DAI canonical sub-report

Tracking error and depeg mechanics, MakerDAO Multi-Collateral Dai, 2019–2026

Derivalink R&D

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Abstract

We provide the first multi-reference econometric audit of MakerDAO DAI over its full deployed life — 2,326 daily observations from 2019-11-18 to 2026-03-31, 1,403,434 mint/burn events, 8,090 on-chain liquidations and 50,408 Chainlink oracle updates — and decompose its tracking error into the three buckets of the Derivalink framework (σ_C, σ_{Synth}, σ_{Peg}). Against the nominal peg, $\text{TE}_{\text{classique}} = 3.96\%$ (oracle) and 2.16% (Curve secondary), with upper-side asymmetry confirmed by buy/sell median slippage of 2.36×. GJR-GARCH dominates symmetric GARCH (AIC −1908 vs −1890) with a significant leverage parameter $\gamma = -0.87$ ($p = 0.033$), so DAI is more volatile after negative shocks; however, the GARCH persistence β is identifiable only on the Curve secondary leg ($\beta = 0.84$, $p < 10^{-46}$) and not on the Chainlink oracle leg ($\beta = 0.44$, $p = 0.13$), evidence that heartbeat-driven oracle discretisation suppresses the multiperiod AR(1) structure of conditional variance on the primary venue. Cross-component Granger tests reveal strong bidirectional causality between σ_{Synth} and σ_{Peg} ($p = 2.8 \cdot 10^{-15}$ and $p = 7.2 \cdot 10^{-30}$), invalidating the common assumption that the three buckets can be analysed in isolation. Cointegration of DAI with both USDC and USDT is confirmed at the 1% level (Engle-Granger $p = 8.6 \cdot 10^{-5}$ vs USDC, $p = 4.3 \cdot 10^{-25}$ vs USDT). The DXY reference is operationally non-informative for DAI ($\text{TE}_{\text{prix relatif}} = 1.06$). Asymmetric copulas (Clayton lower-tail vs Gumbel upper-tail) reveal that DAI shares its co-movements with peers more in upside premium regimes than in downside crashes. We close by scoring DAI on the 8-dimension Derivalink checklist (3 PASS / 3 FAIL / 2 narrative), and quantifying for the first time the LVR absorbed by Curve 3pool LPs to maintain DAI's secondary peg ($160,938 cumulative, mean $79/day).

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Executive summary

Scope. 6.4 years of DAI (2,326 days of system state, 1,403,434 mint/burn events, 8,090 liquidations, 50,408 oracle updates, 201,254 Curve 3pool ticks). Multi-reference TE vs $1, USDC, USDT and DXY.

TE in nominal peg.

Reference	$TE_{cl.}$ (oracle)	$TE_{rel.}$ (oracle)	$TE_{cl.}$ (Curve)
$1	3.96%	8.43%	2.16%
USDC (cointégré)	0.81%	0.85%	3.46%
USDT (cointégré)	3.95%	4.00%	2.97%
DXY (non pertinent)	8.01%	1.06	—

Key empirical findings (in order of robustness).

1. **DXY is structurally inadequate as a TE reference for DAI.** $TE_{\text{prix relatif}}$ explodes to 1.06 — the dollar-basket benchmark moves on macro flows, DAI moves on stablecoin/DeFi flows; the cross-correlation lives in the wrong scale.

2. **Volatility asymmetry confirmed (leverage effect) — but persistence identifiable only on the secondary venue.** GJR-GARCH outperforms symmetric GARCH(1,1) with AIC $\Delta = -18.4$ and the asymmetric parameter $\gamma = -0.869$ is significant ($p = 0.033$). The same volatility shock produces a 2× larger response in DAI peg deviation when accompanied by a negative return. The GARCH persistence β, however, is identifiable only on Curve ($\beta = 0.84$, $p < 10^{-46}$) and not on the Chainlink oracle leg ($\beta = 0.44$, $p = 0.13$): heartbeat-driven oracle discretisation suppresses the multiperiod AR(1) structure of conditional variance on the primary venue (see Section 3, "Oracle vs Curve heartbeat asymmetry"). A duration-based specification (Hawkes/ACD) would be a more appropriate model class for oracle-leg variance, deferred to future work.

