# “Cost accounting-based assessment of the net social benefit of German waste-to-energy plants under stricter environmental valuation: Public-record evidence from 2017 to 2023”


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# COST ACCOUNTING-BASED ASSESSMENT OF THE NET SOCIAL BENEFIT OF GERMAN WASTE-TO-ENERGY PLANTS UNDER STRICTER ENVIRONMENTAL VALUATION: PUBLIC-RECORD EVIDENCE FROM 2017 TO 2023

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## Abstract

Municipal waste-to-energy is often assessed through technical efficiency, energy output, or regulatory compliance. Yet, these indicators do not show whether plants create positive social welfare after operating costs and environmental damages are monetized. This study examines how operational performance, emissions intensity, and stricter environmental valuation shape the net social benefit of German municipal waste-to-energy plants from 2017 to 2023. Germany serves as a benchmark case because its mature waste-to-energy sector, European emissions regulation, and public environmental and energy-market reporting enable transparent public-record welfare assessment. The study constructs a plant-year analytical dataset for 70 facilities from publicly accessible administrative, environmental, market, and technical records, with net social benefit treated as a constructed welfare-accounting measure based on observed records, documented public proxies, and explicit valuation assumptions. It uses plant- and year-fixed-effects models, valuation sensitivity tests, and an optimization-based decision-support layer. The descriptive evidence shows substantial welfare heterogeneity, with a mean traceable-baseline net social benefit of 17.9 euros per metric ton under the central valuation case and lower mean welfare under higher shadow prices. The fixed-effects results do not provide statistical support for the hypothesized operational drivers in the public-data panel: energy recovery, emissions intensity, availability, oxygen instability, and the interaction between emissions intensity and the shadow price index are not statistically significant. The study contributes by integrating cost accounting, externality valuation, and operational performance into a transparent public-record welfare metric for policy appraisal.

**Keywords** incineration, welfare, emissions, externalities, valuation, Germany, cost accounting

**JEL Classification** Q53, Q58, C23



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## INTRODUCTION

Municipal solid waste management remains a central issue in environmental economics because disposal and recovery choices create costs and benefits that are not fully reflected in market prices or municipal accounts. Landfilling can generate climate and local environmental burdens, while treatment and diversion options may reduce some damages but introduce others through energy use, emissions, and residual by-products. Waste-to-energy therefore has a dual function: it treats residual waste and produces usable energy. Its social desirability depends on whether these benefits exceed the full economic and environmental costs.

Waste-to-energy performance is often assessed through technical efficiency, operating cost, energy output, or regulatory compliance. These indicators are useful, but they do not show whether a plant increases net social welfare. A welfare assessment must compare recovered energy value and avoided disposal burdens with operating costs, greenhouse gas damages, local air-pollution damages, and residue-management effects. Conclusions about waste-to-energy can therefore change with system boundaries, valuation assumptions, and regulatory conditions, creating uncertainty for policy appraisal and operational decision-making (Anandan Govindan et al., 2025; Sarvestani et al., 2024).

Operational factors add further complexity. Combustion stability, steam-cycle performance, auxiliary power demand, plant availability, and pollution-control configuration influence both energy recovery and damage intensity. These factors are interdependent, so improvement in one dimension may increase costs or burdens elsewhere. Waste-management and circular-economy decisions therefore require assessment methods that connect operational choices to welfare outcomes on a common monetary scale, rather than treating technical, financial, and environmental indicators as separate scorecards (Halkos & Aslanidis, 2024). More broadly, standards-based internal auditing has been examined as a foundation for value-added tasks in an emerging-market setting (Shaban & Barakat, 2023). We use Germany as a substantive and methodological benchmark, not because of our affiliations. It has a mature municipal waste-management system, a large waste-to-energy infrastructure base, strict European Union industrial-emissions requirements, and active policy debate about incineration within the circular economy. It also provides public records on facilities, emissions, energy-market conditions, inflation adjustment, and valuation inputs. These features make Germany suitable for constructing a reproducible plant-year welfare dataset. The case is relevant beyond Germany because it offers a benchmark for environmental-cost accounting and sustainability performance assessment in countries developing circular economy reforms, including Jordan and the wider region.

## 1. LITERATURE REVIEW

Environmental economics frames municipal solid waste (MSW) management as a welfare problem in which private disposal decisions generate external costs (local air pollution, toxic risks, methane leakage, land use disamenities) and external benefits (energy and heat substitution, avoided landfill burdens, and reduced upstream extraction). In the canonical tradition of externalities and corrective policy, socially efficient waste-treatment choices require aligning marginal private incentives with marginal social damages/benefits (Jiang, 2024; Chicaiza-Ortiz et al., 2024). Within this framing, waste-to-energy (WtE) occupies a contested position: it can internalize part of the landfill-methane externality and produce valuable energy services, yet also impose residual air-emission damages and distributional burdens near facilities (Saha & Naidoo, 2025; Yang, 2024). Because environmental economics evaluates options by net social benefit rather than by engineering output alone, the central question becomes not whether WtE "works," but under which operating, regulatory, and energy-system conditions its social benefits exceed its social costs.

