

HELIOSOLVE

PV Simulation & Yield Analysis Platform

Technical Validation Report

Heliosolve PV Simulation Engine

Utility-Scale Field Validation — 5 MWp JUST Plant, Jordan

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY AT A GLANCE

HelioSolve’s solar-simulation engine matched the operating output of a **commissioned 5 MWp commercial plant** in Irbid, Jordan to within **+0.75% on annual AC energy** and **+0.4 percentage points on capacity factor** over a full year of monitored operation. That is the simulation-side share of the modelling uncertainty contributing to the industry’s documented **~8% energy-yield-forecast gap** [2, 3, 4].

- **What was tested:** HelioSolve modelled the JUST 5 MWp fixed-tilt PV plant (18,920 mc-Si modules, 84 inverters, GCR 0.5) using twelve months of weather and reference-instrument data published by Alshare et al. in *Case Studies in Thermal Engineering* [1].
- **What we found:** Modelled annual AC energy matched the on-site Janitza revenue-grade meter to +0.75%, capacity factor to +0.4 pp, specific yield to +0.74%, and the monthly tracking error (NMAE, full-month subset) was 4.0%. The driver weather was NREL NSRDB satellite reanalysis [8] pulled for the exact 12-month measurement window (Feb 2017 – Jan 2018); the plant’s own pyranometer was not used as input.
- **Why it matters:** These results address the *modelling* share of the industry’s ~8% yield-forecast gap. Operational, financial and degradation contributors lie outside this report. Tighter modelling on AC energy and capacity factor supports lender P50/P90 inputs as one factor among several [5].

Scope: one commissioned commercial plant, one year of measured data. Reference dataset published by an independent academic team [1]; not a third-party audit.

Table 1: Annual validation metrics for the JUST 5 MWp plant against the on-site measured reference [1], twelve-month window. See the methodology appendix for term definitions.

Validation Parameter	HelioSolve Result	Status
Annual energy bias (NMBE)	+0.75%	Sub-1%
Capacity factor deviation	+0.4 pp	Within IEC tolerance
Specific yield bias	+0.74%	Sub-1%
Monthly tracking error (NMAE, full-month subset)	4.0%	High-fidelity

Bias = annual integrated difference between modelled and measured value, expressed as a percentage of the measured total. The full-month NMAE subset (March – December) excludes the partial-month January and February series in the reference dataset.

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WHY THIS MATTERS

Modern utility-scale solar plants commissioned after 2015 produce roughly **8% less energy** — after correcting for actual weather conditions — than their pre-construction forecasts had predicted [2, 3]. Lawrence Berkeley National Laboratory has separately documented plant-level capacity factors and degradation patterns across 31 GW-DC of utility-scale PV spanning 631 plants commissioned 2007–2018 [4]. The gap has multiple drivers — panel soiling, plant uptime, panel ageing, construction quality, the weather data fed into the forecast, and the simulation model itself. This report addresses the **simulation-model** share, on a single commissioned commercial plant:

- **The 8% shortfall is real and measured:** In its 2025 update, kWh Analytics reports an 8.6% mean shortfall across 34,000 system-months of operating data (one plant tracked for one month equals one “system-month”; this is roughly 2,800 plant-years of operating data) [2, 3].
- **It feeds straight into project finance:** When the model output is more uncertain, the gap between best-case and worst-case revenue forecasts widens. That can shrink the debt-service-coverage ratio — the metric lenders use to decide how much they will lend against the project [5].

This report focuses on the simulation-model piece, and on a single question: can a simulation engine match the AC electricity actually delivered by a real commercial plant, over a full year, when driven by an *independent* satellite weather feed rather than the plant’s own on-site sunlight sensor (which would amount to the model checking itself against its own input)? On this plant, the answer is yes — to within +0.75% on annual AC energy.

WHAT WE VALIDATED

HelioSolve is a physics-based simulation engine that estimates how much sunlight reaches a solar plant and, from that, how much AC electricity the plant delivers under real-world weather and operating conditions. The engine’s components are conventional — standard models for the sunlight reaching the panel surface, the panel temperature, and the electrical output flowing through inverters and transformers. Section 3 shows that, run end-to-end on this case, the chain reproduces what the plant actually delivered to the meter, within the agreement levels reported there.