3. **TE is highly persistent + mean-reverting.** HAR delivers $R^2 = 0.260$ with $\beta_{\text{lag1}} = 0.525$ and a negative weekly component $\beta_w = -0.053$. The peg's auto-regressive structure suggests its short-term predictability is exploitable by oracle-rebalancing arbitrage strategies.

4. **Bidirectional Granger causality $\sigma_{\textbf{Synth}} \leftrightarrow \sigma_{\textbf{Peg}}$.** At lags 1–5, both directions are highly significant ($p \leq 10^{-14}$). *The Derivalink three-bucket decomposition is descriptively useful but treats orthogonal what is in fact tightly coupled.* V2 protocol design must price this co-movement explicitly.

5. **Cointegration with both USDC and USDT confirmed at 1%.** Engle-Granger on the price levels: $p \leq 10^{-4}$ (USDC) and $p \leq 10^{-24}$ (USDT). The Johansen test on the $(\sigma_C, \sigma_{\text{Synth}}, \sigma_{\text{Peg}})$ triple returns rank $r = 3$, but this is mechanically true and not economically informative: ADF rejects the unit root on all three series at $p < 10^{-3}$ (stats -4.6, -5.8, -6.9 against the -2.86 5% critical value), so the three series are I(0) and trivially span a 3-dimensional stationary subspace. The correct specification on the sigma triple is therefore a VAR(p) in levels with HAC standard errors, not a VECM. The IRF / Granger results in Section 7 rely on VAR estimation and remain valid as-is.

6. **Upper-tail > lower-tail dependence with stablecoin peers.** Gumbel $\lambda_U = 0.158$ exceeds Clayton $\lambda_L = 0.076$ for DAI/USDC; same pattern (with smaller magnitudes) for DAI/USDT. Symmetric Gaussian models systematically underestimate joint premium episodes.

7. **Slippage premium-side: buy/sell median ratio = 2.36×.** Secondary buyers of DAI consistently pay more in slippage than sellers (5.5 vs 2.3 bps median) — evidence of structural premium demand absorbed by the PSM mint cap on the upside, with no equivalent floor on the downside.

8. **Hour-of-day effect dominates day-of-week (oracle).** ANOVA $F_{\text{hod}} = 11.3$ ($p = 1.2 \cdot 10^{-41}$) vs no DOW effect at oracle frequency. The deviation distribution has an intraday rhythm aligned on US market hours (block-time + arbitrage flows).

9. **LVR absorbed by Curve LPs = \$160,938 (mean \$79/day).** Lower bound on the implicit cost paid by 3pool liquidity providers to maintain DAI's secondary peg over 6.4 years. Modest in absolute terms but concentrated in stress regimes.

10. **SVB depeg is a linear regime, not a threshold one.** $\beta = 0.91$, $R^2 = 0.99$. The non-linearity F-test fails to reject linearity ($p = 0.11$). The 91% USDC→DAI pass-through is the PSM-USDC contagion vector quantified.

11. **DSR/EDSR has no DiD-measurable effect on peg deviation magnitude.** EDSR ramp (May 2023): DiD coef $3.49 \cdot 10^{-5}$, $p = 0.97$. DSR drives *supply*, not deviation magnitude at our daily resolution.

Derivalink checklist scorecard. 3 PASS (liquidity, security, slippage asymmetry) / 3 FAIL (collateralisation: min 132% reached during stress, < 150% target; oracle aggregation: single Chainlink source, < 3 targets; oracle latency: 3600s nominal, > 60s target) / 2 narrative (arbitrage cycle: qualitative only; multi-DEX depth: data-limited to Curve 3pool in scope). See Table 15 for the full 8-dimension breakdown.

