case provides an existence proof and an account of boundary conditions rather than a basis for frequency claims across cities.

Istanbul is well suited to this purpose for three reasons. First, it is one of Europe's largest metropolitan regions, with approximately 15.7 million inhabitants [8] and a correspondingly large municipal waste stream, so that portfolio dynamics are pronounced rather than marginal. Second, the city operates multiple waste-to-energy technologies side by side—landfill-gas recovery, energy-from-waste incineration, and biomethanization—which makes it possible to observe diversification within a single integrated system rather than across heterogeneous jurisdictions. Third, the study window coincides with a period of rapid transformation, during which major new capacity was commissioned, allowing the shift from single-source dependence toward a diversified portfolio to be captured as it unfolds.

Istanbul's municipal solid waste is consolidated through a network of transfer stations and routed to three principal landfill-gas recovery complexes that function as the system's main energy-generation nodes: Odayeri (European side, Eyüpsultan, commissioned 2008), Kömürcüoda (Asian side, Şile, commissioned 2009), and Seymen (European side, Silivri, commissioned 2020). The temporal sequence of these capacity additions—landfill-gas generation at Odayeri and Kömürcüoda (2008–2009), the introduction of refuse-derived fuel (RDF/ATY) production (2018), and the commissioning of the Seymen plant (2020)—provides the institutional chronology that underlies the diversification dynamics traced in this study. The pre-transition baseline is documented in the 2019 İSTAÇ Annual Activity Report [42], which records landfill-gas electricity generation of 327,430 MWh at Odayeri and 150,227 MWh at Kömürcüoda against a combined installed capacity of approximately 71 MW across 51 gas engines; Seymen was not yet in energy-generation service. The 2020 İSTAÇ Annual Activity Report [43] captures the first year of Seymen's operation, reporting site-level generation of 244,494 MWh (Odayeri), 173,349 MWh (Kömürcüoda), and 38,927 MWh (Seymen)—together constituting the 457 GWh total generation baseline used in the analysis. İSTAÇ operates waste collection, transfer-station logistics, landfilling, material recovery, composting, RDF production, and energy generation as components of a single organizational structure, reflected in its dedicated Operations and Waste Logistics Directorate (İşletmeler ve Atık Lojistik Müdürlüğü). The observed diversification process therefore took place within an integrated waste logistics and resource recovery network rather than within isolated energy facilities, a structural feature that bears on the supply-chain interpretation developed in Section 5.1.

A targeted search was carried out for facility-level Odayeri and Kömürcüoda generation figures predating the 2019 baseline, extending back toward each site's 2008–2009 commissioning, in order to establish whether the study window captures a complete growth–peak–decline cycle rather than a single segment of one. İSTAÇ's own annual-report archive is not digitized before 2019; earlier secondary sources (İBB and press materials) report only installed capacity at various undated points (for example, approximately 46 MW combined circa the early 2010s, rising to approximately 109 MW across the three LFG sites by the later 2010s), not annual generation in MWh, and are therefore not usable as a time series. No verifiable pre-2019 facility-level generation series for either site could be located. Because both sites were commissioned roughly twelve to sixteen years before the study window opens, and landfill-gas generation from a given waste deposit typically follows a rise–peak–decline trajectory over the operating life of a cell, the 690–698 GWh plateau observed in 2022–2024 could plausibly represent the declining tail of an earlier peak that occurred before 2019 rather than a plateau reached for the first time within the study window. The 2020–2024 data therefore do not, on their own, establish a complete long-run trajectory for landfill-gas output at Istanbul's sites; this is treated as an explicit scope limitation and revisited in Section 5.5.

3.2. Data Sources

The primary data source is the set of annual İSTAÇ activity and sustainability reports [42–44], which provide facility-level information on electricity generation by pathway, processed waste tonnages, and related operational indicators for the study period. The 2019 Annual Activity Report [42] and the 2020 Annual Activity Report [43] are used specifically to establish the pre-transition baseline and the commissioning context of the Seymen plant; they supply site-level generation figures, installed-capacity data, and the institutional chronology described in Section 3.1. The 2021–2024 Sustainability Reports [44] provide the main longitudinal dataset for the portfolio and concentration analysis. These figures form the basis for the portfolio decomposition and concentration analysis. Because they are self-reported, two independent validation sources are used. Eurostat municipal waste indicators [45] provide a benchmark that situates the Istanbul case within wider European patterns of landfilling, recycling, and energy recovery. Publicly available EPDK (Energy Market Regulatory Authority) licensing records [46] provide an independent cross-check on the commissioning dates and installed capacities of individual facilities. The combination of one primary and two validation sources supports triangulation and is discussed in full, including what was compared against what and what reconciliation rule was applied, in Section Data Validation and Triangulation. A specific data-quality issue concerns the 2021 pathway-level breakdown: İSTAÇ's own Annual Activity Reports (Faaliyet Raporları) do not publish a separate per-pathway split for 2021, reporting only the system-wide total (844 GWh) used in Table 3. A subsequent, more targeted search located a retrospective facility-level breakdown for 2021 in a different İSTAÇ publication—the 2022 Sustainability Report (p. 73)—which reports landfill gas 599 GWh, energy-from-waste 235 GWh, and biomethanization 7 GWh. These three components sum to 841 GWh; İSTAÇ's own report states a total of 842 GWh for this breakdown, 1 GWh above the sum of its own facility-level figures, a discrepancy attributable to independent rounding at the facility level (Section 3.7). Both the 841 GWh component sum and the 842 GWh reported total are within 0.2–0.4% of the previously reported 844 GWh system-wide total. This breakdown, normalized to 841 GWh, is used directly in Tables 3 and 4. Notably, it closely corroborates the İBB-sourced press reports from February 2022 that had given an approximate 2021 split (landfill gas ≈ 600 GWh; incineration ≈ 235 GWh; biomethanization ≈ 9 GWh); we had initially excluded that press estimate as physically implausible, reasoning that

its ≈ 235 GWh incineration figure was difficult to reconcile with a plant commissioned only in late November 2021. The directly sourced breakdown shows the press estimate was in fact broadly accurate, and Section 3.7 discusses the reconciliation, including what it implies about the EfW plant's operational timeline relative to its formal commissioning date.

Table 3. Pathway-level electricity generation (GWh) and the full source-share vector, 2020–2024, compiled from İSTAÇ Annual Activity Reports (Faaliyet Raporları). Reporting each pathway's share alongside its GWh value makes the share vector directly visible rather than requiring it to be inferred from raw generation and the concentration indices in Table 4. Figures are rounded to the nearest GWh; shares are rounded to one decimal place and may not sum to exactly 100% due to rounding. For 2021, the three pathway-level figures (599, 235, and 7 GWh) sum to 841 GWh, which is the total reported here and the value used to normalize the pathway shares in this table and the concentration indices in Table 4; İSTAÇ's own source report states a total of 842 GWh for the same breakdown, a 1 GWh difference attributable to independent rounding at the facility level (Section 3.7). The energy-from-waste and biomethanization plants were commissioned in November 2021. İSTAÇ's Annual Activity Reports do not publish a separate 2021 per-pathway breakdown, but a retrospective breakdown reported in the İSTAÇ 2022 Sustainability Report (p. 73) is used here; see Section 3.7 for the search process, the located figures, and their reconciliation with the previously bounded estimate and the İBB press-reported split. LFG = landfill-gas recovery; EfW = energy-from-waste incineration; Biomethan. = biomethanization. From 2022 onward, Biomethan. sums generation from İSTAÇ's two biomethanization facilities (Kemerburgaz/Işıklar and Kömürcüoda); for 2021, it reflects the Kömürcüoda facility only, as the Kemerburgaz/Işıklar facility had not yet begun reporting measurable output (Section 3.7). The İSTAÇ 2022 Annual Activity Report and 2022–2024 Sustainability Reports report these as separate line items that we aggregate under the single biomethanization pathway used throughout this paper.

Year	LFG (GWh)	EfW (GWh)	Biomethan. (GWh)	Total (GWh)	LFG Share (%)	EfW Share (%)	Biomethan. Share (%)
2020	457	0	0	457	100	0	0
2021	599	235	7	841	71.2	27.9	0.9
2022	698	583	25	1306	53.4	44.6	1.9
2023	697	586	33	1316	53.0	44.5	2.5
2024	691	600	41	1332	51.9	45.0	3.1

Table 4. Source-concentration and diversification indicators, 2020–2024. Indices are computed from the pathway shares in Table 3 for all five years in the study period; the 2021 values reflect the directly sourced pathway split discussed in Section 3.7, with shares normalized to the 841 GWh directly summed total so that the Herfindahl–Hirschman index, effective source count, and Theil index are all derived from the same share vector.

Year	HHI	Effective Source Count (1/HHI)	Theil Index
2020	1.00	1.0	1.099
2021	0.585	1.71	0.461
2022	0.485	2.06	0.328
2023	0.479	2.09	0.309
2024	0.473	2.12	0.291

Data Validation and Triangulation

This section makes explicit what the triangulation referenced in Section 3.2 actually consists of: which figures were compared against which, what the results were, and what reconciliation rule was applied when sources diverged.