A core insight from the waste-policy and instrument-design literature is that optimal treatment is system-dependent: the welfare ranking of recycling, composting/AD, WtE, and landfill shifts with local scarcity constraints (land availability), transaction costs of separation, enforcement capacity, and the relative damages of emissions across media (Mattson et al., 2024; Zaikova et al., 2025). Economic instruments (unit pricing, landfill taxes, deposit–refunds, EPR) are designed to steer waste streams toward socially preferred options, but their effectiveness hinges on credible monitoring and on the technology-specific marginal damages of the residuals that remain after control (Garg & Arora, 2025; Hidalgo et al., 2025). In practice, WtE is often justified as a residual-management technology within a waste hierarchy. Yet, environmental economics cautions that "residual" is endogenous: it depends on policy stringency, sorting economics, and the opportunity cost of burning recoverable materials (Alsabt et al., 2024; Lee et al., 2024). This creates an evaluation challenge for WtE studies: welfare cannot be inferred from plant-level efficiency metrics alone without accounting for behavioral and system feedbacks that determine what is burned and what is displaced.

Monetizing environmental outcomes is therefore pivotal. Broader finance research similarly emphasizes that revaluation can affect financial interpretation and reporting implications (Alsmadi & Alrawashdeh, 2025). Climate damages are typically represented through the social cost of greenhouse gases, while local damages rely on impact-pathway approaches or damage functions that link emissions to exposure and health/ecosystem effects (Salvador & Doong, 2024; Mohan et al., 2024). For waste systems, authoritative assessments emphasize that landfilling's social cost can be dominated by methane because capture is imperfect and leakage persists over long horizons, making the "avoided landfill" benefit of diversion highly sensitive to methane assumptions and discounting (Zhao et al., 2025). Importantly, the climate component is not merely a reporting add-on: the choice of carbon valuation (shadow price) can reverse the welfare ranking of landfill vs. WtE when the energy displaced by WtE is carbon intensive or when landfill gas capture is low (Arimoro & Arinze-Umobi, 2025; Azzone et al., 2025).

External-cost evidence also shows why operations matter. Damage-cost ranges reported for incineration vary widely, largely because they depend on energy-recovery performance and which fuels are displaced (electricity-only vs CHP; marginal grid mix; district heating availability) (Javed et al., 2025; Ustaoğlu, 2024). Where heat can be utilized through district heating networks, the avoided-emissions benefit can be substantial; where heat is wasted, social benefits shrink, and local damage components become more salient (Chen et al., 2024; Marchi et al., 2025). EU policy discussions reflect this logic by distinguishing between low-efficiency incineration and energy recovery (e.g., R1 considerations), implicitly recognizing that "the same plant" can move up or down the social-welfare ladder depending on utilization of useful energy outputs (Hsu et al., 2024; Paulillo et al., 2024).

However, much published evidence evaluates WtE through lifecycle assessment (LCA) or engineering performance and only partially translates results into economic welfare metrics. LCA reviews highlight recurrent sources of variability–system boundaries, substitution assumptions, accounting for recovered metals and residues, and treatment of biogenic vs fossil $CO_2$–that materially change conclusions (Anandan Govindan et al., 2025; Sarvestani et al., 2024). Environmental economics contributes by (i) converting impact indicators into monetary damages/benefits, (ii) making shadow prices explicit, and (iii) clarifying how welfare changes at the margin when operational decisions shift emissions and net energy output. Recent environmental damage-cost frameworks that monetize impacts using endpoint valuation (e.g., LIME-based approaches) demonstrate how damage-cost accounting can be integrated with lifecycle inventories, yet applications to WtE often remain scenario-comparative rather than operation-sensitive (Garlock et al., 2024; King et al., 2024). The implication is a research gap: welfare appraisal is frequently "static" (technology A vs B) rather than "operational," even though day-to-day operating setpoints and stability determine both emissions and energy services delivered.

Operational determinants matter because modern WtE plants are regulated under stringent emission regimes where compliance depends on combustion stability and effective flue-gas cleaning (Cui et al., 2024; Melo dos Santos et al., 2026). Regulatory frameworks, such as the EU Industrial Emissions Directive, specify standardized reference conditions (including oxygen normalization) and embed best-available-technique expectations that shape the compliance–cost–welfare frontier (European Parliament and the Council, 2010; related guidance and consolidated materials (Bachmann & van der Kamp, 2014). This is not a purely legal detail: oxygen normalization and continuous monitoring are directly linked to how plants manage excess air, combustion completeness, and pollutant formation pathways (Ala-Lahti, 2024; Holzleitner-Senck et al., 2025). From an environmental economics perspective, these technical controls are levers that shift marginal damages per ton of waste, which should feed into the social-cost side of the welfare calculus (Halkos & Aslanidis, 2024; Herman, 2024). Comparable sectoral evidence from Hungary shows that green technology, regulatory frameworks, and infra-


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structure availability can materially influence carbon-reduction and sustainability outcomes (AlSheikh, 2025).

The emissions literature further indicates that key pollutants (NOx, $SO_2$, particulates, metals, and persistent organic pollutants such as PCDD/F) are sensitive to operating conditions and to air-pollution-control configurations (Lin et al., 2025; Zhang et al., 2025). For instance, dioxin formation is linked to combustion and post-combustion conditions and remains a central risk driver in public perception and policy scrutiny, even when average emissions are low (Lin et al., 2026; Gao et al., 2025). Because these pollutants carry serious marginal damages, welfare-based evaluation requires attention to not only mean emission levels but also variability, peaks, and stability–features that conventional techno-economic optimization can overlook if it focuses on average energy yield. Environmental justice research adds a distributional layer: even when aggregate welfare is positive, localized burdens and compensation dynamics can shape social acceptability and, in turn, the feasible policy set (Zhang & Li, 2026; Ma et al., 2025).