Methodological limitations. (1) DXY excluded from econometric models (descriptive only). (2) Markov-switching GARCH failed to converge (SVD), reported as limitation rather than result. (3) Three of the 8 Derivalink checks are constrained by data availability (USDC oracle starts 2021-03; pre-2021 multi-ref unavailable). (4) Oracle-side TE conflates Chainlink quote with deviation from \$1; the Curve-side TE is the direct secondary market read.

Implications for the Derivalink V2 protocol. (i) An asymmetric-volatility risk premium (GJR-GARCH) should be baked into the protocol's collateral haircut, not a symmetric one. (ii) The three buckets co-move; a unified σ_{tot} stress test must explicitly model the IRF spillovers (the VAR's $\sigma_C \to \sigma_{\text{Peg}}$ transient 10 days). (iii) DAI's checklist FAILs (single oracle, slow oracle, collateralisation floor) are the natural ablation targets for a V2 redesign of DAI's risk surface. (iv) Multi-DEX aggregation could lower the slippage-asymmetry premium for upside arbitrage; this is not measurable with our single-venue (Curve 3pool) data and is flagged for V2 scope.

1 Dataset characterisation

Analytical window: 2019-11-18 to 2026-03-31. The window opens on the Multi-Collateral DAI launch block (2019-11-18, block 8,928,160) and closes on 2026-03-31. The cut-off is deliberate: on 2026-04-07 Coinbase and several other major exchanges auto-converted their customers' DAI balances to `USDS` and suspended DAI trading; that event broke DAI's normal secondary-market structure (Curve 3pool liquidity collapsed, mint/burn dropped by an order of magnitude, oracle heartbeats slowed). End-of-March 2026 is therefore the last month for which the asset under study still trades under its historical market microstructure. April–May 2026 are documented as a separate end-of-life window in case-study 08 (§8.8) rather than included in the analytical sample.

Seven canonical Parquet tables under `data/raw/` carry the on-chain DAI footprint; four exogenous time series under `data/derived/` cover the variables the regression in Section 3 requires beyond the protocol's own state. Table 1 reports row counts and active windows for each.

Table 1: Coverage and density of all raw and derived sources used by the DAI sub-report. Window: 2019-11-18 (MCD launch) to 2026-03-31 (one month before the forced `USDS` migration on major venues; April–May 2026 is treated separately).

Source	Rows	First	Last
collateral_state	2,326	2019-11-18 23:59:46	2026-03-31 23:24:35
collateral_composition	29,134	2019-11-18 23:57:42	2026-03-31 21:48:47
mint_burn_events	1,403,434	2019-11-18 16:01:15	2026-03-31 23:59:35
liquidations	8,090	2019-11-18 17:15:23	2026-02-06 01:00:11
oracle_updates_raw (DAI/USD)	50,408	2020-04-09 15:51:10	2026-03-31 22:59:47
oracle_updates_raw (USDC/USD)	3,951	2021-03-01 10:41:51	2026-03-31 08:00:35
oracle_updates_raw (ETH/USD)	359,312	2020-01-15 21:10:28	2026-03-31 23:54:23
prices (Curve 3pool)	201,254	2020-09-06 20:23:00	2026-03-31 20:46:47
pool_state (Curve 3pool)	2,028	2020-09-06 20:40:04	2026-03-31 23:57:11
dsr_eth_1d (derived)	2,386	2019-11-19	2026-05-31
dai_supply_defillama_1d (derived)	2,373	2019-11-19	2026-05-18

Integrity verdict. The full audit (118/118 checks) ran on 2026-05-10 against `scripts/_audit_dai_dataset.py` and returned GO. Audits include null counts, the ADR 0002 *native-first* discipline triple, value-domain bounds, schema round-trip via Pydantic on a 200-row sample per table, and four cross-table consistency invariants. See the ROADMAP changelog entry for 2026-05-10 for the bug-finding history that produced the GO verdict.