EPDK cross-check. EPDK's public licensing records were used to verify two categories of information: the commissioning dates and the installed capacities of the individual facilities. For the EfW and biomethanization plants, EPDK licensing is consistent with the commissioning dates already reported in İSTAÇ's own 2022 Annual Activity Report—26 November 2021 for the EfW plant and 11 November 2021 for the biomethanization plant (Section 3.7)—and with the installed capacities used throughout this paper (85 MW and 1.4 MW, respectively). For the landfill-gas sites, EPDK licensing is consistent with the approximately 71 MW combined capacity reported in İSTAÇ's 2019 baseline (Section 3.1). EPDK does not, however, publish a facility-level annual generation (MWh) series comparable to the GWh figures reported in Table 3; its licensing records therefore corroborate the physical characteristics of the facilities—what exists, and since when—but cannot cross-check the year-by-year generation totals themselves. This is the same constraint already identified in Section 3.7's search for a pre-2019 and 2021 generation series, stated here as a general property of the EPDK source rather than a gap specific to any one year.

Eurostat/TÜİK cross-check. Eurostat's municipal waste indicators, and the Turkish Statistical Institute (TÜİK) figures that underlie them, are published at the national level, not the city or facility level, so they cannot validate Istanbul-specific generation figures directly. What they can do, and what they are used for here, is to situate Istanbul's trajectory within the national pattern. National statistics indicate that landfilling remained the dominant disposal route in Türkiye throughout the study period, at roughly 67–70% of municipal waste as of 2020–2022, with waste-recovery facilities receiving only around 13% of national municipal waste as of 2020 [45]. Read against this national backdrop, the İSTAÇ-reported diversification traced in this paper—a near-tripling of energy recovery and a fall in the HHI from 1.00 to 0.47—describes a substantially more advanced energy recovery trajectory than the national average, consistent with Istanbul's position as one of Türkiye's largest and most heavily invested municipal systems (Section 3.1) rather than evidence of a broader national shift. This is a plausibility check on Istanbul's relative standing, not a reconciliation of matching figures: no directly comparable Istanbul-specific Eurostat or TÜİK series exists at the facility or pathway level against which the GWh figures in Table 3 could be checked.

Reconciliation rule. Because neither EPDK nor Eurostat/TÜİK publishes data at the facility-year resolution the analysis requires, İSTAÇ's own annual and sustainability reports are treated throughout this paper as the authoritative primary source for all generation figures; EPDK and Eurostat/TÜİK function only as independent checks on, respectively, the physical facts (commissioning dates, installed capacities) and the broader national context. Where a cross-check source diverges from İSTAÇ's reported figures—as with the İBB press estimate for 2021 discussed in Section 3.2—the discrepancy is reported explicitly and the İSTAÇ- or capacity-anchored figure is retained, rather than being averaged or silently reconciled with the alternative source.

3.3. Analytical Framework

The analysis proceeds in four linked steps, summarized in Figure 1. Municipal waste flows are first allocated to the three recovery pathways. Pathway-level electricity generation is then recorded for each year, providing the raw quantities from which source shares are computed. These shares feed a set of concentration and diversification metrics—the Herfindahl–Hirschman index, the effective source count, and the Theil index—which summarize how concentrated or balanced the portfolio is and how this changes over time. Finally, the resulting trends are interpreted through a qualitative stock–flow interpretation, informed by system-dynamics principles, of the relationships that govern landfill-gas generation, which renders the concept of a self-limiting recovery path empirically observable.

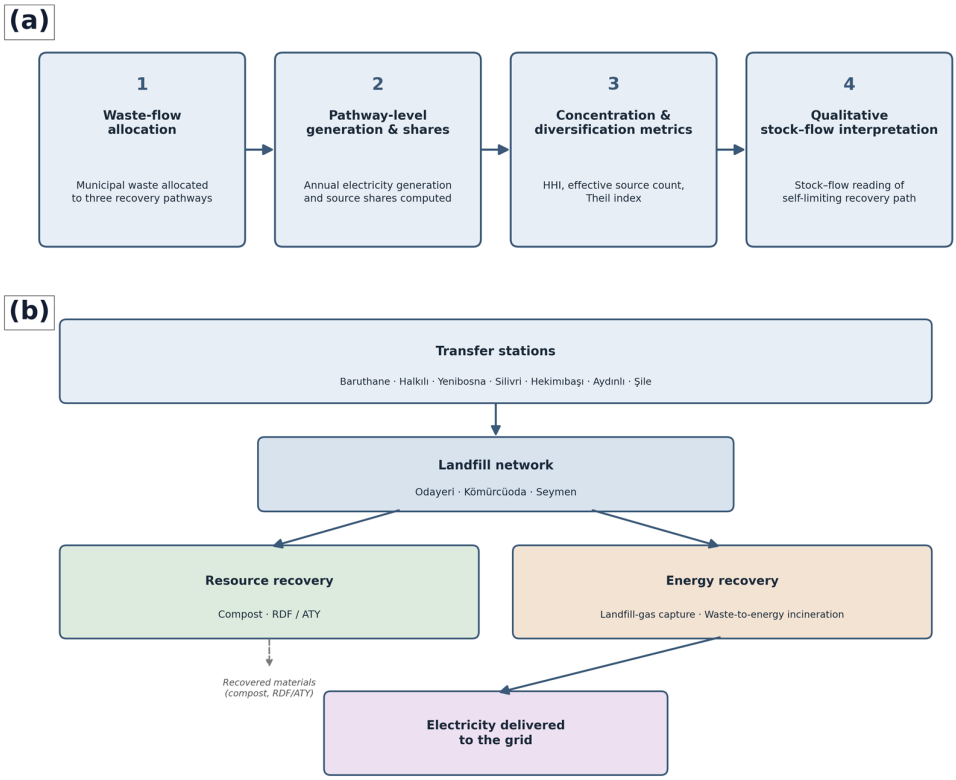


Figure 1. Analytical framework and system structure. (**a**) Analytical framework: from waste flows to concentration metrics and a qualitative stock–flow interpretation. (**b**) The integrated circular energy supply chain of Istanbul's municipal waste system. Municipal waste is consolidated at transfer stations (Baruthane, Halkılı, Yenibosna, Silivri, Hekimıbaşı, Aydınlı, Şile) and routed to the landfill network (Odayeri, Kömürcüoda, Seymen); resource recovery processes (compost and RDF/ATY) and energy recovery pathways (landfill-gas capture and waste-to-energy incineration) then convert the feedstock into electricity delivered to the grid.

Why Not Regression: A Methodological Note

A natural extension of this framework would fit a regression of landfill-gas output, or its portfolio share, against time or a policy-diversion covariate. This is deliberately not attempted here. The pathway-level panel underlying the analysis spans five annual observations (2020–2024), all of which now carry a full per-pathway decomposition following the resolution of the 2021 data gap (Section 3.7). A regression fit to five annual points still offers negligible degrees of freedom, cannot distinguish a genuine continuous time trend from the rapid two-year reconfiguration already documented in Section 4.3, and would report standard errors and significance levels that convey a precision the underlying data do not support. In a single-case, short-panel design of this kind, a fitted coefficient is more likely to mislead readers about the strength of the evidence than to summarize it usefully, and is avoided for that reason rather than for lack of effort. In place of a formal regression, the study relies on two strategies better suited to this data structure: a systematic comparison of competing mechanistic explanations for the observed landfill-gas plateau (Section 4.4), which weighs each candidate account against the same evidence without requiring a fitted trend line, and the direct sourcing and reconciliation of the 2021 pathway split (Section 3.7), which replaces an initially bounded estimate with officially reported figures once located. Together, these substitute qualitative and evidence-based triangulation for a statistical inference the data cannot support. The same data constraint applies with even greater force to a fully quantitative, calibrated system-dynamics simulation of the stock–flow structure sketched in Section 3.6; that extension is discussed, and deferred to future work, in Section 6.

3.4. Portfolio Decomposition

Let i index the recovery pathways (landfill-gas recovery, energy-from-waste incineration, and biomethanization) and t index the years of the study period. Total annual electricity generation is the sum of generation across pathways:

$$G_t = \sum_i G_{i,t} \tag{1}$$

The relative role of each pathway is captured by its source share, defined as the ratio of pathway generation to total generation in a given year:

$$s_{i,t} = \frac{G_{i,t}}{G_t} \tag{2}$$

By construction the shares are non-negative and sum to one within each year, so that changes in the share vector over time describe the reallocation of generation among pathways—that is, the diversification of the portfolio.

3.5. Concentration and Diversification Metrics

Three complementary indices, adapted from the energy-diversity and supply-risk studies [9–11,25,26], summarize the share vector. The Herfindahl–Hirschman index is the sum of squared shares:

$$HHI_t = \sum_i s_{i,t}^2 \tag{3}$$

The HHI equals one under complete single-source dependence and declines toward 1/n as generation becomes evenly distributed across n pathways; lower values therefore indicate greater diversification. Its reciprocal, the effective source count, expresses the same information as an intuitive number of equally weighted sources on which the system effectively relies:

$$N_t = \frac{1}{HHI_t} \tag{4}$$

The Theil index provides a complementary, entropy-based measure of how unevenly generation is distributed across pathways, where $\bar{s}$ denotes the mean share (equal to 1/n):

$$T_t = \sum_i s_{i,t} ln\left(\frac{s_{i,t}}{\bar{s}}\right) \tag{5}$$

Two conventions fix the index precisely. First, n is set to three throughout the analysis—the number of recovery pathways defined in the classification scheme (LFG, EfW, and biomethanization)—rather than to the number of pathways with positive generation in a given year; in 2020, when only LFG generated electricity, this yields a mean share of 1/3 and a Theil value of ln(3) ≈ 1.099 rather than zero, reflecting concentration relative to the three-pathway system defined for the whole study period rather than relative to a hypothetical single-pathway system. Second, for any pathway with zero share the corresponding term in the sum is set to zero by the standard limiting convention used throughout the entropy and inequality literature, since a vanishing share contributes a vanishing term to the index regardless of the logarithm's behavior at zero. Higher Theil values indicate greater concentration. Because all three indices are monotonic transformations of the same underlying share vector, they cannot function as independent pieces of evidence, and this paper does not treat them as such. The Herfindahl–Hirschman index is used throughout as the primary concentration metric, consistent with its standing as the most widely used index in the energy-diversity and supply-risk literature on which this study draws [9–11,25,26]. The effective source count is reported alongside it not as a

separate measure but as its intuitive reciprocal transform, restating the same HHI value as an interpretable number of equally weighted sources rather than adding new information. The Theil index, built on an entropy rather than a sum-of-squares logic, is reported as an alternative functional form of the same share vector: a Theil trajectory that moves with the HHI trajectory is read as a robustness check on the choice of functional form, not as additional corroborating evidence.