Public interpretation of environmental burdens also depends on the communication environment through which technical and regulatory information is encountered. Evidence from media research indicates that information flows across traditional and new media can shape how public issues are received and interpreted (Al-Muntasir, 2022). Related research shows that social media can influence agenda formation among professional communicators (Ahmad et al., 2023). Platform engagement is likewise associated with users' motives and perceived gratifications (Oreqat, 2021). At the organizational level, remote communication has been examined as a mediating mechanism between electronic human-resource management practices and organizational performance (Taqa, 2025). These studies are not specific to waste-to-energy; they are used here only to support the broader contextual point that communication can shape stakeholder interpretation and organizational response, rather than as evidence for the study's welfare estimates.

A notable shift in recent studies is the use of data-driven modeling and intelligent control to predict and optimize operational parameters that drive emissions and efficiency. Machine-learning work has explicitly targeted flue-gas oxygen dynamics and pollutant prediction in MSW incineration, reflecting the operational centrality of excess air management (Cao et al., 2025; Qi et al., 2025). Optimization studies also increasingly treat NOx control as a multi-parameter problem that trades off combustion conditions and downstream denitrification settings (Punukollu et al., 2024). While these contributions improve operational performance, they are rarely embedded in an explicit welfare objective (net social benefit), meaning that the "optimal" point is defined in engineering terms, such as minimizing NOx or maximizing efficiency, rather than in environmental economics terms where damages are monetized and compared with benefits. This disconnect is central: welfare-optimal operation may justify additional abatement or tighter stability even if it slightly reduces net energy output, depending on the shadow price of emissions and local damage functions.

Finally, energy-system interaction remains one of the most decisive drivers of welfare conclusions. Evidence from district heating contexts shows that the assumed displaced heat source can dominate environmental results, with profound implications for monetized benefits under carbon pricing or SCC valuation (Xu et al., 2025; Madadizadeh et al., 2024). Similarly, policy frameworks that classify WtE as "recovery" partly hinge on energy utilization efficiency, implicitly supporting the notion that availability, heat integration, and parasitic loads translate into welfare-relevant outcomes (Mancini et al., 2024; Yıldız et al., 2024). However, despite extensive LCA and engineering work, empirical studies that jointly (i) model operational levers (oxygen stability, steam/CHP performance, uptime), (ii) monetize emissions into environmental damage costs, and (iii) compute net social benefit at the plant-period level remain limited–especially in ways that allow hypothesis testing about which operational dimensions most strongly explain welfare variation.

Overall, the literature establishes that (i) WtE's welfare ranking is highly contingent on monetized externalities and energy substitution assumptions, (ii) operational stability and control systems materially shift marginal damages, and (iii) policy shadow prices can change the welfare-optimal operating point. At the same time, the evidence base is fragmented across welfare appraisal, LCA scenario analysis, and operational control studies, with insufficient integration into a single, testable environmental-economics model of net social benefit. Bridging this fragmentation motivates a welfare-first specification in which operating decisions are treated as determinants of monetized social benefits and costs.

The purpose of this study is to explain and test how operational performance, emission intensity, and stricter environmental valuation jointly determine the net social benefit of German municipal waste-to-energy plants during 2017–2023. The hypotheses are as follows:

H1: *Higher energy recovery is associated with higher net social benefit.*

H2: *Higher emission intensity is associated with lower net social benefit.*

H3: *Greater excess-oxygen instability is associated with lower net social benefit.*

H4: *Higher plant availability is associated with higher net social benefit.*

H5: *Higher shadow prices strengthen the negative effect of emission intensity on net social benefit.*

## 2. METHODS

This study adopts a quantitative, observational design that evaluates municipal waste-to-energy (WtE) performance through an environmental-economics welfare metric, net social benefit (NSB), constructed at the plant–year level for Germany during 2017–2023. The empirical design is organized in four linked stages: panel assembly, variable construction, welfare valuation, and statistical/optimization analysis. Germany is selected because WtE plants operate under stringent and relatively harmonized EU industrial-reporting and emissions-control frameworks that support comparable facility-level environmental data across years. In contrast, German and European energy-market reporting supports consistent monetary valuation of recovered energy. The 2017–2023 period provides a multi-year setting with stable public reporting practices and meaningful variation in energy-market conditions and environmental valuation assumptions that are directly relevant to NSB construction (Papamichael et al., 2024; Schnyder et al., 2025).

We selected Germany for substantive and methodological reasons, not because of our country of residence. Substantively, Germany represents one of Europe's most developed WtE settings and therefore offers a rigorous benchmark for evaluating how mature incineration systems perform when climate and local-pollution damages are assigned monetary values. Methodologically, Germany provides public access to plant registry information, facility-level emissions reporting, electricity-market information, inflation data, and technical benchmarks. These conditions make the country suitable for testing a welfare-based cost-accounting framework that can later be adapted to jurisdictions with less complete data systems, including countries in the Middle East and North Africa where circular economy and waste management reforms are expanding.

The research is implemented as a reproducible procedure. First, facility identifiers and annual records on releases, transfers, capacity, energy indicators, and operating characteristics are compiled from public German and European reporting systems and filtered to retain municipal waste-incineration and WtE installations. Second, the records are organized into a plant–year panel through unit standardization, duplicate removal, plausibility screening, and documented treatment of outliers. Third, operational variables are constructed at the plant–year level and classified before estimation as observed public records, documented public proxies, or valuation-derived components. Energy recovery is measured as net electricity output and useful heat where publicly quantifiable, scaled by waste treated; emissions intensity is measured per ton treated and, in robustness checks, per MWh delivered; plant availability is proxied using consistently observable public indicators, such as realized throughput relative to typical or permitted capacity and publicly reported outage information where available. Where public environmental statements provide additional process indicators, including oxygen-instability information, we in-



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corporate these indicators only in restricted-sample estimates and explicitly identify them as limited-coverage variables. The baseline models therefore rely on variables observable or transparently constructible across the broader screened panel.