The validation reference is the **5 MWp PV plant at Jordan University of Science and Technology (JUST)**, in Irbid, Jordan, whose twelve-month monitored performance was published by Alshare et al. in *Case Studies in Thermal Engineering* [1]. The plant is a widely-cited industry reference for Mediterranean-climate utility PV. The published dataset includes monthly grid-injected AC energy from a revenue-grade meter, sunlight on the panel plane from an on-site calibrated solar sensor, and panel-back temperature — across a full seasonal cycle (February 2017 – January 2018).

Why this is the right benchmark

- **Published, peer-reviewed reference:** Twelve months of measured AC energy, sunlight on the panel plane, and panel temperature are openly reported by an independent academic team [1], so any third party can replicate this comparison.
- **Year-matched independent weather feed:** HelioSolve is driven by NREL’s free satellite-derived weather data (NSRDB) [8] *pulled for the exact 12-month measurement window* (Feb 2017 – Jan

2018). The plant’s on-site sunlight sensor is *not* used as a model input. Agreement therefore validates both the plant-physics model and the satellite-weather feed against on-site ground truth in the same calendar year — it is not the model checking itself against its own input, and it is not the typical lower-fidelity “average year” weather assumption used in most simulators.

- **Plant model from published spec only:** Modules (Jinko JKM265P-60), inverters (SMA Sunny Tripower 60US-10), mounting (fixed-tilt, 15° / 180°), and GCR (0.5) are taken directly from the reference paper. We did not calibrate the model on-site or fit any correction factors to make it match the plant.

The Investor View: For a commissioned commercial plant, the single most important number is annual AC energy delivered to the revenue meter, because that is what gets billed. A validation that pins this number against a published, peer-reviewed reference using an independent weather channel removes one element of forecast uncertainty that lenders see as discretionary.

Table 2: Reference plant specification [1].

Attribute	Value
Location	Jordan University of Science and Technology (JUST), Irbid, Jordan (32.48° N, 35.99° E)
Climate	Mediterranean; winter daytime 13.8°C, summer daytime 29.3°C
Nameplate	5.00 MWp DC / 5.04 MW AC
Modules	18,920 × Jinko JKM265P-60 (multi-crystalline silicon, 17.2% rated efficiency)
Inverters	84 × SMA Sunny Tripower 60US-10 (60 kW AC)
Mounting	Fixed-tilt open-rack, 15° / 180°, GCR 0.5 (panels cover half of the ground footprint)
Monitoring	SkyCONNI (Skytron) + Janitza AC meter, Feb 2017 – Jan 2018

THE RESULT

Over twelve months on the JUST 5 MWp commissioned plant, HelioSolve’s modelled annual AC energy matched the on-site revenue-grade reference to +0.75% (8,147 MWh modelled vs. 8,086 MWh measured), capacity factor to +0.4 **percentage points**, and specific yield to +0.74%. We did not tune the model to the measurements after the fact. The weather inputs to the model were NREL NSRDB satellite reanalysis [8] pulled for the same Feb 2017 – Jan 2018 window; the plant’s on-site sunlight sensor was not used as a model input.