3.6. Qualitative Stock–Flow Interpretation

The concentration metrics describe how the portfolio changes, but not why one pathway in particular ceases to grow. To address this, landfill-gas recovery is interpreted as a stock-dependent technology embedded in the stock–flow structure shown in Figure 2. In the physical chain (A), a stock of biodegradable waste in place undergoes anaerobic decomposition, which generates gas and, in turn, electricity. Because this stock is finite and depletes as it decomposes, gas generation from any given deposit declines over time, a behavior well established in first-order decay models of landfill gas [30–32,47].

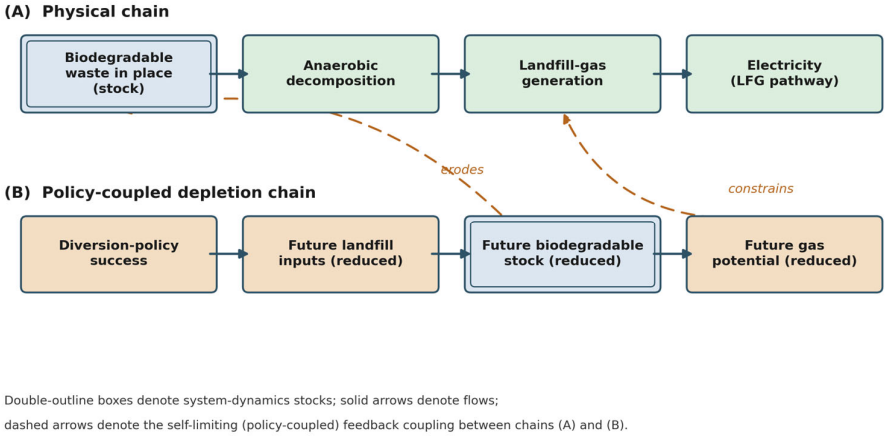


Figure 2. Qualitative stock–flow interpretation of landfill gas as a stock-dependent, self-limiting pathway.

The distinctive feature of the system is the policy-coupled depletion chain (B). Successful landfill diversion—the very objective of the energy-from-waste and biomethanization investments—reduces future landfill inputs, which lowers the future biodegradable stock and therefore the future gas potential on which landfill-gas recovery depends. The dashed coupling in Figure 2 captures this self-limiting relationship: the success of diversion policy erodes the resource base of the incumbent pathway. This interpretation is qualitative and structural; it is used to explain observed trends rather than to calibrate a simulation model.

This reading renders the concept of a self-limiting recovery path empirically tractable by specifying potential observable signatures. First, a self-limiting pathway should exhibit a plateau or decline in absolute output even as total generation rises (tested through pathway-level trends and the falling landfill-gas share). Second, the marginal contribution of the depleting pathway per unit of in-place stock should decline. Third, landfilled tonnage should decouple from recovered energy as diversion advances. Of these, the first and third are directly observable in the available facility-level data and are evaluated in the analysis that follows; the second, which would require stock-resolved estimates of in-place biodegradable waste, cannot be measured directly under present data constraints and is therefore retained as a conceptual rather than an empirically tested signature. Together with the concentration metrics of Section 3.5, these signatures operationalize Proposition 1 and provide the empirical basis for the research questions set out in Section 1.5.

3.7. The 2021 Pathway Split: Resolving the Data Gap

The absence of a reliable pathway-level breakdown for 2021 was identified as a specific limitation of the data, and a targeted search was carried out to close it. Beyond the İSTAÇ annual and sustainability reports [42–44] already used throughout the study, this search covered İBB public communications and EPDK licensed-generation records. İSTAÇ's 2022 Annual Activity Report confirms the precise commissioning dates and installed capacities of the two new pathways: the Kemerburgaz Atık Yakma ve Enerji Üretim Tesisi (EfW; 85 MW installed capacity) was formally opened on 26 November 2021, and the Kemerburgaz Biyometanizasyon Tesisi (1.4 MW installed capacity) on 11 November 2021. EPDK's licensing records confirm these commissioning dates but, like İSTAÇ's own annual reports, do not publish a monthly or facility-level generation series for 2021. Initially, no reliable pathway-level decomposition for 2021 could be located in any of the three source types consulted, and a bounded sensitivity range was constructed instead, as summarized below.

In the absence of a reported series, a bounded sensitivity range can be constructed from information that is independently verifiable: the official commissioning dates, the plants' installed capacities, and their realized 2022 capacity factors. Scaling installed capacity by the days available before commissioning gives an absolute physical ceiling of approximately 71 GWh (EfW) and 2 GWh (biomethanization); applying the plants' own 2022 capacity factors narrows this to a combined upper bound of approximately 56 GWh, and a more conservative ramp-up capacity factor typical of a newly commissioned thermal plant's first weeks of operation would place combined output closer to 14–19 GWh. On this basis, 15–60 GWh is treated here as a defensible bounded range for combined EfW and biomethanization generation in 2021 (full calculation in the Supplementary Data File).

Applying this range to the 844 GWh total previously reported for 2021 implied a landfill-gas output above, not below, the 690–698 GWh plateau observed in 2022–2024, and was difficult to reconcile with the previously circulated İBB press figures for 2021 (landfill gas $\approx$ 600 GWh; incineration $\approx$ 235 GWh; biomethanization $\approx$ 9 GWh). This tension prompted a further, more targeted search rather than an outright exclusion of the press estimate, described next.

That further search located a retrospective facility-level breakdown for 2021 in a different İSTAÇ publication than the Annual Activity Reports used elsewhere in this study: the İSTAÇ 2022 Sustainability Report (p. 73) reports a comparative 2020–2022 table giving, for 2021, landfill-gas generation of 599 GWh (Odayeri 202 GWh, Kömürcüoda 190 GWh, Seymen 207 GWh), energy-from-waste generation of 235 GWh, and biomethanization generation of 7 GWh (from the Kömürcüoda biomethanization facility; the Kemerburgaz/Işıklar facility, commissioned 11 November 2021, had not yet begun reporting measurable output), for a total of 842 GWh. These three facility-level figures sum to 841 GWh rather than 842 GWh; the 1 GWh difference is attributable to independent rounding of the underlying facility-level figures in İSTAÇ's own report and is not treated as a discrepancy requiring reconciliation. Both the 841 GWh directly summed total and İSTAÇ's own reported 842 GWh figure are within 0.2–0.4% of the 844 GWh system-wide figure previously reported for 2021, and we treat these as consistent, directly sourced measurements. Table 3 reports the pathway-level figures together with their directly summed total of 841 GWh; the concentration indices in Table 4 are computed from the pathway shares normalized to this 841 GWh total, ensuring that the Herfindahl–Hirschman index, the effective source count, and the Theil index are all derived from the same share vector.

This directly sourced breakdown falls well outside the bounded range constructed above: realized 2021 EfW output (235 GWh) is more than three times the approximately 71 GWh physical ceiling implied by the plant's official 26 November 2021 commissioning date, and exceeds even the more generous 56 GWh capacity-factor-based upper bound

by a factor of four. This may imply that the EfW plant was delivering grid electricity before its formal commissioning date, although an earlier start-of-generation date cannot be independently confirmed from the sources consulted; the plant may instead have been in a testing or ramp-up phase preceding the inauguration recorded in İSTAÇ's Annual Activity Report and in EPDK's licensing records. The discrepancy may also reflect a difference in how "commissioning" is defined across data sources, since the term can denote formal licensing or inauguration in company reporting rather than the commencement of grid-connected generation, a distinction not always made explicit in corporate sustainability reporting; the present data cannot adjudicate between these readings. Consistent with this, the directly sourced breakdown corroborates the previously circulated İBB press figures (landfill gas $\approx$ 600 GWh; incineration $\approx$ 235 GWh; biomethanization $\approx$ 9 GWh) rather than contradicting them; our initial exclusion of that estimate as physically implausible is revised in light of this evidence.

With a directly sourced 2021 breakdown now available, Tables 3 and 4 report the 2021 pathway split and concentration indices alongside the other study years, rather than treating 2021 as an excluded or imputed observation. The resulting trajectory—HHI falling from 1.00 in 2020 to 0.585 in 2021 and 0.485 in 2022, then declining only modestly through 2024—is discussed in Section 4.3.

4. Results

4.1. Growth of Total Generation

Total electricity generation from Istanbul's municipal waste-to-energy system rose markedly over the study period, increasing from 457 GWh in 2020 to 1332 GWh in 2024—an increase of approximately 191%, or close to a threefold expansion. The growth was substantial and sustained rather than the product of a single exceptional year. Table 3 reports the year-by-year trajectory of total generation alongside its decomposition by recovery pathway.