The source inventory clearly distinguishes between public source records and the constructed analytical dataset. Public inputs include plant registry and capacity records, facility-year pollutant releases, German PRTR records, EU ETS verified emissions, electricity-generation and outage or availability proxies where publicly observable, Eurostat waste-management benchmarks, German and harmonized inflation series, WtE technical benchmarks, BAT guidance, electricity-price and carbon-price inputs, and external damage-cost references. These public inputs are not presented as separate empirical results. We use them to construct the documented plant–year dataset, the valuation components, and the NSB measures reported in the empirical tables. Appendix A, Table A3 summarizes the provenance, construction status, coverage, and analytical use of the main variables.

*NSB* is computed by monetizing market-valued outputs and environmental externalities on a common welfare scale. For plant *i* in year *t*, the welfare metric is:

$$NSB\_it = EV\_it + OV\_it - OCC\_it - CD\_it - LPD\_it + AD\_it, \quad (1)$$

where *EV* values recovered electricity and heat; *OV* captures other observable revenue items where disclosed; *OCC* denotes operating and compliance costs; *CD* measures climate damages; *LPD* measures local air-pollution damages; and *AD* captures avoided damages from displaced marginal electricity and heat generation. The baseline *NSB* measure includes only traceable components with documented source categories, units, and construction rules. Residue-handling costs are not included in the baseline welfare measure when complete plant-year public coverage is not available; in such cases, they are retained only as sensitivity information in the research materials. Electricity valuation parameters are drawn from German wholesale market reporting documented in the source inventory. Climate damages are valued using the updated social cost of greenhouse gases framework of the U.S. Environmental Protection Agency (2023), and local pollutant damages are monetized using the Environmental Prices Handbook 2024 EU version (CE Delft, 2024). All monetary values are expressed in constant euros using German and harmonized inflation series documented in the source inventory. We report low, central, and high valuation cases to make the role of shadow prices explicit rather than assumed away.

Hypotheses H1–H5 are tested using panel econometric models in which NSB is regressed on energy recovery, emission intensity, oxygen instability (where available), and availability, together with an interaction between emission intensity and a time-varying shadow-price index that represents stricter environmental valuation. The baseline specification includes plant fixed effects to absorb time-invariant heterogeneity such as location and technology vintage, and year fixed effects to absorb common shocks. Standard errors are clustered at the plant level. Robustness checks re-estimate the model using alternative intensity scaling, alternative tail-treatment rules, balanced-panel restrictions, and low/central/high shadow-price scenarios derived from the valuation sources (Voss et al., 2024).

To complement, rather than replace, the econometric hypothesis tests, the study also uses a two-layer computational component to characterize nonlinear trade-offs in feasible operating space. The broader accounting literature likewise documents growing applications of artificial intelligence and big-data analytics for decision support (Bader et al., 2025). An adaptive neuro-fuzzy inference system (ANFIS) learns nonlinear mappings between operational performance drivers and NSB-related outcomes, after which a genetic algorithm (GA) searches feasible operating regions for settings that maximize NSB subject to compliance and feasibility bounds. Training and validation follow time-consistent splitting, predictive error metrics are reported transparently, and the GA settings are fixed ex ante and re-run across multiple random seeds to check solution stability. This component is used only as exploratory decision support. It does not validate the constructed dataset, replace the fixed-effects tests, or provide causal evidence of observed plant optimization.

This research does not involve human participants, surveys, interviews, or personally identifiable information. It also does not rely on confidential internal plant records, private operator files, or unpublished administrative datasets. The empirical material consists of publicly accessible administrative, environmental, market, and technical records organized into a new analytical dataset created specifically for this study. The public records are best understood as official source records rather than author-collected primary data. Baseline variables are retained only where source categories, measurement units, and construction rules are documented within the final screened estimation frame, including plant identification, registry information, capacity indicators, emissions variables, valuation parameters, and price-adjustment inputs. Where public coverage is incomplete, observations are either excluded from the baseline panel or the variable is used only in restricted-sample analysis. Access is more limited for some operational proxies, especially oxygen instability and selected availability indicators, because these are observable only where public reporting permits. For this reason, we estimate oxygen instability only in the restricted sample and interpret it cautiously. Because all inputs are document-based and publicly accessible, informed consent procedures were not applicable and research ethics committee approval was not required.

We deposited the research materials in Zenodo to support transparency and reproducibility (Ramadan, 2026). The transparency emphasis is consistent with recent accounting evidence linking AI-enabled information practices with financial transparency and corporate governance (Shaban & Omoush, 2025). The repository includes downloadable research files, not only links to external resources: the constructed analytical plant–year dataset, the source-inventory file, the data dictionary, variable definitions, measurement units, and the construction rules for net social benefit (NSB). The source-inventory file documents the origin and role of each public input, while the analytical dataset contains the plant–year observations used to produce the reported results. No confidential, unpublished, or proprietary plant-level dataset from previous work was reused. Any public source used in constructing the dataset is documented in the source inventory and reflected in the data dictionary and Appendix A, Table A3.

# 3. RESULTS

The empirical analysis draws on a plant–year panel of German waste-to-energy (WtE) facilities observed from 2017 to 2023. After screening for completeness and unit consistency, the final analytical sample comprises 70 plants, yielding 476 plant–year observations (unbalanced panel). A restricted subsample of 45 plants (210 observations) includes the oxygen-instability indicator. Appendix A, Table A1 lists the 66 municipal solid waste incineration plants in the analytical frame, while Table A2 identifies the four RDF power plants included to complete the 70-plant analytical sample.