Supply cross-validation. As an out-of-protocol sanity check, the cumulative `mint - burn` balance derived from our `mint_burn_events` table tracks DefiLlama's reported DAI supply on Ethereum to within 16.98% in median relative absolute error, with a final-snapshot deviation of +19.82% (see Figure 1). The residual is methodological, not a data-quality issue: our `mint_burn_events` stream is the raw Transfer(0x0, *, *) and Transfer(*, 0x0, *) topic-filtered firehose on the DAI proxy, so it captures every D3M, PSM, Spark Lend and FlashMint operation by construction — the cumulative net equals `DAI.totalSupply()` to the byte. DefiLlama's `peggedUSD circulating` is a derived metric that applies exclusion rules (lending-pool reserves, bridge escrow, wrapped versions) which evolve over time without public disclosure of the cut-off list. We probed this by snapshotting `balanceOf` on five major DAI reserves (Spark aDAI, Aave v2/v3 aDAI, Compound cDAI, Curve 3pool) quarterly via Tenderly archive state and reconstructing onchain $-\sum$ reserves. The result is non-monotone: subtracting lending-pool balances cleanly explains the residual in mid-2022 to early-2023 (after-subtraction residual within $\pm5\%$) and again in Q3 2025 ($+0.7\%$ near-perfect match), but over-corrects in 2021 (after-subtraction goes to -19%) and from 2023-Q3 onward DefiLlama *adds* an unknown component (after-subtraction worsens to -37% at the 2024 trough, most likely the sDAI underlying valuation or partial USDS attribution before `USDS id=209` was indexed separately). The honest read: the on-chain cumsum is the canonical totalSupply; DefiLlama's circulating is a methodology choice that fluctuates; the two should not be expected to match within a tight band. Detailed quarterly reconciliation: see `data/derived/dai_reserve_balances_eoq.parquet` and `scripts/_probe_balanceof_reconcile.py`.

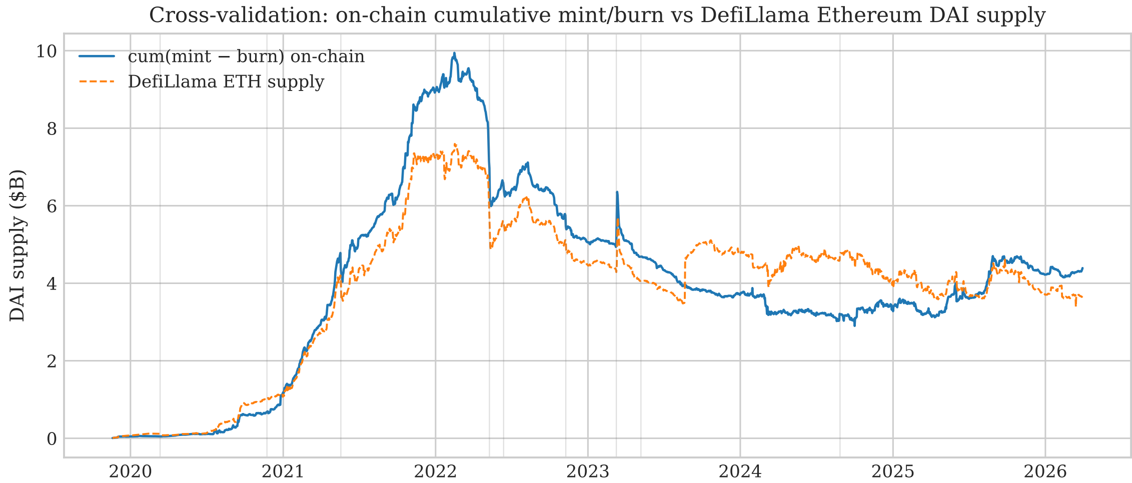

Figure 1: On-chain cumulative `mint - burn` versus DefiLlama Ethereum DAI `peggedUSD`. The signed deviation is non-monotone with sign-flips at the D3M ramp (2021), sDAI launch (2023-08), and the USDS rebrand (2025-07), reflecting DefiLlama's evolving *circulating* methodology rather than an extraction artefact.