4.2. Portfolio Evolution

The composition of the portfolio changed fundamentally over the same interval. In 2020 the system was effectively mono-source: landfill-gas recovery (LFG) supplied virtually all generation. From 2021 onward, the commissioning of energy-from-waste (EfW) capacity and, subsequently, biomethanization introduced additional pathways whose contributions grew over time. Crucially, landfill-gas output did not expand in step with the system; it settled onto a plateau of approximately 690–698 GWh. As a result, growth was predominantly driven by diversification into EfW and biomethanization: of the 875 GWh increase in total generation between 2020 and 2024, approximately 234 GWh (26.7%) came from landfill gas and approximately 641 GWh (73.3%) came from EfW and biomethanization combined, and the relative share of LFG fell substantially by 2023. The full share vector reported in Table 3 makes clear that this diversification is, in practice, overwhelmingly a two-pathway story: EfW's share rose from 0% in 2020 to roughly 44–45% by 2022–2024, closely tracking the fall in the LFG share, while biomethanization's share ramped up more slowly from 1.9% in its first full year of operation (2022) to 3.1% of total generation by 2024. Table 3 reports pathway-level generation and the corresponding source shares for each year. Figure 3 shows the resulting year-by-year composition.

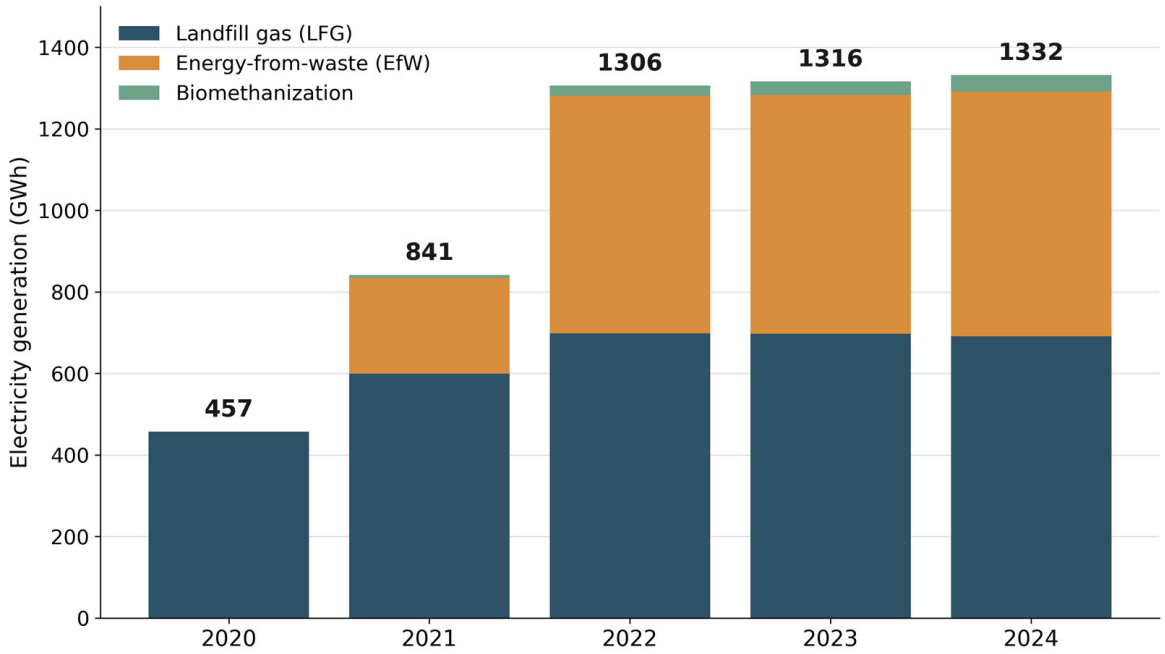


Figure 3. Electricity generation by recovery pathway, 2020–2024. The EfW and biomethanization facilities were formally commissioned in November 2021; however, the retrospective 2021 generation data may imply that electricity generation, particularly at the EfW facility, began before the formal commissioning date, though this cannot be independently confirmed (see Section 3.7). The 2021 breakdown shown here is drawn from the İSTAÇ 2022 Sustainability Report rather than the Annual Activity Reports used for other years (see Section 3.7 and the note to Table 3).

4.3. Diversification Indicators

The structural shift away from single-source dependence is captured by the three concentration measures defined in Section 3.5. The Herfindahl–Hirschman index fell from 1.00 in 2020—its maximum, corresponding to complete single-source dependence—to 0.47 in 2024, the primary evidence for this shift. Restating the same value, the effective source count rose from 1.0 to approximately 2.1, indicating a move from reliance on a single effective source to roughly two. As a robustness check on this functional-form choice, the Theil index moves in the same direction, from 1.099 to 0.291. Because all three are transformations of the same share vector, this agreement confirms internal consistency rather than providing three independent lines of evidence; the HHI-based reading is what the paper treats as established. This shift, however, is concentrated in a rapid two-year decline between 2020 and 2022—when the EfW plant's first, partial year of operation was followed by its and biomethanization's first full year—rather than a gradual, year-on-year process, the HHI falls from 1.00 in 2020 to 0.585 in 2021 and 0.485 in 2022, after which the portfolio is comparatively stable, moving only from 0.485 in 2022 to 0.473 in 2024, a far smaller shift than the initial two-year decline. The 2020 starting point remains a degenerate single-source observation, but with the 2021 pathway split now directly sourced (Section 3.7), the indices rest on five complete annual values across the full study period; the headline decline should therefore be read as a rapid two-year reconfiguration followed by a stable post-2022 portfolio, rather than a single discrete jump or a sustained, continuously increasing diversification trend. Table 4 reports their year-by-year values. Figure 4 plots these trajectories.

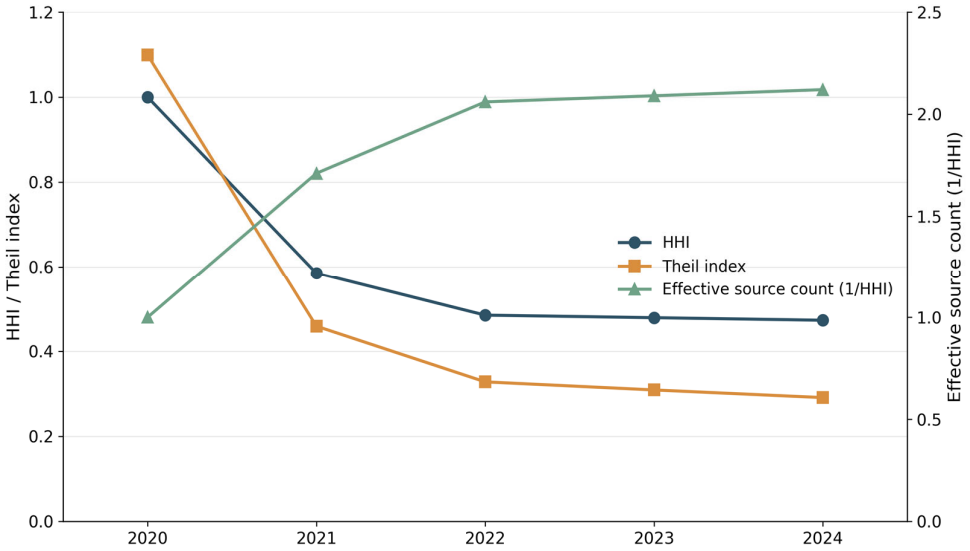


Figure 4. Trajectories of the source-concentration and diversification indicators—the Herfindahl–Hirschman index, the effective source count (1/HHI), and the Theil index—across the study period. Note. Indices are computed from the pathway shares in Table 3, as tabulated in Table 4, for all five study years; the 2021 values are drawn from the İSTAÇ 2022 Sustainability Report (Section 3.7).

4.4. Evidence for a Self-Limiting Recovery Path

The preceding results allow a direct examination of Research Question 2, which asks whether landfill-gas recovery displays the empirical signature of a self-limiting recovery path—a plateauing, resource-constrained output even as the overall portfolio expands. Landfill-gas generation grew initially and then settled onto a plateau of approximately 690–698 GWh; it did not scale with the rest of the system, while total generation nearly tripled. The expansion of the system therefore decoupled from landfill-gas recovery. The plateau on its own, however, does not uniquely identify a self-limiting mechanism: a flat landfill-gas output is equally consistent with the natural maturation of gas production in existing cells, the closure of the Odayeri site, and an effective capacity ceiling on gas collection. The present data cannot fully separate these explanations, so the plateau is treated here as necessary but not sufficient evidence, with the self-limiting reading resting in addition on the plant-level decline at Odayeri reported in Section 5. Table 5 compares these four candidate explanations directly, alongside the pattern each predicts and the available evidence.

Table 5. Competing explanations for the landfill-gas plateau.

Candidate Explanation	Expected Pattern	Available Evidence	Assessment
Policy-coupled depletion (self-limiting mechanism)	Decline concentrated at sites no longer receiving significant new waste; decline tracks the success of diversion policy rather than the mere passage of time; need not appear at the city scale for the mechanism to operate at the plant level.	Odayeri (largely closed) shows a sustained decline, 189 → 180 → 165 GWh (2022–2024); city-wide landfilled tonnage rose over 2021–2024.	Plant-level evidence supportive but non-exclusive; not supported at the city scale (Section 5.4).