Descriptive statistics are presented in Table 1. Net social benefit (NSB) displays substantial variation across plants and over time, with a mean traceable-baseline value of €17.9/ton (SD €17.7) and an interquartile range of €5.2–€30.6/ton, suggesting pronounced heterogeneity in welfare performance. Energy recovery averages 0.60 MWh/ton, emissions intensity averages 0.61 $tCO_2e$/MWh, and plant availability averages 87.0%. The shadow price index (SPI) shows moderate variation, averaging 0.53, while the oxygen-instability index averages 0.33 within the restricted sample.

**Table 1.** Descriptive statistics for plant–year variables (Germany, 2017–2023)

| Variable | Unit | Obs. | Mean | SD | P25 | Median | P75 |
|---|---|---|---|---|---|---|---|
| Net social benefit (NSB) | €/t | 476 | 17.9 | 17.7 | 5.2 | 17.2 | 30.6 |
| Energy recovery (ER) | MWh/t | 476 | 0.60 | 0.11 | 0.52 | 0.59 | 0.67 |
| Emissions intensity (EI) | $tCO_2e$/MWh | 476 | 0.61 | 0.14 | 0.51 | 0.59 | 0.69 |
| Availability (Avail) | % | 476 | 87.0 | 5.9 | 83.4 | 87.2 | 90.9 |
| Shadow price index (SPI) | 0–1 | 476 | 0.53 | 0.21 | 0.37 | 0.52 | 0.71 |
| $O_2$ instability ($O_2$Instab) | Index | 210 | 0.33 | 0.15 | 0.22 | 0.31 | 0.43 |

*Note:* Obs. = plant–year observations. $O_2$Instab is available for a restricted sample (45 plants; 210 observations). t = metric ton.



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**Table 2.** NSB decomposition based on traceable baseline components (€/t), sample mean (Germany, 2017–2023)

| Component | Mean (€/t) | SD (€/t) |
|---|---|---|
| Energy value | 49.0 | 12.8 |
| Other value | 2.3 | 1.8 |
| Operating & compliance cost | –27.8 | 9.4 |
| Climate damage | –12.9 | 5.6 |
| Local pollution damage | –3.7 | 2.2 |
| Avoided damage (displacement) | 11.0 | 4.3 |
| Net social benefit (NSB) | 17.9 | 17.7 |

*Note:* Positive values increase NSB (benefits); negative values decrease NSB (costs/damages). All components are expressed per ton of waste treated. The baseline decomposition includes only traceable components with documented source categories, units, and construction rules.

To clarify what drives welfare variation, NSB was decomposed into market, cost, and externality components, as shown in Table 2. On average, recovered energy value contributes €49.0/ton, while operating and compliance costs reduce welfare by €27.8/ton. Monetized climate damages and local air-pollution damages further reduce NSB by €12.9/ton and €3.7/ton, respectively, while avoided damages from displaced generation add €11.0/ton. The traceable baseline decomposition sums to a mean NSB of €17.9/ton. Residue-handling costs are not included in this baseline where complete plant-year public coverage is not available; they are retained only as sensitivity information in the research materials.

Hypotheses H1–H5 were evaluated using plant and year fixed-effects regressions with standard errors clustered at the plant level. The results, summarized in Table 3, do not provide statistical support for the proposed operational relationships under the traceable-baseline NSB measure. In the full sample, energy recovery, emissions intensity, availability, and the emissions intensity × shadow-price interaction are not statistically significant. In the restricted sample, energy recovery, emissions intensity, oxygen instability, availability, and the emissions intensity × shadow-price interaction also remain statistically insignificant. Therefore, H1–H5 are not supported by the fixed-effects evidence. These results should be interpreted as conditional plant–year associations from a public-record welfare-accounting panel, not as causal estimates from confidential process-level operating records.

To assess valuation-level sensitivity, we recomputed NSB under low, central, and high shadow-price scenarios and re-estimated the fixed-effects model (Table 4). Mean traceable-baseline NSB declines

**Table 3.** Fixed-effects estimates for NSB (€/t), hypothesis tests (Germany, 2017–2023)

| Hyp. | Term | Sign | Full β (SE) | p | Restr. β (SE) | p | Decision |
|---|---|---|---|---|---|---|---|
| *H1* | ER | + | –7.76 (9.17) | 0.40 | –15.34 (14.10) | 0.28 | Not supported |
| *H2* | EI | – | 6.06 (8.59) | 0.48 | 12.11 (9.31) | 0.20 | Not supported |
| *H3* | $O_2$Instab | – | – | – | –1.33 (9.09) | 0.89 | Not supported |
| *H4* | Avail | + | 0.05 (0.19) | 0.79 | –0.15 (0.25) | 0.55 | Not supported |
| *H5* | EI×SPI | – | 4.62 (8.21) | 0.58 | 3.15 (11.62) | 0.79 | Not supported |

*Note:* Plant and year fixed effects included; standard errors clustered at plant level. Full sample: 476 obs., 70 plants. Restricted sample (with $O_2$Instab): 210 obs., 45 plants. Model $R^2$: 0.16 (full), 0.31 (restricted). Decisions are based on coefficient direction and $p < 0.05$.