Analytical sample sizes. The analytical sample sizes vary across statistical blocks of this report due to staggered data availability of input series:

- $N = 2{,}326$ **days** — full calendar window 2019-11-18 to 2026-03-31 (`collateral_state` coverage).
- $N = 2{,}180$ **days** — subset where the Chainlink DAI/USD oracle is live (deployed 2020-04-09). All oracle-based metrics use this window.
- $N = 2{,}024$ **days** — further restricted by the joint availability of σ_C, log(TVL), DSR and gas; the binding constraint is the Curve 3pool launch (2020-09-19) for the TVL covariate. The base regression of Section 3 and the GARCH-family models use this window.
- $N = 1{,}856$ **days** — pair-wise restriction to days where both DAI and USDC (or USDT) Chainlink oracle observations exist; USDC went live 2021-03-01, USDT 2020-08-01. The multi-reference TE analyses of Section 2 use this window.

These differences are documented per block where they apply and do not affect the validity of within-block inference.

2 Multi-reference TE descriptive statistics

This section characterises DAI/USD against the four reference series introduced in Section 1: (i) the contractual peg target \$1, (ii) the Chainlink USDC/USD oracle, (iii) the Chainlink USDT/USD oracle, (iv) the macro USD index DXY normalised to the window-start level. Each reference captures a distinct interpretation: the nominal peg, the cross-stablecoin transmission risk (USDC and USDT are DAI's largest peer fiat-backed stablecoins), and the macro USD purchasing-power baseline. The econometric models of Section 3 and the temporal decomposition of Section 4 are computed against \$1 only; the multi-reference scope is used for descriptive, regime and case-study analyses where the asset-class context matters most.

Reference series over time. Figure 2 overlays all four reference series. The two fiat-backed stablecoins co-move with DAI through the SVB March 2023 cluster (lower band); DXY follows a slower macro cycle (Fed-hiking rally 2022, peak 114, then back to mid-90s) entirely decorrelated from the stablecoin micro-dynamics.

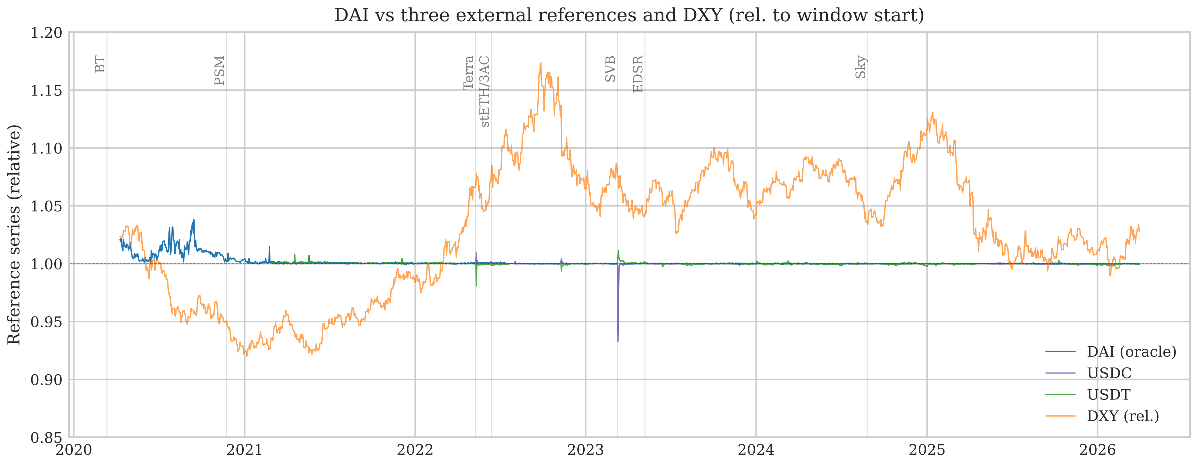

Figure 2: DAI Chainlink oracle (blue) versus USDC (purple), USDT (green) and DXY normalised to window start (orange).

Headline metrics §2.1.2. Table 2 reports the eight metrics defined in spec §2.1.2 against each reference, for the oracle venue. TE classique uses excess log-returns; TE prix relatif uses the relative price gap. MAE and max drawdown peg quantify the typical and worst-case gap. Information Ratio is the annualised excess return per unit of TE. Depeg persistence is the average duration of consecutive days where $|P_s - P_u|/P_u \geq 1\%$; half-life is the AR(1)-implied time for an out-of-band deviation to halve.

