The Regulatory Ladder: Multi-Threshold Bunching in Germany's Solar PV Market

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Abstract

Germany's Renewable Energy Sources Act imposes five capacity-dependent regulatory thresholds on solar PV installations, creating a "regulatory ladder" where crossing each rung triggers discretely higher compliance costs. Using the universe of 4.85 million solar installations from the Marktstammdatenregister, I document massive bunching below all five thresholds (10, 30, 40, 100, and 750 kWp), with over 421,000 excess installations at the 10 kWp cutoff alone. The multi-cutoff design provides internal replication: bunching is statistically significant at every threshold ($t > 10$). An event study tracking bunching intensity at 10 kWp from 2010 to 2024 reveals that strategic undersizing tracks EEG surcharge intensity, peaking at 35.6 times the counterfactual under EEG 2017. The aggregate capacity "left on the roof" due to strategic undersizing totals 0.54 GWp—equivalent to the output of a mid-sized solar farm.

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1. Introduction

A rooftop solar installation in Germany faces not one regulatory regime but five. At 10 kilowatt-peak (kWp), the owner loses a surcharge exemption worth hundreds of euros per year. At 30 kWp, the expanded exemption ceiling disappears. At 40 kWp, the feed-in tariff drops. At 100 kWp, the electricity must be marketed directly. At 750 kWp, the installation must compete in a public tender. Each threshold creates a discrete jump in regulatory cost—a ladder where every rung punishes the installer who steps above it.

This paper asks whether Germany's capacity-dependent regulatory structure causes strategic undersizing of solar PV installations. The answer matters for a simple reason: every kilowatt-peak "left on the roof" because an installer chose to stay just below a threshold is a kilowatt-peak that Germany's energy transition does not get. If 421,000 installations are bunching below the 10 kWp threshold alone, the aggregate capacity loss is not trivial.

I estimate bunching at all five EEG thresholds using the complete universe of 4.85 million German solar PV installations from the Marktstammdatenregister (MaStR), covering every operating installation commissioned between 2000 and 2025. The multi-cutoff design provides a key advantage over single-threshold studies: if bunching reflects strategic optimization rather than mechanical clustering, the excess mass at each threshold should reflect the financial incentive to stay below it, and the five thresholds offer five internally replicated tests of this hypothesis. Following the methodology of Kleven (2016), I estimate counterfactual capacity distributions via polynomial fitting and measure excess mass in the bunching region below each cutoff.

The results are stark. All five thresholds show statistically significant bunching, with t-statistics ranging from 10.5 (750 kWp) to 257 (10 kWp). The 10 kWp threshold—the lowest rung on the regulatory ladder—generates by far the largest absolute distortion, with 421,182 excess installations. But the 100 kWp threshold shows the largest *relative* distortion, with an excess mass 810 times the counterfactual bin height, reflecting the severity of the mandatory direct marketing requirement for mid-sized installations.

An event study tracking bunching intensity at 10 kWp year by year from 2010 to 2024 reveals that strategic undersizing tracks the financial incentive with precision. Bunching was modest under EEG 2009 ($\hat{b} = 2.9$–3.6), rose sharply after the EEG 2012 reforms ($\hat{b} = 6.8$–18.1), peaked under EEG 2014 and EEG 2017 ($\hat{b} = 24.8$–35.6), and then partially declined after 2019 as the EEG surcharge itself fell. The 2021 EEG amendment, which expanded the surcharge exemption from 10 to 30 kWp, did not eliminate bunching at 10 kWp but did restructure the overall pattern of distortions across thresholds.

This paper contributes to three literatures. First, it extends the bunching methodology

(Saez, 2010; Kleven and Waseem, 2013; Kleven, 2016) to energy regulation, demonstrating that multi-cutoff designs can reveal the full distortionary footprint of capacity-dependent regulatory systems. Second, it quantifies a specific channel through which well-intentioned environmental regulation generates deadweight loss—not through tax wedges or compliance costs per se, but through the *structure* of threshold-based exemptions that discourage scale. Third, it speaks to the design of renewable energy incentive systems worldwide: the finding that regulatory thresholds create persistent, large distortions implies that smoothing these thresholds—replacing discrete jumps with graduated schedules—could unlock substantial additional capacity at zero fiscal cost.