**Table 4.** Shadow-price sensitivity of NSB and key coefficients (Germany, 2017–2023)

| Scenario | Mean NSB (€/t) | ER β | EI β | EI×SPI β |
|---|---|---|---|---|
| Low shadow prices | 26.1 | –7.8 | 6.1 | 4.6 |
| Central shadow prices | 17.9 | –7.8 | 6.1 | 4.6 |
| High shadow prices | 8.2 | –7.8 | 6.1 | 4.6 |

*Note:* Mean NSB is recomputed under each valuation scenario. Coefficients (β) are from the corresponding plant and year fixed-effects model estimated on the analytical dataset. Coefficient stability across scenarios indicates level sensitivity rather than a significant change in slope effects.

**Table 5.** GA–ANFIS operating configurations and implied NSB (central valuation case)

| Solution | ER (MWh/t) | EI ($tCO_2e$/MWh) | Avail (%) | NSB (€/t) |
|---|---|---|---|---|
| Sample mean | 0.60 | 0.61 | 87.0 | 17.9 |
| Welfare-optimal (NSB-max) | 0.66 | 0.55 | 90.1 | 29.7 |
| Emissions-min (constraint) | 0.62 | 0.49 | 89.0 | 25.8 |
| Energy-max (output) | 0.71 | 0.64 | 88.2 | 27.9 |

*Note:* "Sample mean" reports observed averages on the traceable-baseline central valuation scale. Other rows are feasible GA solutions under model bounds for the central valuation scenario and are interpreted only as exploratory decision-support outputs.

from €26.1/ton under low shadow prices to €17.9/ton under the central case and €8.2/ton under high shadow prices. This confirms that the level of welfare performance is sensitive to environmental valuation assumptions. However, in the available analytical dataset, the estimated slope coefficients remain effectively unchanged across the three scenarios and should not be interpreted as evidence that the emissions penalty significantly strengthens under stricter valuation. The sensitivity analysis therefore supports the importance of valuation assumptions for NSB levels, while the interaction hypothesis itself is not supported in Table 3.

The ANFIS predictive layer achieved an out-of-sample RMSE of €7.2/ton and an $R^2$ of 0.69, consistent with the empirical scale of NSB. Under the central valuation scenario, the genetic algorithm (GA) identified a welfare-oriented configuration characterized by higher energy recovery, lower emissions intensity, and greater availability. Relative to the observed traceable-baseline sample mean. The welfare-oriented solution in Table 5 increases NSB from €17.9/ton to €29.7/ton while remaining within feasible operational bounds.

# 4. DISCUSSION

The results show that the welfare performance of waste-to-energy (WtE) plants is best understood as a combined valuation and accounting outcome rather than as a fixed technology label. The decomposition indicates that recovered energy value is substantial but partly offset by operating and compliance costs, climate damages, and local pollution damages. At the same time, the fixed-effects regressions do not identify statistically significant operational drivers under the traceable-baseline NSB measure. Energy recovery, emissions intensity, availability, oxygen instability, and the emissions intensity × shadow-price interaction are not statistically significant after plant and year effects are controlled. The empirical message should therefore be framed cautiously: the public-data panel demonstrates meaningful welfare heterogeneity and valuation sensitivity, but it does not support the claim that the hypothesized operational channels are statistically confirmed.

These findings remain broadly consistent with earlier evidence that the environmental economics case for WtE depends on energy utilization and on the counterfactual energy system being displaced. District-heating and energy-integration studies show that when heat is productively used, avoided emissions and monetized benefits can strengthen the welfare case, whereas unused heat compresses the benefit margin and makes the damage side more salient (Marchi et al., 2025; Paulillo et al., 2024). The present plant–year estimates do not confirm this relationship econometrically in the traceable baseline panel. Similarly, the emissions-intensity estimates are not statistically significant and should not be interpreted as confirming a measurable annual plant-level emissions penalty in the available public records (Alshehadeh et al., 2025).

The emissions intensity × shadow-price interaction is also not statistically significant, so H5 is not supported by the fixed-effects results. This distinction is important. The scenario analysis shows that mean NSB decreases materially when environmental valuation becomes stricter, but this is a level effect of the valuation assumptions rather than evidence that the marginal coefficient on emissions intensity becomes statistically stronger. The oxygen instability coefficient in the restricted sample is likewise not statistically significant. These results do not remove the theoretical importance of com-


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bustion stability or emissions control; instead, they show that the publicly observable annual data used here are not sufficient to confirm those mechanisms econometrically with strong precision. Higher-frequency plant-control data may be needed to test these mechanisms more directly.

The optimization results should therefore be interpreted as a decision-support exercise rather than as independent causal proof of the regression hypotheses. The GA–ANFIS layer identifies feasible configurations that combine stronger recovery with lower emissions intensity and higher availability within observed operating bounds, but these configurations are model-based welfare scenarios. Their value lies in showing how a cost-accounting and externality-valuation framework can organize trade-offs among energy recovery, emissions, and availability, especially in regulatory contexts where shadow prices and decarbonizing grids change the value of both damages and displaced generation (Papamichael et al., 2024; Halkos & Aslanidis, 2024). These outputs do not validate the constructed dataset or substitute for the fixed-effects hypothesis tests.

The study is subject to public-data limitations. Public records strengthen transparency and reproducibility, but they do not provide the same operational detail as confidential plant-control systems or direct operator data. Some variables are therefore measured using documented public proxies, and oxygen-instability is available only for a restricted subsample. These limitations are handled by separating the full-sample baseline models from restricted-sample estimations, disclosing the observed/proxy/valuation status of variables, and interpreting results as plant–year associations based on harmonized public records. Residue-handling costs are not included in the baseline NSB measure where complete public plant-year coverage is not available. The findings should not be interpreted as evidence from confidential, high-frequency process-monitoring records.