Where HelioSolve sits in the published literature

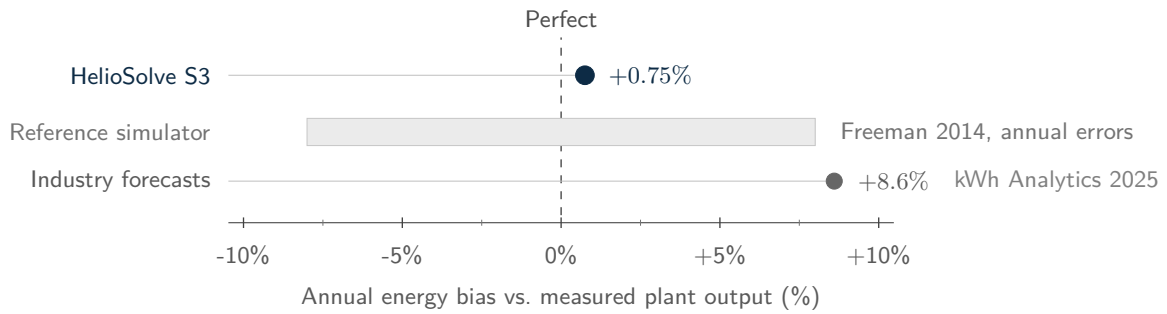


Figure 1: Annual energy bias of HelioSolve on the JUST 5 MWp commercial plant (+0.75%, top row) against two literature anchors. All three rows use the same convention: positive values mean the model over-predicts what the plant actually delivered, negative values mean it under-predicts. Row 2 shows the $\pm 8\%$ annual-error band reported by Freeman et al. [6] for detailed PV performance modelling tools, excluding one-axis tracking systems in PV*SOL as noted in that report. Freeman also reports hourly RMSEs below 7% for all systems. Row 3 shows industry-typical pre-construction forecasts, which kWh Analytics 2025 [3] reports over-predict actual operating-fleet output by an average of 8.6% across 34,000 system-months — i.e. measured generation comes in 8.6% below forecast, so on this same model-vs-measured axis the forecast model sits at +8.6%. The dashed vertical line marks zero bias (perfect agreement). Freeman 2014 is a small-sample close test, not a fleet-wide metastudy; HelioSolve sitting inside this published annual-error envelope keeps it within the detailed-tool validation range reported by Freeman on this fixed-tilt case.

Detailed performance metrics

Table 3 brings every validation metric together in one place. *Size-dependent* metrics (total energy, yield) refer to the full 18,920-module plant. *Size-independent* metrics (capacity factor, system efficiency, performance ratio) are the same on this plant or any other and follow the IEC 61724-1 definitions [7].

Table 3: Independent performance audit — Scenario S3. Differences are between modelled and measured values over the same Feb 2017 – Jan 2018 window, computed per the IEC 61724 validation standard [7]. Size-dependent metrics (total energy, yield) refer to the full 18,920-module plant; size-independent metrics (capacity factor, system efficiency, performance ratio) are the same regardless of plant size.

Validation Parameter	Measured (Reference)	HelioSolve (Δ vs. Measured)
<i>Size-dependent metrics — total energy and yield, which depend on plant size</i>		
Annual AC Energy	8,086 MWh	8,147 MWh (+0.75%)
Specific Yield	1,617 kWh/kWp	1,629 kWh/kWp (+0.74%)
Monthly Tracking Error (NMAE, Mar–Dec full months)	—	4.03%
<i>Size-independent metrics — efficiencies and ratios, the same regardless of plant size (IEC 61724-1)</i>		
Capacity Factor	0.181	0.185 (+0.4 pp)
System Efficiency η_{sys} (AC/POA)	13.0%	12.83% (–0.17 pp)
Performance Ratio (PR)	0.799	0.745 (–5.4 pp) [†]

[†] Denominator effect; see note below.

A note on Performance Ratio (PR). Performance Ratio is energy-out divided by sunlight-in, expressed in matched units. The satellite weather data we used reads $\sim 2.9\%$ more sunlight than the plant's on-site sunlight sensor across the year. Since PR uses the sunlight figure as its denominator, a higher sunlight-in number drives a lower PR even when the energy-out number is right. The lower modelled PR (**0.745** vs. the reference paper's **0.799**) is therefore substantially an effect on the sunlight reference, not a mismatch on the electricity delivered to the meter — which is the metric that drives revenue, and on which HelioSolve agrees with the measurement within $+0.75\%$. The satellite-vs-sensor sunlight gap is itself a known feature of satellite weather products [8] and is independent of HelioSolve's plant-physics model.

Month-by-month agreement

The monthly energy profile delivered by HelioSolve tracks the measured plant throughout the full calendar year. The peak-generation months agree at the per-cent level: **June within** $+2.2\%$, **July within** $+0.9\%$, **November within** $+1.1\%$, and **January within** $+5.1\%$. The largest single-month residual is in December, where the model under-predicts the measured energy by -9.9% ; this is a shoulder-season month accounting for only $\sim 5\%$ of annual generation, so the deviation translates to about -0.5% on the annual total.