Table 5. *Cont.*

Candidate Explanation	Expected Pattern	Available Evidence	Assessment
Natural first-order decay	Gas generation from any given waste deposit declines predictably over time following standard landfill-gas decay kinetics, independent of policy or diversion.	Consistent with the observed Odayeri decline and the system-wide plateau; well established in first-order decay models of landfill gas [30–32].	Cannot be ruled out with available data; predicts the same directional signature as policy-coupled depletion, so the two are observationally equivalent here.
Site closure (Odayeri)	Output falls specifically at the closing site while other LFG sites maintain or grow output—a site-specific step-decline rather than a system-wide trend.	Decline recorded at Odayeri; no reported closure events at Kömürcüoda or Seymen during the study period.	Consistent with the Odayeri-specific pattern but does not on its own explain why combined LFG output (all three sites) failed to scale with the rest of the system.
Collection/capacity ceiling	Output plateaus once gas-collection infrastructure (wellfields, blowers, engines) operates near installed capacity, regardless of the underlying gas resource, consistent with documented gas-capture efficiency limits [36].	Installed LFG capacity (≈71 MW combined at the 2019 baseline) is broadly consistent with the observed plateau level; no facility-level capacity-utilization series is available to test this directly.	Cannot be tested directly with available data; remains a plausible competing account that the present dataset cannot rule out.

These four accounts are not mutually exclusive and may operate in combination. The plant-level evidence at Odayeri is consistent with policy-coupled depletion, but natural first-order decay [30–32] predicts the same directional signature and cannot be distinguished from it with the present data; site closure and a collection/capacity ceiling remain plausible contributing factors that the available evidence can neither confirm nor rule out. The self-limiting reading advanced in this paper is therefore best read as the most theoretically productive of several observationally compatible accounts, not as the uniquely established one.

Proposition 1 specifies a sharper, testable signature: a decline—gradual or discrete—in the output share of the depleting pathway together with falling source concentration, observed even as total recovery expands. The data are consistent with each element of the signature predicted by Proposition 1, and the trajectory is a discrete reconfiguration rather than a smooth, continuously increasing trend: the Herfindahl–Hirschman index, the paper's primary concentration metric, falls from 1.00 in 2020 to 0.585 in 2021 and 0.485 in 2022, coinciding with the EfW plant's first partial year and then the EfW and biomethanization plants' first full year of operation, and then declines more gradually through 2024 (0.479, then 0.473); the effective source count restates this same movement as a rise from 1.0 to about 2.1 effective sources, and the Theil index moves in the same direction as a robustness check (1.099 to 0.291), rather than as separate confirmation. The landfill-gas share fell from near-total dominance in 2020 to roughly 52% in 2024, while total generation rose from 457 to 1332 GWh. The landfill-gas plateau and this largely one-off drop in HHI, followed by a stable post-reconfiguration portfolio, thus co-occur during a period of overall expansion, matching the discrete-reconfiguration reading of the signature stated in Proposition 1. Figure 5 illustrates this decoupling of total generation from the plateauing landfill-gas trajectory. This co-occurrence should not be read as independent confirmation

of the depletion mechanism: because the HHI is computed from the same portfolio shares, its decline is a mechanical accounting consequence of LFG output remaining flat while EfW and biomethanization output grew, and would appear under any explanation for the LFG plateau, not only a policy-coupled depletion mechanism. The HHI decline therefore documents that diversification occurred; the causal question of why LFG failed to scale is addressed separately, through the LFG output trajectory itself and the plant-level Odayeri evidence weighed against competing explanations in Table 5.

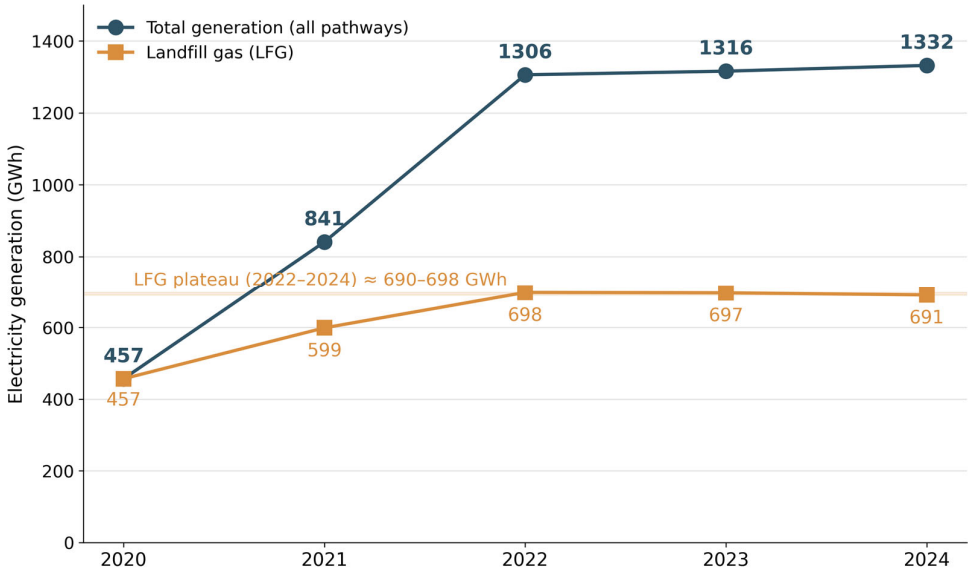


Figure 5. Decoupling of total generation from landfill-gas recovery: total output nearly triples while landfill gas settles onto a plateau of roughly 690–698 GWh, a pattern consistent with the proposed self-limiting recovery path interpretation. Note. Pathway-level electricity-generation figures are compiled from İSTAÇ Annual Activity Reports (Faaliyet Raporları) for 2020, 2022–2024, and from the İSTAÇ 2022 Sustainability Report for 2021 (Section 3.7), and denote net electricity delivered to the grid; landfill-gas figures aggregate the Odayeri, Kömürcüoda, and Seymen plants. The 2021 landfill-gas figure (599 GWh) sits below, not above, the 690–698 GWh plateau observed in 2022–2024, indicating that the system reached the plateau in 2022 rather than having already exceeded it in 2021. Press reports attributing an approximate 2021 split to İBB (see the note to Table 3) are corroborated by, rather than excluded in favor of, this directly sourced breakdown.

Two accompanying system-level indicators are reported for completeness, but both rest on limited evidence and should be read as suggestive rather than firm. The energy recovery rate reported by İSTAÇ is available only as a single figure—about 185 kWh per ton of total processed waste—with no year-by-year series, so its near-constancy cannot in fact be assessed over time. Per-ton emission intensity, in turn, is comparable across just two years, moving only marginally from 214.60 kg CO2e/t in 2022 to 213.66 in 2023; the 2024 value of 191.68 is reported on a revised Scope 1-2-3 accounting basis and is therefore excluded, leaving a two-point basis that can support at most a weak claim of stability. The interpretation of these results—their implications for lock-in theory, transition dynamics, and waste-to-energy planning—is developed in Section 5.

5. Discussion

5.1. Beyond an Istanbul Story: Diversification as a System Property

A natural first reading of these results is that Istanbul diversified because it chose to invest in energy-from-waste and biomethanization capacity. On this account, diversification would be a contingent outcome of municipal preference, managerial vision, or the timing of particular investment decisions. A self-limiting mechanism offers a deeper explanation,

consistent with the data. Structural diversification is directly observed: the newer EfW and biomethanization pathways absorbed essentially all of the system's growth while landfill-gas output plateaued. Although city-wide landfilled tonnage continued to rise over 2021–2024—so the aggregate biodegradable stock was not shrinking—landfill-gas output plateaued, and at the plant level the largely closed Odayeri site shows a clear, sustained decline (189 → 180 → 165 GWh). This pattern is consistent with the continued growth of the system coming from newly commissioned EfW and biomethanization capacity rather than from landfill gas because the latter's resource base was constrained; the self-limiting dynamic is offered here as a plausible plant-level explanation—an existence proof rather than a demonstrated city-wide regularity or a uniquely established causal mechanism. The evidence is consistent with endogenous resource constraints having generated diversification pressure, with the form and timing of the resulting portfolio reconfiguration depending on deliberate municipal investment, institutional capacity, and available technology choices. Notably, this trajectory was made possible by a sequence of discrete infrastructure additions—LFG energy at Odayeri and Kömürcüoda (2008–2009), RDF/ATY production (2018), and the Seymen plant (2020)—which means that diversification was driven by sequential infrastructure additions rather than by market forces alone.

This reframing carries a direct theoretical implication. Diversification should not always be interpreted as a strategic choice made independently of system dynamics. In some circular energy systems, a self-limiting incumbent pathway may instead generate diversification pressure; whether and how that pressure materializes as an actual diversification response is mediated by strategic investment decisions, institutional capacity, and available technology choices, rather than following from the declining viability of the incumbent pathway as a structural necessity. The inclusion of Seymen represented the emergence of a third major energy node within the metropolitan waste management network, extending the landfill-gas recovery geography from two European and Asian sites to a broader tri-site configuration. Crucially, what changes here is the architecture of the supply chain itself, not merely the level of energy output. The full extent of that chain—spanning transfer-station logistics (Baruthane, Halkılı, Yenibosna, Silivri, Hekimıbaşı, Aydınlı, and Şile), landfill processing, resource recovery, and energy generation—means that the diversification documented here is best read as a reconfiguration of an integrated waste logistics–processing–energy recovery chain, not simply a reshuffling of generation technologies. In the feedstock-to-energy chain set out in Figure 1, a single upstream feedstock—municipal waste flows—is progressively re-routed across a broader set of parallel processing nodes (the landfill-gas, energy-from-waste, and biomethanization facilities) before conversion into the downstream output, grid electricity. Over the study period it is the configuration of these nodes—how the upstream feedstock is allocated across them—that is reconfigured, rather than any single conversion technology being scaled up. The phenomenon is therefore best read as a reconfiguration of the circular energy supply chain, in which the locus of conversion shifts from a single resource-constrained node toward a more balanced set of nodes, and not as an energy-generation trend alone; the concentration metrics, in supply-chain terms, track exactly this redistribution of throughput across the chain's processing nodes. Read through the supply-chain lens developed in Section 2, the measured fall in concentration (the Herfindahl–Hirschman index from 1.00 to 0.47, and the effective source count from 1.0 to about 2.1) records exactly this structurally driven shift from single-source dependence toward a more balanced, less supply-risk-exposed portfolio—an architectural change in the circular energy supply chain rather than a discretionary operational adjustment. The analysis measures concentration and its reduction; resilience in the sense of the response to a specific shock is not directly tested.