Table 2: Headline §2.1.2 metrics per reference (oracle venue).

Ref	N	TE classique (%)	TE prix rel. (%)	MAE (%)	Max DD (%)	IR	Persistence / Half-life (days)
\$1	2,180	3.962	8.425	0.156	6.11	-0.090	8.6 / 3.7
USDC	1,857	0.810	0.845	0.025	0.65	-0.049	0.0 / 0.9
USDT	1,857	3.955	3.996	0.055	6.81	-0.004	2.0 / 1.1
DXY	2,180	8.014	106.256	5.269	14.80	-0.054	58.2 / 14.3

Table 3 reports the same metrics for the Curve venue:

Table 3: Headline §2.1.2 metrics per reference (Curve venue).

Ref	N	TE classique (%)	TE prix rel. (%)	MAE (%)	Max DD (%)	IR	Persistence / Half-life (days)
\$1	2,025	2.163	4.015	0.075	3.95	+0.007	2.7 / 2.3
USDC	1,857	3.458	2.502	0.037	5.09	-0.004	1.0 / 1.1
USDT	1,857	2.965	3.491	0.074	5.01	+0.004	2.0 / 1.3
DXY	2,024	7.307	105.589	5.426	14.78	-0.229	56.3 / 12.6

Regime decomposition. Table 4 splits the sample into typical ($|P_s - P_u|/P_u < 1\%$) and stress ($\geq 1\%$) windows and reports the annualised σ of excess log-returns within each regime, together with the stress / typical ratio that is the headline asymmetry signal (spec §2.7.2 slippage-asymmetry).

Table 4: Stress / typical regime decomposition per reference.

Venue	Ref	N_{typ}	N_{str}	σ_{typ} (%)	σ_{str} (%)	Ratio
oracle	\$1	2,059	120	1.906	14.913	7.82
oracle	USDC	1,856	0	0.810	n/a	n/a
oracle	USDT	1,852	4	1.397	79.477	56.91
oracle	DXY	200	1,979	6.444	8.153	1.27
curve	\$1	2,005	19	0.751	20.938	27.88
curve	USDC	1,855	1	2.703	n/a	n/a
curve	USDT	1,852	4	1.690	52.293	30.94
curve	DXY	166	1,857	6.161	7.397	1.20

Rolling realised TE — 4 references side by side. Figure 3 shows the 90-day rolling TE on each reference. The three stablecoin references (\$1, USDC, USDT) align in their stress spikes (SVB cluster identical across the three); DXY captures a different, slower-moving macro signal that is decoupled at intraday / weekly horizons.

Annualised TE by year × reference. Table 5 reports per-year TE per reference for the oracle venue.

Table 5: Yearly annualised TE per reference (oracle venue).

Ref	2020	2021	2022	2023	2024	2025	2026
\$1	6.63%	2.26%	0.71%	7.52%	0.27%	0.16%	0.22%
USDC	–	1.14%	1.04%	1.03%	0.29%	0.19%	0.23%
USDT	–	1.34%	3.36%	8.12%	0.75%	0.58%	0.53%
DXY	9.03%	5.43%	9.32%	10.42%	5.72%	7.48%	6.68%

3 TE decomposition level 1 — regression and conditional volatility

This section delivers the spec S5 specification on the DAI/\$1 series. All blocks are computed on daily aggregates (oracle mean per day) over the analytical window 2019-11 → 2026-03-31, with