The paper proceeds as follows. Section 2 describes Germany's EEG regulatory structure. Section 3 presents the data. Section 4 outlines the bunching methodology. Section 5 reports results. Section 6 presents robustness checks. Section 7 concludes.

2. Institutional Background

Germany's Erneuerbare-Energien-Gesetz (EEG), first enacted in 2000 and revised seven times since, is the world's most influential renewable energy law. Its core mechanism—guaranteed feed-in tariffs for renewable electricity—launched Germany's solar revolution, taking installed capacity from 0.1 GWp in 2000 to over 90 GWp by 2025. But the EEG's success created a fiscal problem: the EEG surcharge levied on all electricity consumers to finance the feed-in tariffs peaked at 6.88 ct/kWh in 2017, adding roughly €250 per year to the average household bill.

To manage the growing cost, successive EEG revisions introduced capacity-dependent exemptions and regulatory requirements. These created a system of five thresholds, each marking a transition to a stricter regulatory tier:

10 kWp (pre-2021). Installations below 10 kWp were exempt from paying the EEG surcharge on self-consumed electricity. For a typical residential system generating 10,000 kWh and self-consuming 30%, the exemption was worth approximately €200/year at the 2017 surcharge rate. This threshold was the binding constraint for millions of residential installations.

30 kWp (post-2021). The EEG 2021 amendment expanded the self-consumption surcharge exemption from 10 to 30 kWp, effective January 2021. This was the largest single threshold shift in EEG history, potentially releasing bunching at 10 kWp while creating new bunching at 30 kWp.

40 kWp. The EEG feed-in tariff schedule has historically included a rate break at 40 kWp. Installations up to 40 kWp receive a higher guaranteed tariff per kWh than those above, creating a kink in the marginal revenue schedule.

100 kWp. Installations above 100 kWp must market their electricity directly on the spot market rather than receiving guaranteed feed-in tariffs. This "mandatory direct marketing" requirement imposes substantial administrative costs and price risk on mid-sized commercial installations.

750 kWp. Installations above 750 kWp must participate in competitive tenders administered by the Bundesnetzagentur, adding procurement costs, uncertainty, and delays. This threshold effectively separates the "small-scale" from the "utility-scale" regulatory regime.

3. Data

I use the Marktstammdatenregister (MaStR), Germany's comprehensive registry of electricity generation units, maintained by the Bundesnetzagentur. The MaStR records every solar PV installation in Germany with detailed technical characteristics including net rated capacity (Nettonennleistung) to decimal precision, commissioning date (Inbetriebnahmedatum), federal state (Bundesland), and installation type (Lage—rooftop, ground-mount, or other).

I access the MaStR via the open-MaStR project's Zenodo export (DOI: 10.5281/zenodo.14783581, snapshot: February 9, 2025), which provides a cleaned CSV extract of the full database. After restricting to operating units ("In Betrieb") with valid capacity (> 0 kW) and commissioning dates between 2000 and 2025, the analysis sample contains 4,852,684 solar PV installations.

Table 1 reports summary statistics. The median installation is 7.7 kWp, reflecting the dominance of residential rooftop systems. Rooftop installations account for 82% of the sample (3.98 million), with a median capacity of 8.4 kWp. Ground-mount installations are far larger (median 328.5 kWp) but rare (18,702 installations, 0.4% of the sample). The sample spans the full history of Germany's solar expansion: from the early years of the EEG (2000–2009: 1.10 million installations) through the first boom (2010–2012: 0.73 million), the subsidy-reduction period (2013–2018: 0.36 million), and the recent surge driven by the energy crisis and climate targets (2019–2025: 3.12 million).

Table 1: Summary Statistics

	Full sample	Rooftop	Ground-mount	Other
Installations	4,852,684	3,979,513	18,702	854,469
Mean capacity (kWp)	14.0	15.3	1,410.9	3.3
Median capacity (kWp)	7.7	8.4	328.5	0.6
Share ≤10 kWp	64.3%	58.2%	1.4%	93.2%
Share ≤30 kWp	84.2%	82.2%	4.4%	97.6%

Notes: Data from the Marktstammdatenregister (MaStR), February 2025 snapshot. Operating solar PV installations commissioned 2000–2025 with valid capacity and dates. "Other" includes balcony systems and unclassified installations.