5.2. Challenging the Lock-In Account

These dynamics sit uneasily with the path-dependency tradition that dominates the energy-transition literature. From David [4] and Arthur [5] to Unruh's [6,7] account of carbon lock-in, that tradition repeatedly emphasizes increasing returns, reinforcement, lock-in, and persistence—mechanisms through which an incumbent technology becomes progressively more entrenched. Applied to Istanbul, this lens would predict that an early reliance on landfill-gas recovery should have deepened over time. The data show the opposite: landfill-gas output plateaued and its share fell even as the system expanded.

The present findings suggest that not all transition pathways are governed by reinforcing dynamics. Some pathways may instead contain self-eroding feedback that progressively undermine their own future viability. Where lock-in describes pathways that strengthen with use, the pathway examined here weakens with use and, more strikingly, with the success of the policies built around it. The Istanbul case suggests that lock-in theory is not so much wrong as incomplete: it captures one mode of path behavior—reinforcement and persistence—while overlooking a second mode characterized by decline and adaptation.

5.3. A Typology of Recovery Pathways: Persistent Versus Self-Limiting Resources

If landfill gas was described simply as a declining resource, the observation would be unremarkable; that landfill-gas output eventually falls is well understood. The contribution lies in recognizing that landfill gas is not a special case but an example of a broader category of self-limiting recovery paths—technologies whose resource base contracts over time and whose dominance is therefore inherently temporary. This points to a simple but consequential distinction between two types of recovery and generation technologies, summarized in Table 6.

Table 6. A typology of recovery and generation technologies by resource-base behavior.

Dimension	Type A: Persistent-Resource	Type B: Self-Limiting-Resource
Resource base	Continuously renewed; does not deplete with use	Finite stock; depletes over time
Representative examples	Solar, wind, hydro	Landfill gas; some biomass streams; some mining/industrial-waste recovery
Feedback over time	Stable or reinforcing	Self-eroding
Role in the transition	Long-term anchor	Transitional bridge (bounded, self-extinguishing)

Type A, persistent-resource technologies, draw on resource flows that are continuously renewed and do not deplete with use; solar, wind, and hydro are paradigmatic, since the underlying resource persists regardless of how much energy is extracted. Type B, self-limiting-resource technologies, draw on a finite stock that diminishes over time and, in the cases considered here, with the success of the surrounding policy regime; landfill gas is the clearest example, but certain biomass streams and the recovery of energy or materials from accumulated mining and industrial waste share the same structure. The two types imply markedly different transition dynamics: Type A pathways can anchor a system over the long run, whereas Type B pathways are best understood as bridges whose contribution is bounded and ultimately self-extinguishing. The typology is heuristic and intended as an analytical simplification: the boundary between the two types is not always sharp, and a given pathway may sit closer to one type or the other depending on its resource base and the surrounding policy context.

5.4. Policy-Induced Depletion as a Distinct Mechanism

This section addresses Research Question 3, which asks to what extent the observed patterns are consistent with a policy-coupled depletion mechanism and at what spatial scale that consistency is supported. The mechanism proposed to contribute to the decline of Type B pathways is the most distinctive theoretical element of this study. In conventional resource economics, depletion emerges from extraction: a fixed stock is drawn down as it is consumed [33]. In contrast, the plant-level pattern observed here is consistent with depletion that may emerge from the success of diversion policies. Where effective diversion routes biodegradable waste away from landfill, the stock that feeds landfill-gas generation can contract—not because the gas is consumed for energy, but because the future input is reduced, lowering future gas potential. Depletion would then be, in this precise sense, policy-induced rather than extraction-induced. The answer to Research Question 3 differs sharply by spatial scale. City-level evidence is insufficient: landfilled tonnage rose across Istanbul over 2021–2024, the opposite of what a city-wide policy-coupled depletion mechanism would predict, so no city-scale claim is supported by the present data. Plant-level evidence is supportive but non-exclusive: the largely closed Odayeri site shows a clear, sustained decline (189 $\rightarrow$ 180 $\rightarrow$ 165 GWh) consistent with policy-induced depletion, but the present data cannot rule out competing explanations—natural maturation of gas production in existing cells, or an effective capacity ceiling on gas collection—so the mechanism is presented as a conceptual account and plant-level existence proof rather than a demonstrated city-wide trend.

This also distinguishes the dynamic from standard accounts of regime destabilization, which usually locate the source of decline outside the incumbent—in landscape pressures, niche competition, or the erosion of political and economic legitimacy [34,35]. Under the self-limiting interpretation advanced here, the decline would be endogenous: it would originate in the pathway's coupling of resource-base dynamics and policy success, so that the success of the transition would actively erode one of its own early pillars. For transition theory, this implies a category of pathways whose contribution is self-limiting by construction, and whose decline may, under the specified boundary conditions, emerge partly as a consequence of successful policy rather than being solely attributable to an external disruption.

5.5. Implications for Urban Waste-to-Energy Systems

For the planning of urban waste-to-energy systems, the central implication is one of sequencing. Cities that rely heavily on landfill-gas recovery should anticipate its plateau and decline and plan diversification before the resource constraint becomes binding, treating landfill gas as a bridging rather than a stable long-term source. Where strong diversion policies substantially reduce future biodegradable landfill inputs, declining landfill-gas potential may emerge as a foreseeable consequence of policy success, although its timing and magnitude remain contingent on site-specific decay dynamics, continued waste inputs, and gas-collection capacity, and capacity planning for energy-from-waste, biomethanization, and material recovery should be timed accordingly.

More generally, self-limiting recovery paths may be particularly important during transitional phases. They can deliver substantial environmental and energy benefits in the early stages of a transition, yet their long-term contribution is inherently bounded by the depletion of their resource base. In this sense, they function less as destination technologies than as transitional bridge technologies—valuable precisely because, and only while, their resource base lasts. Recognizing this temporal position also clarifies when diversification pressure should be expected to arise: not at the outset, while the incumbent pathway is still ascending, but at the point at which its resource base begins to bind.

The mechanism identified here—stock-dependent generation coupled to policy-driven diversion—is general to landfill-gas systems undergoing waste diversion, so the qualitative lesson is likely to transfer beyond Istanbul, even though magnitudes and timing are context-specific. It is also worth noting that the diversification trajectory required substantial organizational and operational capacity to execute: the İSTAÇ structure supporting this system encompasses several thousand employees across operations, logistics, and engineering functions, a scale of institutional capability that city-level planners elsewhere should factor into transition timelines. The limits of the design should nonetheless be acknowledged. As a longitudinal case analysis capturing a rapid two-year structural reconfiguration rather than a sustained, continuously evolving trend, the study establishes that the predicted signature is present in one large system and characterizes the mechanism that plausibly produces it; it cannot, on its own, establish how common self-limiting recovery paths are across cities. A related temporal limitation, noted in Section 3.1, is that no verifiable pre-2019 facility-level generation series could be located for Odayeri or Kömürcüoda despite a targeted search; since both sites were commissioned in 2008–2009, the 2020–2024 window may capture only the declining or plateau segment of a longer growth–peak–decline trajectory rather than that trajectory in full. The findings are therefore best understood as an existence proof and as an account of the mechanism—and the proposed Type A/Type B distinction—to be tested for generality in future multi-case and cross-national research.

The findings suggest that not all renewable energy pathways exhibit persistent growth dynamics. Some pathways function as transitional bridge technologies whose resource base erodes over time, creating endogenous diversification pressures. This distinction may be relevant beyond waste-to-energy systems and could inform broader debates on renewable energy transitions and supply-chain resilience.

5.6. Cross-City Perspectives: Convergent and Divergent Evidence from the Literature

Although the present study retains its single-case design, existing literature on other cities offers a preliminary basis for asking whether the self-limiting signature identified for Odayeri travels beyond Istanbul, and under what conditions it does not; this is not a new multi-city empirical analysis, but a reading of published evidence through the boundary conditions set out in Section 2.5. Two cases point toward convergence. In the United Kingdom, national landfill-gas electricity generation peaked at roughly 5300 GWh in 2011 and had fallen to about 3100 GWh by 2022, a decline widely attributed to the escalating Landfill Tax, which progressively diverted biodegradable waste away from disposal [48]—a gradual, policy-coupled depletion pattern consistent with Proposition 1, though further along the decline curve than Istanbul's current plateau. Germany illustrates a more extreme variant of the same mechanism: the 1993 Technical Ordinance on Municipal Solid Waste and its 2005 ban on landfilling untreated, biodegradable waste curtailed fresh organic input to landfills almost entirely, sharply reducing new methane formation even as existing sites continued to emit residual gas for years afterward [49]—an outcome consistent with several of the boundary conditions in Section 2.5 (high diversion intensity, near-complete closure to new organic inputs) being satisfied simultaneously and to a far greater degree than the partial, ongoing diversion observed in Istanbul.