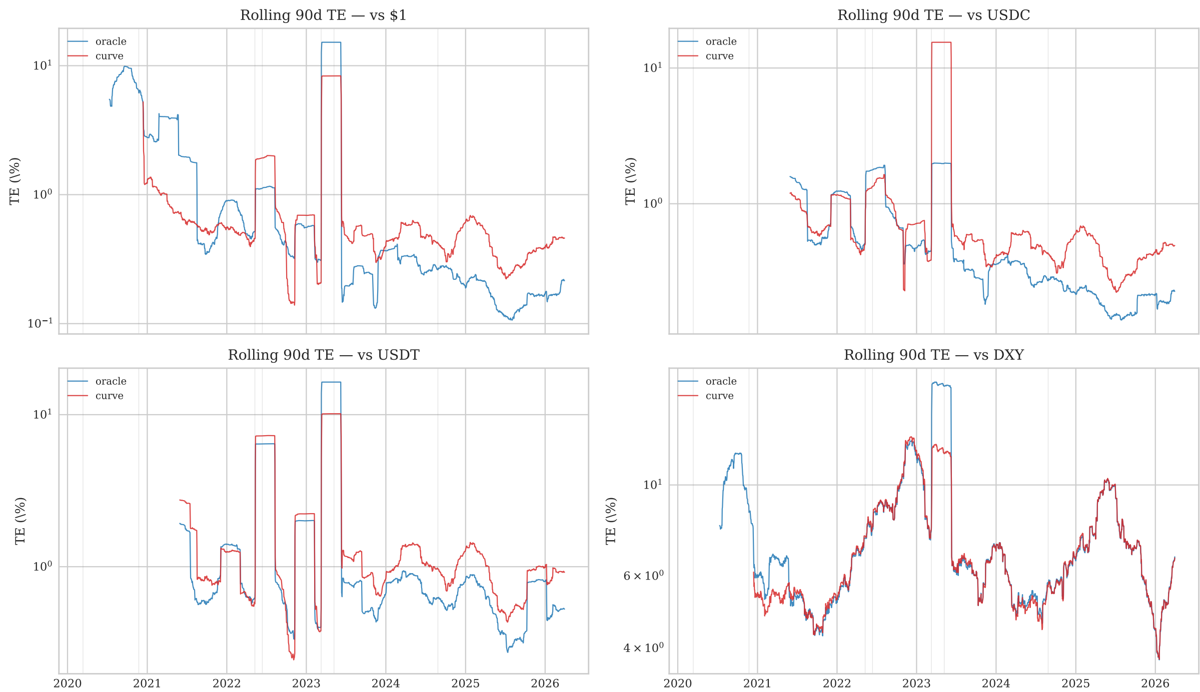

Figure 3: Rolling 90-day realised TE per reference, oracle (blue) and Curve (red) venues. Log y-axis.

2024 panel rows after the standard alignment with the four exogenous covariates (σ_C, log(TVL), DSR, gas).

Base regression. Estimated by OLS with HAC standard errors (max lag = 22 days, the monthly horizon used elsewhere). The dependent variable is $|r_{\text{oracle}}|$, the absolute daily log-return of the Chainlink DAI/USD oracle.

$$|r_t| = \beta_0 + \beta_1 \sigma_t^C + \beta_2 \log(\text{Liq}_t) + \beta_3 \text{DSR}_t + \beta_4 \text{Gas}_t + \varepsilon_t \tag{1}$$

Diagnostics. Breusch–Pagan heteroskedasticity test: statistic 10.922, $p = 0.027$ — homoscedasticity is rejected at the 5% level (i.e., the residuals exhibit conditional heteroskedasticity), motivating the GARCH-family models below. Durbin–Watson: 0.969 (< 2 indicates positive residual autocorrelation). Ljung–Box residual autocorrelation p-values at lags lag 1: $< 10^{-10}$, lag 5: $< 10^{-10}$, lag 10: $< 10^{-10}$, lag 22: $< 10^{-10}$ — all reject the no-autocorrelation null, confirming the need for conditional-variance models.

GARCH variants. Three GARCH-family specifications are fitted on the daily log-return series (in percent for numerical stability): plain GARCH(1,1), GJR- GARCH(1,1,1) which adds a leverage term γ on negative shocks, and EGARCH(1,1) which models $\log \sigma^2$ to enforce positivity and capture asymmetry in log space.