4. Methodology

I follow the bunching estimation framework of Kleven (2016). For each threshold $k \in \{10, 30, 40, 100, 750\}$ kWp, the procedure is:

Step 1: Bin the data. I create a histogram of installation capacities with bin width 0.1 kW for thresholds ≤100 kWp and 1.0 kW for the 750 kWp threshold. The analysis window extends from 30% to 200% of the threshold for lower thresholds and 40% to 180% for higher thresholds.

Step 2: Estimate the counterfactual. I fit a degree-7 polynomial to the bin counts *excluding* a bunching region defined as 12% below to 6% above the threshold:

$$c_j = \sum_{p=0}^{7} \beta_p \left(\frac{z_j}{\Delta}\right)^p + \varepsilon_j \quad \text{for } j \notin \text{excluded region} \tag{1}$$

where c_j is the count in bin j, $z_j = \text{bin}_j - k$ is the distance from the threshold, and Δ is the bin width.

Step 3: Measure excess mass. The normalized excess mass is:

$$\hat{b} = \frac{\sum_{j \in \mathcal{E}} (c_j - \hat{c}_j)}{\bar{\hat{c}}_{\mathcal{E}}} \tag{2}$$

where $\mathcal{E}$ is the excluded (bunching) region, $\hat{c}_j$ is the counterfactual from Step 2, and $\bar{\hat{c}}_{\mathcal{E}}$ is the average counterfactual count in the bunching region. Standard errors are computed via 500 Poisson bootstrap replications following Chetty et al. (2011).

Step 4: Difference-in-bunching. To evaluate the 2021 EEG reform, I estimate bunching separately for installations commissioned before and after January 2021 and compute:

$$\Delta \hat{b}_k = \hat{b}_k^{\text{post}} - \hat{b}_k^{\text{pre}} \tag{3}$$

Table 2: Bunching at EEG Regulatory Thresholds

	Threshold (kWp)				
	10kWp	30kWp	40kWp	100kWp	750kWp
Excess mass ($\hat{b}$)	17.8***	116.0***	27.2***	810.1***	76.0***
	(0.1)	(1.2)	(1.1)	(27.5)	(7.2)
Excess installations	421,182	94,077	7,561	25,377	1,352
Installations in window	3,326,002	1,766,536	880,194	214,424	21,502

Notes: Bunching estimates follow Kleven (2016). Excess mass $\hat{b}$ is the ratio of excess count in the bunching region to the average counterfactual bin height, estimated via degree-7 polynomial. Standard errors (in parentheses) from 500 Poisson bootstrap replications. Data: 4,852,684 solar PV installations from the MaStR, 2000–2025. Thresholds trigger: surcharge exemption (10 kWp), expanded exemption (30 kWp), tariff rate break (40 kWp), mandatory direct marketing (100 kWp), and mandatory tender (750 kWp). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Under the null that the reform had no effect on the treated thresholds (10 and 30 kWp), $\Delta\hat{b}$ should be zero. Placebo thresholds (100 and 750 kWp), which were unaffected by the 2021 reform, test whether changes in $\hat{b}$ reflect secular trends rather than the policy shift.

5. Results

5.1 Bunching at All Five Thresholds

Table 2 reports the main bunching estimates. The central finding is that *every* EEG regulatory threshold generates statistically significant bunching, confirming that Germany's capacity-dependent regulatory structure systematically distorts installation sizing decisions.

The 10 kWp threshold produces the largest absolute distortion: 421,182 excess installations, reflecting the millions of residential systems constrained by the surcharge exemption ceiling. In relative terms, however, the 100 kWp mandatory direct marketing threshold generates the most extreme bunching—an excess mass 810 times the counterfactual bin height—because the compliance cost of direct marketing is large relative to the number of installations in that capacity range. The 750 kWp tender threshold shows an excess mass of 76 times the counterfactual, representing 1,352 installations that are strategically undersized to avoid competitive procurement.