A contrasting case illustrates divergence rather than convergence. In Jakarta, where municipal solid waste generation continues to grow by roughly 3% annually and formal recovery captures well under a third of the waste stream, landfill-gas potential at the Bantargebang site is projected to keep expanding rather than plateau [50]. In terms of the boundary conditions set out in Section 2.5, this reflects continued replenishment of the biodegradable stock together with low diversion intensity—precisely the combination

under which Proposition 1 does not predict a self-limiting signature. Read together, the UK, German, and Jakarta cases cannot substitute for the multi-city comparison called for in Section 6, and no causal claim is made across such heterogeneous settings; they are offered only as a preliminary, literature-based illustration that whether a landfill-gas pathway behaves as self-limiting appears to depend less on the technology itself than on the policy and waste-stream conditions under which it operates—the same boundary conditions identified analytically for the Istanbul case.

5.7. Sustainability Trade-Offs: Environmental, Economic, and Social Dimensions

The dynamics analyzed above are not confined to energy output and source concentration; the transition they describe unfolds simultaneously across the environmental, economic, and social dimensions of sustainability, and reading the results through all three exposes trade-offs that a purely techno-environmental account would miss. Environmentally, diversification away from a single landfill-gas pathway raises aggregate energy recovery, yet city-wide landfilled tonnage nonetheless rose over the study period (Section 5.4), so more energy recovery has not translated into less waste disposed. Per-ton emission intensity is reported by İSTAÇ for only two comparable years—214.60 kg CO2e/t in 2022 and 213.66 in 2023 (Section 4.4)—and this two-point series cannot support a claim of long-term environmental benefit, whether directional or otherwise; at most it is consistent with short-run stability, and even that reading should be treated as provisional. For a longer horizon than İSTAÇ's own facility-level reporting allows, national statistics offer contextual—not substitutive—evidence: Türkiye's municipal recycling rate rose from roughly 13% in 2017 to about 35% by 2023 and 36% by 2024, while its landfill rate has remained comparatively high and largely stagnant since the mid-2010s [38,39], and national waste-sector greenhouse-gas emissions have fluctuated in the range of roughly 14–17 Mt CO2e per year since 2019 without a clear sustained trend in either direction [51]. These are country-level series that describe the waste sector as a whole, not Istanbul-specific figures for the electricity-generation portfolio examined here; they are reported only to situate the study's own two-year emission-intensity figures within a longer national backdrop, not to extend the study's claims beyond what its facility-level data can support. Economically, the move from single-source dependence toward a more balanced portfolio reduces exposure to the supply risk of a depleting resource base, but it is achieved through substantial capital investment in energy-from-waste and biomethanization capacity; the reduced concentration exposure documented here is therefore purchased rather than free, and the resulting cost structure and tariff implications are themselves part of the trade-off.

The diversification into EfW documented here should not, on its own, be read as an unambiguous circular economy improvement; it carries trade-offs specific to incineration that a headline reduction in source concentration does not capture. In the waste hierarchy that underpins most circular economy policy frameworks, energy recovery from mixed waste ranks above landfilling but below prevention, reuse, and recycling; a portfolio shift that substitutes EfW for landfill gas therefore improves the system's position within the hierarchy without necessarily advancing it toward the higher-ranked options the hierarchy is designed to prioritize. Several concrete risks follow from the scale of the investment involved. Incineration lock-in is the first: a facility of this size (85 MW, approximately one million tons of annual throughput) is a long-lived asset with a design life typically measured in decades, and its capital structure creates an institutional incentive to keep it running near capacity for the life of the investment, independent of whether waste-reduction or recycling policy would otherwise be shrinking the volume of material available to burn. Minimum feedstock requirements compound this: EfW plants operate most efficiently, and are frequently contracted, against a guaranteed minimum waste throughput, so operators

and municipalities alike face pressure to maintain or secure a stable supply of combustible waste rather than to reduce it. This creates a third risk, competition with recycling: much of the material with the calorific value that makes it attractive as EfW feedstock—paper, card, and certain plastics—is also the material that source-separation and recycling programs target, so a facility calibrated to a given throughput can create a structural disincentive to divert that same material toward recycling instead. Finally, stranded-capacity risk follows from the tension among these three: if future waste-reduction and recycling policy succeeds in reducing the volume of combustible municipal waste, a city that has built substantial EfW capacity confronts a choice between underutilizing that capacity, which raises its per-ton and per-MWh costs, or maintaining waste flows sufficient to keep it economical, in tension with the same policy goals. None of these risks is visible in the concentration and diversification indices reported in Sections 4.3 and 4.4, which register only that the portfolio moved away from single-source dependence, not whether it moved toward the top or the bottom of the waste hierarchy. Cities considering a similar diversification path should weigh the concentration-risk benefits documented here against these circular economy trade-offs, which the facility-level generation data used in this study cannot themselves resolve.

The social dimension is the least visible in facility-level generation data, yet it is integral to the trade-offs that a self-limiting transition imposes, and the systems perspective adopted here makes its omission conspicuous rather than incidental. Nothing in this subsection is derived from, or tested against, the generation and concentration data reported in Sections 4 and 5.1–5.4; it is a qualitative discussion, grounded in published literature and municipal reporting, of dimensions the present single-case dataset was not designed to measure, and no quantitative claim about Istanbul's own distributional outcomes should be read into it. Incinerator siting sits at the center of such literature. Cross-national reviews of waste-facility location have repeatedly found that landfills and incinerators are disproportionately sited in, or come to be surrounded by, lower-income and minority neighborhoods, raising environmental-justice concerns about who locally bears the air-quality and amenity burden of a facility whose electricity serves the wider metropolitan grid [52]. A closely related study on public acceptance documents a recurring "Not-In-My-Backyard" (NIMBY) pattern around proposed energy-from-waste plants: opposition tends to be strongest in areas without prior experience of thermal treatment, softens somewhat where consultation and compensation are offered, and is shaped as much by trust in local authorities and perceived risk as by the facility's technical performance [53]. Neither body of evidence has been tested for the Odayeri, Kömürcüoda, or Seymen sites specifically; it is noted here because the portfolio shift documented in Section 4.2—away from a single landfill-gas site and toward EfW and biomethanization capacity distributed across a wider tri-site geography (Section 5.1)—necessarily raises siting and acceptance questions at each new node, independent of whether the system-level concentration indices improve.

Formal and informal waste labor raise a second, largely separate set of questions. Istanbul's recycling stream has long depended on an informal workforce of itinerant waste pickers (kağıt toplayıcıları or çekçekçi)—estimated at roughly 500,000 nationally and reported to handle a large share of the country's recovered recyclables—who work outside formal employment protections and are not represented in İSTAÇ's own reporting, on which this study's operational-capacity figures (Section 5.5) are based [40]. Türkiye's 2022 initiative to formalize waste collection, and municipal responses such as the Şişli district cooperative launched in 2023, illustrate that diversion and recovery policy of the kind examined in this study can reshape livelihoods along the recovery chain—for better, where formalization extends recognition and access to designated collection zones, and

for worse, where informal workers are displaced without an equivalent alternative [54]. Because the electricity recovered through diversification feeds a shared urban grid while its costs (siting, displacement, capital recovery through tariffs) fall unevenly across residents, workers, and neighborhoods, distributional effects of this kind need not move in step with the concentration and diversification indices reported in Sections 4.3 and 4.4. None of this is measured in the present study; it is flagged as a structured gap that the facility-level generation data cannot fill, and as a direction—alongside the multi-case and cross-national research already called for in Section 6—for future work using distributional, employment, and survey-based instruments designed to capture it directly.

Acknowledging all three dimensions clarifies that diversification is not Pareto-improving by construction. The shift away from a self-limiting pathway can strengthen environmental performance and move the supply chain toward a configuration theoretically associated with greater resilience, while leaving distributional and social outcomes indeterminate, and these need not move together. For the governance of circular energy supply chains, the implication is that managing a self-limiting transition is not only a problem of capacity sequencing but also one of balancing environmental, economic, and social objectives that can pull in different directions. The present study directly measures energy-output and portfolio concentration dynamics, provides limited contextual evidence on environmental and economic dimensions, and treats the social dimension as a structured empirical gap—one that the data available here cannot close, but that multi-case and mixed-method designs incorporating distributional, employment, and acceptance indicators would be well placed to address. Making the social dimension explicit in this way ensures that the trade-offs across the three pillars of sustainability, rather than environmental efficiency alone, are explicitly incorporated into the interpretation.

5.8. Supply-Chain Implications

The diversification dynamics documented in this study can be reinterpreted directly in supply-chain terms. Within the circular energy supply chain described in Section 1.1, each recovery pathway functions as a distinct conversion pathway delivering electricity to the downstream grid. Landfill-gas recovery, as the sole source of electricity generation in 2020, occupied the position of a dominant pathway; energy-from-waste (EfW) and biomethanization entered subsequently as alternative pathways, each drawing on independent conversion processes and, to a degree, on different fractions of the waste feedstock. Read in this way, the structural transition from 2020 to 2024 is a transition in the pathway base of the circular energy supply chain—from single-pathway dependence toward a three-pathway configuration.

Three supply-chain implications follow from this reframing. First, source concentration falls substantially: the arrival of EfW and biomethanization reduced the system's dependence on a single conversion pathway (Section 4.3), thereby reducing the concentration exposure associated with single-source supply arrangements. Second, pathway dependence is reduced: as LFG output plateaued and the newer pathways absorbed a growing share of generation, the chain's reliance on any single pathway diminished. A disruption to LFG output—whether from site closure, resource depletion, or operational constraint—that in 2020 would have endangered the entire electricity supply now affects, at most, roughly half of total generation. Third, concentration exposure is reduced and structural redundancy is greater, a configuration theoretically associated with greater resilience: with three parallel conversion pathways drawing on partly independent resource bases (deposited biodegradable waste for LFG, incoming residual waste for EfW, and organic fractions for biomethanization), the chain exhibits greater structural redundancy than a mono-source configuration. This redundancy is nonetheless bounded by the common-

mode risk channels discussed in Section 2.2—feedstock correlation between LFG and biomethanization, shared collection and logistics infrastructure across all three pathways, and shared exposure to regulatory and tariff shocks—so the fall in HHI should not be read as a proportionate reduction in overall systemic risk. As elsewhere in this paper, this is a claim about reduced structural exposure, not about realized resilience, which would require observing the system's response to an actual disruption.