## CONCLUSION

The study aimed to assess the welfare performance of German municipal waste-to-energy plants by combining operational indicators, monetized environmental effects, and valuation stringency within a cost-accounting framework. The analysis used public plant, environmental, technical, and market records for 2017–2023.

The results show that welfare outcomes differ across facilities and years. Recovered energy is the main positive component, while operating and compliance costs, climate damages, and local pollution damages reduce the final welfare balance. Avoided damages from displaced generation improve the outcome, but the sensitivity analysis shows that stricter shadow-price assumptions lower average net social benefit. The fixed-effects estimates do not provide statistical support for the operational hypotheses under the traceable-baseline NSB measure. Energy recovery, emissions intensity, availability, oxygen instability, and the emissions intensity × shadow-price interaction are not statistically significant in the available public-data panel.

These results suggest that waste-to-energy appraisal should combine financial, technical, and environmental components rather than rely only on output or compliance indicators. They also show that valuation assumptions must be transparent because they materially affect welfare estimates. Public data can support reproducible benchmarking, but stronger operational inference requires more complete process-level information.

Future research should use higher-frequency plant data, direct process indicators, location-sensitive damage values, alternative displacement baselines, and quasi-experimental designs to compare welfare outcomes across countries.

## AUTHOR CONTRIBUTIONS

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# APPENDIX A

**Table A1.** Municipal solid waste incineration (MSWI) plants in the analytical frame (n = 66)

| No. | Plant | Grate | Lines | Start-up | Energy mode | Thermal firing capacity (MW) | Capacity (Mg a-1) |
|---|---|---|---|---|---|---|---|
| 1 | Augsburg | FAG | 3 | 1994 | CoG | 75 | 255,000 |
| 2 | Bamberg | CAG | 3 | 1978 | CoG | 53 | 145,000 |
| 3 | Berlin | RG | 5 | 1967 | CoG | – | 550,000 |
| 4 | Bielefeld | CAG | 3 | 1981 | CoG | 180 | 400,000 |
| 5 | Böblingen | FAG | 2 | 1999 | CoG | 58 | 157,000 |
| 6 | Bonn | FAG | 3 | 1992 | CoG | 86 | 315,000 |
| 7 | Bremen | FAG | 4 | 1969 | CoG | 221 | 550,000 |
| 8 | Bremerhaven | FAG | 4 | 1977 | CoG | 140 | 401,500 |
| 9 | Burgkirchen | FAG | 2 | 1994 | CoG | – | 230,000 |
| 10 | Coburg | RAG | 2 | 1988 | CoG | 53 | 142,000 |
| 11 | Darmstadt | FAG | 3 | 1967 | CoG | 77 | 212,000 |
| 12 | Düsseldorf | RG | 6 | 1965 | CoG | 137 | 450,000 |
| 13 | Emlichheim (Laar) | FAG | 2 | 2008 | E | – | 454,176 |
| 14 | Essen | RG | 4 | 1987 | CoG | – | 745,000 |
| 15 | Frankfurt | FAG | 4 | 1965 | CoG | – | 525,300 |
| 16 | Freiburg / Eschbach | FAG | 1 | 2005 | CoG | 61 | 185,000 |
| 17 | Göppingen | RG | 1 | 1975 | CoG | 57 | 157,680 |
| 18 | Hagen | RG | 3 | 1966 | CoG | – | 144,000 |
| 19 | Hamburg (MVB) | FAG | 2 | 1994 | CoG | 116 | 320,000 |
| 20 | Hamburg (MVR) | FAG | 2 | 1999 | CoG | 120 | 320,000 |
| 21 | Hameln | FAG \| RG | 3 | 1977 | CoG | 141 | 300,000 |
| 22 | Hamm | FAG | 4 | 1985 | CoG | – | 295,000 |
| 23 | Hannover | FAG | 2 | 2005 | E | 105 | 280,000 |
| 24 | Helmstedt / Buschhaus | FAG | 3 | 1998 | E | 173 | 525,000 |
| 25 | Herten | FAG \| CAG | 4 | 1982 | CoG | 208 | 600,000 |
| 26 | Ingolstadt | RAG \| CAG | 3 | 1977 | CoG | 99 | 255,000 |
| 27 | Iserlohn | FAG | 3 | 1970 | CoG | 102 | 295,000 |
| 28 | Kamp-Lintfort | RG | 2 | 1997 | CoG | 99 | 270,000 |
| 29 | Kassel | FAG | 2 | 1968 | CoG | 61 | 200,000 |
| 30 | Kempten | RAG | 2 | 1996 | CoG | 52 | 160,000 |
| 31 | Kiel | RG | 2 | 1996 | CoG | 44 | 140,000 |
| 32 | Köln (Cologne) | RG | 4 | 1998 | CoG | 241 | 780,000 |
| 33 | Krefeld | RG | 3 | 1975 | CoG | 162 | 375,000 |
| 34 | Lauta | FAG | 2 | 2004 | CoG | 87 | 225,000 |
| 35 | Leuna | FAG | 2 | 2005 | CoG | 153 | 420,000 |
| 36 | Leverkusen | FAG | 3 | 1970 | CoG | 84 | 280,320 |
| 37 | Ludwigshafen | RG | 3 | 1967 | CoG | 88 | 210,000 |
| 38 | Ludwigslust | FAG | 1 | 2005 | E | 16 | 50,000 |
| 39 | Magdeburg / Rothensee | FAG | 4 | 2006 | CoG | 267 | 650,000 |
| 40 | Mainz | RAG | 3 | 2004 | CoG | – | 350,000 |
| 41 | Mannheim | FAG | 3 | 1965 | CoG | 263 | 650,000 |
| 42 | München (Munich) | RAG | 4 | 1983 | CoG | 172 | 685,000 |
| 43 | Neunkirchen | RAG | 2 | 1969 | CoG | 56 | 150,000 |
| 44 | Neustadt | FAG | 1 | 1984 | CoG | 24 | 56,000 |
| 45 | Nürnberg (Nuremberg) | FAG | 3 | 2001 | CoG | 105 | 230,000 |
| 46 | Oberhausen / Niederhein | RG | 4 | 1972 | CoG | 267 | 700,000 |
| 47 | Offenbach | RG | 3 | 1970 | CoG | 84 | 250,000 |
| 48 | Olching / Geiselbullach | FAG | 3 | 1975 | CoG | 44 | 120,000 |
| 49 | Pirmasens | FAG | 2 | 1998 | CoG | 70 | 180,000 |
| 50 | Rosenheim | CAG | 1 | 1964 | CoG | 28 | 100,000 |
| 51 | Salzbergen | FAG | 1 | 2004 | CoG | 47 | 130,000 |
| 52 | Schwandorf | CAG | 4 | 1982 | CoG | 205 | 450,000 |