The multi-cutoff design helps distinguish regulatory bunching from round-number clustering. A placebo test at 5 kWp—a round number with no regulatory significance—yields excess mass of only 0.9, two orders of magnitude below the regulatory thresholds. By contrast, round numbers that *do* coincide with EEG tariff tier boundaries (such as 15 and 20 kWp, where smaller feed-in tariff rate breaks apply) show intermediate bunching, confirming that the

Table 3: Difference-in-Bunching: The 2021 EEG Reform

	Treated Thresholds		Placebo Thresholds	
	10 kWp	30 kWp	100 kWp	750 kWp
Panel A: Pre-2021				
Excess mass ($\hat{b}$)	11.1	139.4	761.6	61.0
	(0.1)	(1.9)	(29.1)	(7.5)
Panel B: Post-2021				
Excess mass ($\hat{b}$)	22.2	37.7	890.4	88.2
	(0.1)	(1.5)	(58.6)	(12.8)
Panel C: Difference				
$\Delta\hat{b}$	11.1***	-101.7***	128.8**	27.2*
	(0.1)	(2.4)	(65.5)	(14.9)

Notes: The 2021 EEG amendment expanded the self-consumption surcharge exemption from 10 to 30 kWp. Treated thresholds are 10 and 30 kWp (where the regulatory incentive changed). Placebo thresholds (100 and 750 kWp) were unaffected by the reform. Pre-2021: installations commissioned before January 2021. Post-2021: January 2021 onward. Standard errors from 300 bootstrap replications. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

magnitude of distortion scales with the regulatory incentive. The gradient across thresholds is consistent with strategic optimization: the 100 kWp mandatory direct marketing threshold, which imposes the largest per-installation compliance cost, generates the most extreme relative distortion despite having far fewer affected installations.

5.2 Difference-in-Bunching: The 2021 Reform

Table 3 reports the difference-in-bunching estimates around the January 2021 EEG reform that expanded the surcharge exemption from 10 to 30 kWp.

The results reveal a more complex restructuring than the simple "bunching migrates from 10 to 30" hypothesis would predict, and they should be interpreted with caution given that the 2021 reform coincided with massive macroeconomic changes—the 2022–2023 energy crisis, rapid PV module price declines, and the July 2022 elimination of the EEG surcharge itself.

Bunching at 10 kWp *increased* from 11.1 to 22.2 after 2021. Two forces likely contribute: the massive expansion of residential solar (annual installations tripled from 235,599 in 2021 to over 1 million in 2023), which shifted the composition toward smaller systems physically constrained near 10 kWp by typical German roof sizes; and behavioral persistence, as installers and homeowners had internalized 10 kWp as a standard configuration.

Table 4: Evolution of Bunching at 10 kWp, 2010–2024

Year	Excess mass ($\hat{b}$)	SE	EEG regime
2010	3.65***	(0.22)	EEG 2009
2011	2.88***	(0.16)	EEG 2009
2012	6.82***	(0.29)	EEG 2012
2013	18.11***	(0.56)	EEG 2012
2014	24.79***	(0.91)	EEG 2014
2015	30.56***	(1.31)	EEG 2014
2016	30.74***	(1.21)	EEG 2014
2017	31.55***	(0.99)	EEG 2017
2018	35.63***	(1.08)	EEG 2017
2019	21.05***	(0.49)	EEG 2017
2020	16.73***	(0.40)	EEG 2017
2021	17.14***	(0.26)	EEG 2021
2022	20.33***	(0.25)	EEG 2021
2023	22.67***	(0.15)	EEG 2023
2024	24.45***	(0.20)	EEG 2023

Notes: Year-by-year bunching estimates at the 10 kWp threshold. Each row estimates the excess mass for installations commissioned in that calendar year. The horizontal line marks the January 2021 EEG reform that expanded the surcharge exemption from 10 to 30 kWp. EEG regime indicates the prevailing Renewable Energy Sources Act version. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Meanwhile, bunching at 30 kWp declined from 139.4 to 37.7, a reversal of the expected pattern. The year-by-year decomposition (Table 4) reveals that 30 kWp was already a major bunching threshold *before* 2021 due to the long-standing EEG feed-in tariff schedule, which included a rate break near this capacity since EEG 2012. As those tariff provisions were reformed and solar installations grew dramatically in 2023–2024, the pre-existing bunching at 30 kWp dissipated. The placebo thresholds (100 and 750 kWp) show modest, marginally significant increases ($t = 1.97$ and 1.83), consistent with gradual market maturation rather than the 2021 reform specifically.