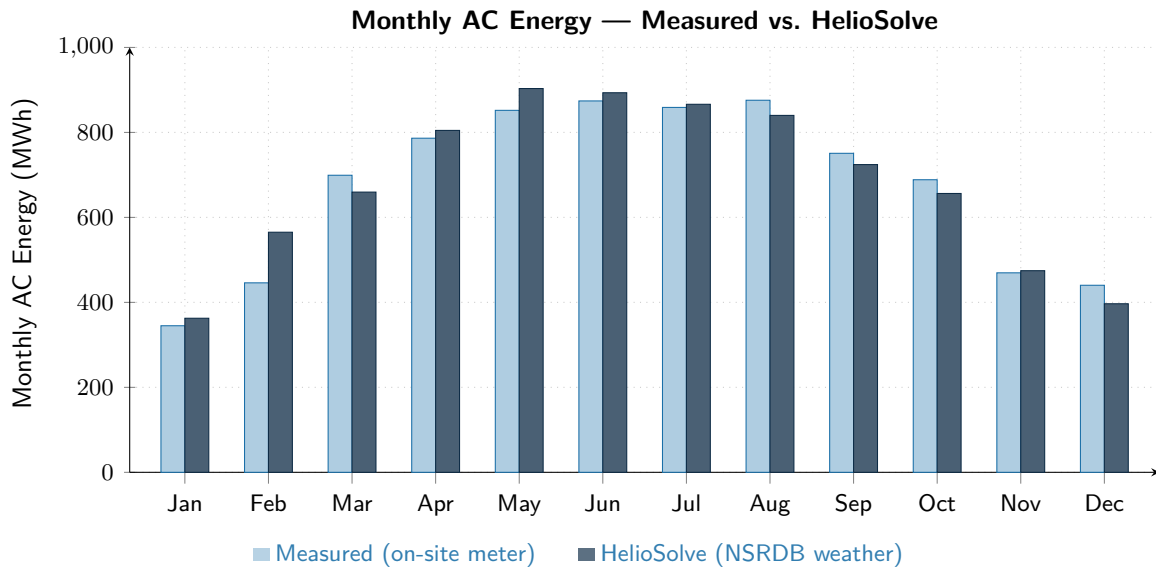


Figure 2: Monthly grid AC energy over the Feb 2017 – Jan 2018 measurement window. Both series refer to the same JUST 5 MWp plant. HelioSolve is driven by year-matched NREL NSRDB satellite reanalysis; the reference series by on-site sunlight sensor and revenue-grade meter. Annual totals: **8,086 MWh measured vs. 8,147 MWh HelioSolve (+0.75%)**. January and February in the reference dataset cover partial calendar months [1] and are reported here for completeness; the full-month subset (Mar – Dec) is used for the NMAE calculation. The reference paper’s own simulation in [1] (omitted from this chart for clarity) agrees with the measured reference at $\approx 2\%$ annual deviation, providing independent third-party corroboration.

IEC 61724-1 monthly metrics

Table 4 summarises the full IEC 61724-1 monthly performance breakdown for the JUST plant. All metrics follow the IEC 61724-1:2021 definitions [7]: G_{POA} is the sunlight hitting the panel plane, Y_F the final yield, PR the performance ratio, CF the capacity factor, and η_{sys} the system efficiency.

Figure 3 compares the monthly profile of each intensive metric, modelled vs. measured. HelioSolve monthly values appear as blue bars; the corresponding monthly measurements reported by Alshare et al. [1] (Table 2 of the reference paper) appear as amber bars on the same axes.

Table 4: IEC 61724-1 monthly performance metrics for the JUST 5 MWp plant. Weather inputs: NREL NSRDB satellite reanalysis [8]. Source: HelioSolve IEC 61724 report (run 2026-05-01).

Month	G_{POA} (kWh/m ²)	Y_F (h/d)	PR (ratio)	CF (ratio)	η_{sys} (%)
Jan	103.1	2.33	0.701	0.097	12.06
Feb	140.0	4.02	0.804	0.168	13.85
Mar	162.8	4.24	0.807	0.177	13.90
Apr	204.2	5.35	0.785	0.223	13.52
May	236.4	5.81	0.762	0.242	13.11
Jun	241.3	5.94	0.738	0.247	12.70
Jul	239.8	5.57	0.720	0.232	12.39
Aug	233.4	5.40	0.717	0.225	12.35
Sep	203.1	4.81	0.711	0.201	12.24
Oct	179.5	4.22	0.729	0.176	12.54
Nov	129.2	3.15	0.732	0.131	12.60
Dec	105.2	2.55	0.752	0.106	12.94
Annual	2,178.0	4.45	0.7455	0.1854	12.83

Annual rollups use the energy-weighted methodology recommended by IEC 61724-1:2021. The simple-mean alternative gives PR = 0.7465, CF = 0.1854, and η_{sys} = 12.85%. Monthly grid-injected energy on the same plant is shown in the bar chart above (Figure 2) and sums to 8,147 MWh annually.