A further implication concerns the interpretation of the HHI itself. Conventionally applied in this study as a metric of energy-source diversity, the HHI functions simultaneously as a supply-chain concentration metric when the recovery pathways are treated as parallel conversion pathways within that chain. The decline from 1.00 to 0.47 therefore records not only an improvement in energy diversity but also a structural de-concentration of the pathway base—a reframing that connects waste-to-energy planning directly to the supply-chain risk-management literature [27–29] and underscores that the concentration indices reported in Table 4 carry a dual interpretation: as energy-diversity indicators and as pathway-concentration indicators within the circular energy supply chain.

This reframing is not merely terminological. It positions the study's findings within a broader supply-chain management discourse in which single-pathway dependence is a recognized vulnerability and pathway diversification is the principal structural remedy [27–29]. The proposed self-limiting dynamic of LFG recovery offers one plausible mechanism through which a highly concentrated supply chain may generate pressure toward a multi-pathway configuration theoretically associated with greater resilience, though actual resilience is not tested here. For urban energy planners and supply-chain managers alike, the implication is concrete: the structural shift documented here represents a reduction in supply-chain concentration risk that is both measurable and consequential, and its compatibility with the proposed self-limiting trajectory of the dominant pathway suggests that similar transitions may be anticipated wherever resource-constrained single-source dependencies are found in circular energy systems.

5.9. Theoretical Contribution

Taken together, these arguments locate the study's contribution at the level of theory rather than description. The contribution of this study is not the observation that landfill-gas output eventually stabilizes, a phenomenon already well understood in engineering models. Rather, the contribution lies in showing how energy diversification in metropolitan waste systems emerges through the co-evolution of waste logistics infrastructure, landfill capacity expansion, and energy recovery technologies—a process that is as much organizational and logistical as it is technological. Conceptualizing this as the joint operation of physical resource depletion and a policy-mediated reduction in that resource's future replenishment (operative at the plant level, as an existence proof) generating diversification pressure within an integrated circular energy supply chain extends path-dependency discussions in a direction that reinforcing-feedback accounts cannot reach. The notion of a self-limiting recovery path shifts attention from lock-in and persistence toward decline and adaptation as alternative transition dynamics. Diversification is not, on this account, a passive inevitability that follows automatically once the constraint binds. The theoretical model proposed here is explicitly two-stage: an endogenous resource constraint generates diversification pressure on the incumbent pathway, and a strategic and institutional response—deliberate investment decisions, sequenced infrastructure commissioning, and the organizational capacity to execute them—converts that pressure into an actual portfolio reconfiguration. The two stages are analytically and empirically distinct. The first is supported at the plant level, in the Odayeri decline, although competing explanations cannot be excluded (Section 4.4, Table 5); the second is documented in the sequence of discrete

infrastructure investments—EfW and biomethanization capacity commissioned during the period in which the landfill-gas constraint became increasingly apparent (Section 5.1)—that İSTAÇ undertook as a matter of active municipal investment behavior rather than automatic system adjustment. Making this second stage explicit addresses a potential concern: that framing diversification as a direct consequence of resource depletion would understate the discretionary investment behavior through which a municipal operator actually built the additional capacity. In the model advanced here, that behavior is the necessary second stage through which pressure becomes reconfiguration, not an implementation detail of an otherwise automatic process.

Four linked ideas carry this contribution. The first is that the self-limiting recovery path supplies an analytical concept that jointly conceptualizes, within a path-dependency framework, physical resource depletion and a policy-mediated reduction in future resource replenishment—not a claim to a wholly new depletion mechanism, but a coupling between two processes previously treated separately—for pathways whose resource base erodes over time. The second is that policy-induced depletion—evidenced at the plant level by the Odayeri decline, and not yet visible in city-wide landfilled tonnage, which rose over the study period—identifies a plausible mechanism, distinct both from extraction-driven depletion and from externally driven regime destabilization, through which that erosion could occur. The third is that the strategic and institutional response—İSTAÇ's sequenced investment in EfW and biomethanization capacity, backed by the organizational capacity described in Section 5.5—is the stage through which diversification pressure is converted into actual portfolio reconfiguration; this stage is documented as a matter of active municipal investment behavior, not treated as an automatic implication of the constraint. The fourth is that structural diversification is itself directly documented at the city level in the portfolio data, and is offered as compatible with—rather than proof of—the constraint-and-response model as its cause. It is the connection among these four ideas—concept, mechanism, response, and consequence—and not the Istanbul case in itself, that constitutes the study's contribution to transition theory.

6. Conclusions

This study examined how Istanbul's municipal waste-to-energy portfolio evolved between 2020 and 2024 and what that evolution reveals about resource constraints and diversification in circular energy supply chains. Three findings stand out. Total electricity generation nearly tripled, rising from 457 GWh to 1332 GWh, and this growth was predominantly driven by diversification rather than by the incumbent pathway: landfill-gas recovery settled onto a plateau of approximately 690–698 GWh rather than scaling with the system, contributing roughly 27% of the increase against the roughly 73% contributed jointly by EfW and biomethanization. As the newer energy-from-waste and biomethanization pathways absorbed most of the expansion, source concentration fell sharply—the Herfindahl–Hirschman index declined from 1.00 to 0.47 and the effective source count rose from 1.0 to about 2.1—so that a system once dependent on a single source became a measurably diversified recovery portfolio.

The central finding follows from the timing of these movements. Landfill-gas output plateaued while the rest of the system continued to expand, so the resulting portfolio diversification is directly observed in the data rather than inferred. A self-limiting mechanism—in which landfill-gas output is bounded by a finite and depleting resource base—offers a parsimonious explanation for why the continued growth of the system originated elsewhere, and is consistent with the plant-level decline documented at Odayeri, though the present single-case evidence cannot uniquely establish this mechanism as the cause. On this reading, diversification reflects the interaction of structural resource constraints with

strategic municipal investment, producing an architectural change in the circular energy supply chain rather than a purely operational adjustment.

These observations support a theoretical contribution organized around four linked ideas. The first is the notion of a self-limiting recovery path that jointly conceptualizes physical resource depletion and a policy-mediated reduction in that resource's future replenishment within a single path-dependency framework, extending path-dependency and carbon lock-in discussions beyond their customary emphasis on reinforcement and persistence. The second is policy-induced depletion—illustrated at plant level by the Odayeri decline, and not yet visible in city-wide landfilled tonnage, which rose over the study period—which is proposed as a plausible mechanism behind that erosion: on this account, the resource base contracts not through extraction, as in the classical economics of exhaustible resources, nor through external landscape pressure, as in conventional accounts of regime destabilization, but through the very success of the diversion policies within which the pathway operates; the present single-case evidence is consistent with, but does not uniquely establish, this mechanism. The third is a strategic and institutional response—the sequenced, deliberate investment through which İSTAÇ built EfW and biomethanization capacity—which is the stage that converts diversification pressure into actual reconfiguration; diversification is treated here as an outcome of active municipal investment behavior, not as a passive inevitability that follows automatically once the constraint binds. The fourth is that structural diversification is itself directly documented in the data, and is offered here as compatible with—rather than proof of—the constraint-and-response model as its cause, reframing a familiar empirical outcome as a plausible consequence of that model rather than as simply a strategic choice made independently of it. Taken together, concept, mechanism, response, and consequence shift attention from lock-in and persistence toward decline and adaptation as a distinct mode of transition dynamics.

As a longitudinal case analysis of a multi-year structural transition—rather than a sustained, continuously evolving diversification trend—this analysis establishes that the predicted signature is present in one large system and characterizes the mechanism that plausibly produces it, but it cannot, on its own, establish how widespread self-limiting recovery paths are. Four directions for future research follow directly. Multi-city comparisons could test whether the same plateau-and-diversification signature recurs across urban systems pursuing landfill diversion. Cross-national studies could examine how differing policy regimes, waste compositions, and institutional settings shape the pace and form of policy-induced depletion. And extending the analysis to other recovery technologies—certain biomass streams and the recovery of energy or materials from accumulated mining and industrial waste—would test the generality of the proposed Type A/Type B distinction beyond landfill gas. A fourth, complementary direction would formalize the qualitative stock–flow interpretation of Section 3.6 into a fully quantitative, calibrated system-dynamics simulation of the depletion–diversification coupling, capable of being validated against, and used to project beyond, the observed trajectory. Such a model would be a genuinely valuable extension of the framework proposed here, but it is not attempted in this paper because the present dataset cannot support reliable calibration: as detailed in Sections 3.1, 3.3 and 3.7, the available series comprises only five annual observations even now that the 2021 pathway split has been located and reconciled, with no verifiable pre-2019 facility-level data. Calibrating a dynamic simulation on a series this short would risk fitting the model to noise rather than to the underlying mechanism. Assembling the denser, ideally monthly, multi-year per-pathway series such a model would require is left as a concrete direction for future work. Pursuing these directions would clarify the boundary conditions of the self-limiting recovery path and sharpen its value as a lens for renewable energy transitions and circular energy supply chains.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/systems14091072/s1, Supplementary Data File: İSTAÇ facility-level source data, aggregation rules, pathway shares, concentration-index calculations, and the 2021 pathway-split reconciliation.

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