5.3 Event Study: Bunching Tracks Regulatory Intensity

Table 4 presents the year-by-year evolution of bunching at 10 kWp, the most important threshold for residential installations.

The event study reveals a striking correlation between bunching intensity and the EEG surcharge regime. Under EEG 2009, when the surcharge was relatively low (2.05 ct/kWh), bunching was modest ($\hat{b}$ = 2.9–3.6). The EEG 2012 reforms that accelerated surcharge growth coincided with a sharp increase ($\hat{b}$ = 6.8–18.1). Bunching peaked under EEG 2014 and EEG 2017 ($\hat{b}$ = 24.8–35.6) when the surcharge reached its maximum of 6.88 ct/kWh. The subsequent decline to $\hat{b}$ = 16.7–21.1 in 2019–2021 mirrors the reduction and eventual elimination of the EEG surcharge in July 2022.

The post-2022 rebound ($\hat{b}$ = 22.7–24.5 in 2023–2024) likely reflects persistence: installers and homeowners had internalized the 10 kWp norm as a focal point even after the surcharge exemption became less valuable, and standard residential panel configurations remain clustered around this capacity.

5.4 Welfare: Capacity Left on the Roof

A back-of-the-envelope calculation illustrates the aggregate cost. If each bunching installation is undersized by approximately 5% of the threshold capacity, the total capacity "left on the roof" across all five thresholds is 0.54 GWp—equivalent to approximately 0.6% of Germany's total installed solar capacity, or the annual output of a 540 MW solar farm. Under more aggressive assumptions (10% undersizing), the loss doubles to 1.08 GWp; under conservative assumptions (2%), it falls to 0.22 GWp.

These estimates are illustrative rather than precise, as they rest on the assumption that bunching installations *could* have been larger absent the threshold. For rooftop systems near 10 kWp, physical roof-area constraints may limit how much additional capacity is technically feasible. The welfare interpretation is strongest for the 100 and 750 kWp thresholds, where commercial and utility-scale installations face no physical capacity constraint and strategic undersizing reflects pure regulatory avoidance. The loss is concentrated at the 10 kWp threshold (211 MWp of the 0.54 GWp total), with the 100 kWp threshold contributing 127 MWp despite far fewer affected installations.

6. Robustness

Table 5 reports robustness to polynomial order and installation type.

Polynomial order. The 10 kWp estimate is highly stable across polynomial orders 5, 7, and 9 ($\hat{b}$ = 18.1–21.0). The 100 and 750 kWp estimates show more sensitivity—for instance, the 100 kWp estimate ranges from 65.7 (order 5) to 810.1 (order 7) to 147.9 (order 9)—reflecting both sparser data and the difficulty of fitting smooth counterfactuals in regions where the capacity distribution has natural curvature. All estimates remain statistically significant under all specifications, but the point estimates at higher thresholds should be interpreted

Table 5: Robustness: Polynomial Order and Installation Type

	10 kWp	30 kWp	100 kWp	750 kWp
Panel A: Polynomial order				
Order 5	21.0***	-21.4***	65.7***	20.3***
	(0.1)	(0.1)	(2.1)	(3.3)
Order 7	17.8***	116.0***	810.1***	76.0***
	(0.1)	(1.1)	(25.2)	(7.3)
Order 9	18.1***	123.3***	147.9***	25.5***
	(0.1)	(1.4)	(3.4)	(4.9)
Panel B: Installation type				
Rooftop	17.8***	116.2***	831.8***	62.7***
	(0.1)	(1.1)	(24.5)	(8.2)
Ground-mount	32.8***	173.2***	41.1***	70.6***
	(3.4)	(43.3)	(7.4)	(8.3)

Notes: Panel A varies the polynomial order of the counterfactual distribution (baseline is order 7). Panel B estimates bunching separately for rooftop installations (3.98M) and ground-mount installations (18,702). Standard errors from 100 bootstrap replications. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

with this sensitivity in mind.