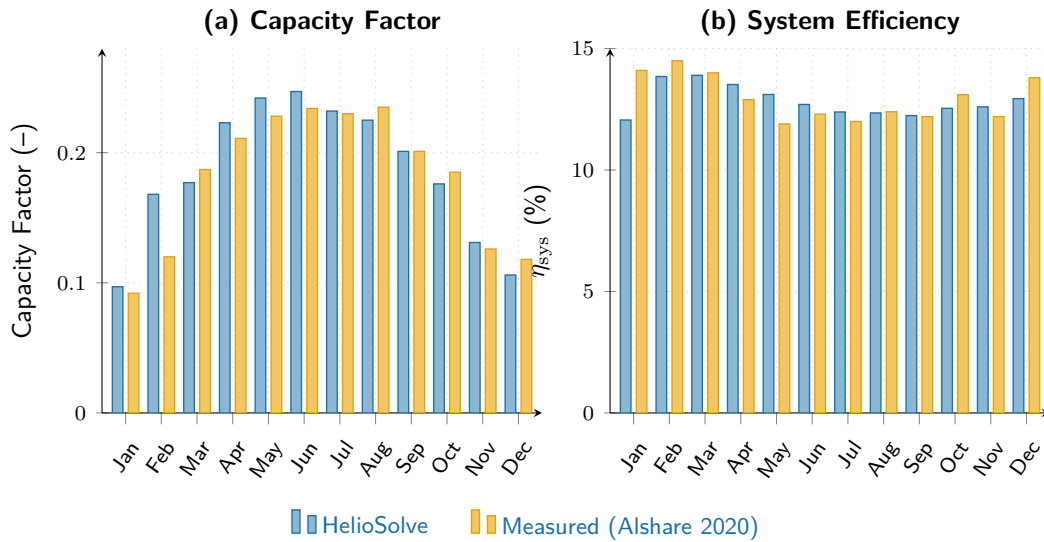


Figure 3: Monthly IEC 61724-1 size-independent performance metrics — modelled vs. measured. Blue bars: HelioSolve modelled monthly values; amber bars: on-site measured monthly values from Alshare et al. [1] (Table 2). HelioSolve tracks the measured monthly profile closely on both metrics across the full seasonal cycle.

SCOPE, LIMITATIONS, AND THE NEXT STEP

What this validation reports. HelioSolve’s modelled annual AC energy matches what a real commercial plant delivered to its revenue meter, when the model was driven by an independent satellite weather feed. Translating that accuracy into a financial outcome on any specific project depends on the project’s own financing terms (PPA price, capital structure, lender coverage requirements, useful life) and is outside the scope of this whitepaper.

This validation covers **one site** (the JUST 5 MWp plant in Irbid, Jordan) over a **twelve-month window** drawn from the public Alshare et al. dataset [1]. The weather inputs are satellite-derived, not on-site sensor; panel soiling, snow, and ground albedo (how much sunlight the ground reflects back onto the panels) are taken from public defaults rather than measured on-site; and the comparison is against monthly totals from the revenue meter, not against hourly module-level data. Before the engine can be considered generally validated for everyday forecasting on commercial plants, this same exercise needs to be repeated on more sites, more years, and more climate zones. That is the next phase of work.

Request a pilot / technical review

Asset owners, lenders, and developers are invited to compare their own forecasts against a HelioSolve run on the same inputs.

Request a pilot / technical review

Contact the HelioSolve team to schedule an independent audit of your project’s yield projections.