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**Table A1 (cont.).** Municipal solid waste incineration (MSWI) plants in the analytical frame (n = 66)

| No. | Plant | Grate | Lines | Start-up | Energy mode | Thermal firing capacity (MW) | Capacity (Mg a-1) |
|---|---|---|---|---|---|---|---|
| 53 | Schweinfurt | FAG | 3 | 1994 | CoG | 62 | 196,806 |
| 54 | Solingen | FAG | 2 | 1969 | CoG | 63 | 175,000 |
| 55 | Stapelfeld | FAG | 2 | 1979 | CoG | 116 | 350,000 |
| 56 | Staßfurt | FAG | 2 | 2007 | CoG | 111 | 380,000 |
| 57 | Stuttgart | FAG \| RG | 3 | 1965 | CoG | 193 | 420,000 |
| 58 | Tornesch-Ahrenlohe | FAG | 2 | 1974 | CoG | 29 | 80,000 |
| 59 | Ulm | FAG | 2 | 1997 | CoG | – | 165,000 |
| 60 | Velsen / Saarbrücken | FAG | 2 | 1997 | E | 83 | 255,000 |
| 61 | Weißenhorn | FAG | 2 | 1991 | E | 48 | 116,000 |
| 62 | Weisweiler / Eschweiler | RAG | 3 | 1996 | CoG | 135 | 360,000 |
| 63 | Wuppertal | RAG | 5 | 1976 | CoG | 186 | 400,000 |
| 64 | Würzburg | FAG \| (FAG-RAG) | 3 | 1984 | CoG | – | 219,000 |
| 65 | Zella-Mehlis | RAG | 1 | 2008 | CoG | 60 | 160,000 |
| 66 | Zorbau | FAG | 2 | 2005 | CoG | 107 | 338,000 |

**Table A2.** RDF power plants included in the analytical sample (to complete n = 70)

| No. | Plant | Combustion type | Lines | Start-up | Energy mode | Thermal firing capacity (MW) | Capacity (Mg a-1) |
|---|---|---|---|---|---|---|---|
| 67 | Bernburg | GF | 3 | 2009 | CoG | 214 | 552,000 |
| 68 | Bremen (MKK) | GF | 1 | 2009 | CoG | 110 | 330,000 |
| 69 | Eisenhüttenstadt | CFBC | 1 | 2011 | CoG | 150 | 340,000 |
| 70 | Frankfurt (T2C) | RFBC | 3 | 2012 | CoG | – | 700,000 |

**Table A3.** Variable provenance and construction status used to construct the analytical dataset

| Variable/component | Status and construction rule | Source category and use |
|---|---|---|
| Plant frame/capacity | Observed public records matched by plant name, location, operator, and registry fields; defines the 70-facility frame. | MaStR/plant registry and technical records; baseline identification and capacity controls. |
| Waste treated/throughput | Observed where plant-year public records exist; otherwise documented proxy from permitted/ typical capacity and screened utilization. | Plant reports, registry/capacity records, Eurostat waste benchmarks; scaling variable. |
| Energy recovery | Observed or public-proxy measure; net electricity and useful heat are divided by waste treated where quantifiable. | Electricity/heat records, market reporting, and technical records; baseline/robustness use. |
| Emissions intensity | Observed facility-year emissions converted to common mass or CO2e units and scaled by waste or MWh. | German PRTR/Thru.de, EEA industrial reporting, EU ETS where applicable; hypothesis testing. |
| Availability | Documented proxy from observable throughput/ capacity ratios and public outage or unavailability indicators. | Outage/unavailability records and capacity data; baseline or robustness depending on coverage. |
| O2 instability | Limited-coverage process proxy constructed only where public environmental statements permit consistent measurement. | Public environmental statements and technical records; restricted-sample analysis only. |
| Climate/local damages | Valuation-derived components: physical emissions multiplied by external damage prices and converted to constant euros per ton. | EPA SC-GHG, CE Delft, EEA damage-cost references, Destatis/Eurostat inflation; baseline valuation. |
| Avoided damages/residue sensitivity | Avoided damages use documented displacement assumptions. Residue handling is not used in baseline NSB; it is retained only as sensitivity information where public plant-year coverage is incomplete. | Electricity/carbon prices, technical benchmarks, source inventory; baseline for avoided damages and sensitivity treatment for residue handling. |