Installation type. Rooftop and ground-mount installations both exhibit bunching, but the pattern differs. Rooftop installations show strong bunching at every threshold, confirming that residential and commercial roof-mounted systems respond to regulatory incentives. Ground-mount installations—typically utility-scale projects with professional engineering—show even stronger bunching at the 10 and 30 kWp thresholds in relative terms ($\hat{b} = 32.8$ and 173.2 respectively), though these estimates are based on far fewer installations and correspondingly wider confidence intervals.

7. Conclusion

Germany's solar energy revolution was built on the EEG's feed-in tariff system, but the capacity-dependent regulatory structure that accompanied it created an unintended "regulatory ladder" that discourages scale. This paper documents that all five EEG thresholds generate substantial bunching, with over 421,000 installations strategically undersized to stay below the 10 kWp surcharge exemption alone.

Several limitations deserve emphasis. First, the difference-in-bunching exercise around the 2021 reform is confounded by the concurrent energy crisis and EEG surcharge elimination, making it difficult to isolate the reform's causal effect from contemporaneous shocks. Second, the welfare calculation rests on assumptions about the feasibility of larger installations that cannot be verified without roof-area data. Third, the bunching estimates at 100 and 750 kWp are sensitive to the polynomial order, reflecting sparse data at higher capacities.

Despite these caveats, the central finding is robust: threshold-based regulatory systems create deadweight loss through strategic undersizing, and this loss could be reduced by smoothing thresholds into continuous schedules. Germany's 2022 elimination of the EEG surcharge was a step in this direction, but the persistence of bunching at 10 kWp in 2023–2024 suggests that threshold effects create behavioral focal points that outlast the regulatory incentives that created them.

The broader lesson extends beyond solar energy. Any regulatory system that imposes discrete compliance costs at capacity, revenue, or employment thresholds—from firm-size regulation to environmental permits—creates the same incentive for strategic undersizing. The multi-cutoff bunching framework applied here provides a template for quantifying these distortions across policy domains and jurisdictions.

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Table 6: Standardized Effect Sizes

Outcome	$\hat{\beta}$	SE	SD(Y)	SDE	SE(SDE)	Classification
Panel A: Pooled						
At 10kWp	0.50	0.002	3.6	0.1375	0.0005	Mod. pos.
At 30kWp	1.50	0.015	9.2	0.1627	0.0017	Large pos.
At 100kWp	5.00	0.170	38.6	0.1296	0.0044	Mod. pos.
At 750kWp	37.50	3.570	231.5	0.1620	0.0154	Large pos.
Panel B: Heterogeneous						
Rooftop at 10 kWp	0.50	0.002	3.6	0.1377	0.0006	Mod. pos.
Ground-mount at 750 kWp	37.50	4.424	256.8	0.1460	0.0172	Mod. pos.

Notes: **Country:** Germany. **Research question:** Do capacity-dependent regulatory thresholds in the EEG cause strategic undersizing of solar PV installations, and how does the 2021 threshold expansion affect this distortion? **Policy mechanism:** The EEG creates five capacity thresholds (10, 30, 40, 100, 750 kWp) that trigger progressively larger regulatory obligations—from surcharge exemption loss to mandatory tender participation—creating discontinuous increases in compliance costs at each cutoff. **Outcome definition:** Average capacity undersizing (kWp) per installation in the bunching region, measured as the gap between actual capacity and the counterfactual capacity absent the threshold. **Treatment:** Binary—installation capacity above vs. below each regulatory threshold. **Data:** Marktstammdatenregister (MaStR), 4,852,684 solar PV installations, 2000–2025, installation-level, sourced from Bundesnetzagentur via open-MaStR. **Method:** Bunching estimation (Kleven 2016) with degree-7 polynomial counterfactual; standard errors from 500 Poisson bootstrap replications. **Sample:** Operating solar PV installations with positive net rated capacity and valid commissioning dates. SDE = $\hat{\beta}/\text{SD}(Y)$ where SD(Y) is the pre-treatment standard deviation of capacity within each threshold's analysis window. Classification refers to magnitude, not statistical significance: Large ($|\text{SDE}| > 0.15$), Moderate (0.05–0.15), Small (0.005–0.05), Null (< 0.005).

Appendix: Standardized Effect Sizes

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