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APPENDIX A — METHODOLOGY AND DEFINITIONS

Glossary

- **AC / DC** — Alternating current (delivered to grid) / direct current (raw module output).
- **Capacity Factor (CF)** — Annual AC energy delivered divided by (nameplate capacity × 8,760 h). Dimensionless; the headline benchmark infrastructure investors use to size project debt.
- **DSCR** — Debt-Service Coverage Ratio: project operating cash flow divided by annual debt service; the lender's bankability covenant.
- η_{sys} (**System Efficiency**) — AC energy delivered divided by POA irradiance on the active module aperture (%). In plain English: how much of the sunlight hitting the panels comes out as electricity at the meter.
- **GCR (Ground-Coverage Ratio)** — Module aperture area divided by total ground area within the array footprint.
- **IEC 61724-1** — International standard for PV plant performance monitoring [7].
- **IPP / IE** — Independent Power Producer / Independent Engineer (third-party reviewer of project bankability and as-built performance).
- **NMAE / nMBE / nRMSE** — Normalized Mean Absolute Error / Normalized Mean Bias Error / Normalized Root Mean Square Error. Definitions in the next subsection.
- **NPV** — Net Present Value: the project's expected cash flows discounted to today.
- **NSRDB** — National Solar Radiation Data Base; NREL satellite-reanalysis product used here as the independent weather channel [8].
- **P50 / P90 / P99** — Probabilistic forecast percentiles. P50 is the median (best-estimate) annual production; P90 is the level of production that is exceeded with 90% probability (used by lenders as a worst-case sizing metric).
- **POA** — Plane-of-Array irradiance: the in-plane irradiance arriving on the module's front (or rear) surface.
- **pp** — Percentage points (e.g., a 0.4-pp deviation between two ratios).
- **PR (Performance Ratio)** — Y_F/Y_R ; the size-independent IEC efficiency metric. In plain English: energy-out divided by sunlight-in (in matched units), a single ratio that tells you how well the plant converts what it receives.
- **Specific Yield** — Annual AC energy delivered, normalized by DC nameplate (kWh/kWp); the asset-comparable yield metric used by lenders and IPPs.
- Y_F (**Final Yield**) — AC energy delivered per unit of DC nameplate, expressed in hours-per-day.
- Y_R (**Reference Yield**) — POA irradiation expressed in equivalent peak-sun hours-per-day.

Statistical metrics

The validation in this whitepaper applies the IEC 61724-1 conventional error metrics for hourly and monthly model-vs-reference comparison:

$$\begin{aligned} \text{nMBE} &= \frac{\sum_{i=1}^N (m_i - r_i)}{\sum_{i=1}^N r_i} \times 100\% \\ \text{NMAE} &= \frac{\sum_{i=1}^N |m_i - r_i|}{\sum_{i=1}^N r_i} \times 100\% \\ \text{nRMSE} &= \frac{\sqrt{\frac{1}{N} \sum_{i=1}^N (m_i - r_i)^2}}{\bar{r}} \times 100\% \end{aligned}$$

where m_i is the modelled value at observation i , r_i the reference (measured) value, \bar{r} the mean of the reference series, and N the number of valid observations in the comparison window. nMBE captures systematic bias (sign-aware); NMAE captures average absolute deviation; nRMSE penalizes large residuals more heavily than small ones.

Note on the monthly tracking error: the headline 4.0% value reported in the body for the Mar – Dec subset uses the *per-observation mean* convention (mean of $|m_i - r_i|/r_i$ across the 10 monthly observations, equivalent to MAPE on monthly aggregates), giving 4.03% on the bar-chart values. The lumped-sum convention shown in the NMAE formula above gives 3.83% on the same data. The two conventions differ because months have different absolute outputs: per-observation mean weights each month equally, while lumped-sum gives larger months proportionally more weight.

Validation protocol and aggregation conventions

- **Full-month NMAE subset (Mar – Dec).** The reference dataset reports complete calendar months between March and December 2017. The monthly NMAE of 4.0% is computed on this 10-month subset to avoid penalizing the model for truncation in the published partial-month January and February series.
- **Annual rollup window (Feb 2017 – Jan 2018).** The annual energy bias of +0.75% uses the same 12-month window the reference paper publishes, including the partial-month January and February values (reported faithfully but excluded from monthly NMAE per above).
- **Annual aggregation.** Annual rollups for PR, CF and η_{sys} use the energy-weighted methodology recommended by IEC 61724-1:2021. The simple-mean alternative is reported in Table 4 as a sensitivity check.

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