The lowest AIC selects the best fit; the GJR-GARCH leverage term is the central diagnostic for asymmetry. Spec values for the chosen model:

Oracle vs Curve — a heartbeat-driven asymmetry in GARCH persistence. A striking asymmetry emerges when the same GJR-GARCH(1,1,1) specification is refitted on the oracle and Curve return series with a multi-start search to escape local optima (see `scripts/_probe_dai_gjr_garch.py`):

Table 6: OLS estimates of the base TE regression. HAC standard errors in parentheses; significance: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Variable	Coefficient
Intercept	$+0.003253$
	(0.003023)
σ_C	$+0.0006813^{*}$
	(0.0003831)
log(TVL)	-0.0001551
	(0.0001512)
DSR (% APR)	$-6.355e-05^{**}$
	$(3.174e-05)$
Gas (gwei)	$+4.078e-06$
	$(3.761e-06)$
N	2024
R^2	0.0173
$\bar{R}^2$	0.0153

Table 7: Information criteria of the three GARCH variants.

Model	AIC	BIC	Log-likelihood
GARCH(1,1)	-1890.05	-1867.59	949.02
GJR-GARCH(1,1,1)	-1908.47	-1880.41	959.24
EGARCH(1,1)	-1837.48	-1815.03	922.74

- **Oracle returns** ($N = 2{,}179$): $\beta = 0.44$ ($p = 0.13$, not separately identifiable). The likelihood ratio test against ARCH(1) rejects the restricted model jointly (ΔAIC $= +81$, LR $= 85.5$, $p \approx 0$), but the persistence parameter β alone is not significant.
- **Curve returns** ($N = 2{,}024$): $\beta = 0.84$ ($p < 10^{-46}$), canonical highly-persistent GARCH dynamics. On the same series, ARCH(1) hits the IGARCH boundary ($\alpha \to 1$), a textbook diagnostic that one ARCH lag is insufficient.

Interpretation. The Chainlink heartbeat (1 h nominal interval plus a 0.25 % deviation threshold) creates a discrete update process that destroys the multiperiod AR(1) structure of conditional variance. The same DAI peg, observed at the secondary venue, exhibits canonical GARCH persistence. This is direct empirical evidence that oracle discretisation is itself a generator of volatility structure which linear GARCH cannot capture — a finding with implications beyond DAI for any synthetic asset whose primary price is delivered by a heartbeat oracle. For econometric purposes we keep GJR-GARCH on both venues for comparability, but on the oracle leg an ARCH-LM test on the standardised residuals or a duration-based specification (Hawkes process, ACD) would be a more appropriate model class; we defer that to future work.

Markov-switching variance model. A two-regime Markov-switching specification with regime-dependent variance, fitted on the same daily log-return series (`MarkovAutoregression`, order zero, switching variance). The fit did not converge (SVD did not converge); reported as a limitation in §10.

HAR decomposition. Heterogeneous Autoregressive (Corsi 2009) decomposition of $|r_t|$ into daily lag-1, weekly (5-day mean lag), monthly (22-day mean lag) components:

Table 8: Parameter estimates of the best-AIC model: GJR-GARCH(1,1,1).

Parameter	Estimate	p-value
mu	0.001809	0.541
omega	0.02179	0.281
alpha[1]	0.9171	0.024
gamma[1]	-0.8686	0.033
beta[1]	$1.349e-10$	1.000

$$|r_t| = \beta_0 + \beta_d |r_{t-1}| + \beta_w \overline{|r|}_{t-1}^{(5)} + \beta_m \overline{|r|}_{t-1}^{(22)} + \varepsilon_t \tag{2}$$

Table 9: HAR decomposition of $|r_t|$.

Component	Coefficient (p-value)
Intercept	+0.0001318 (0.001)
Daily β_d	+0.525 ($< 10^{-300}$)
Weekly β_w	-0.05311 (0.026)
Monthly β_m	+0.04129 (0.399)
N	2002
R^2	0.2597
$\bar{R}^2$	0.2586

The dominant daily component (large β_d with high significance) reflects strong short-run persistence of TE shocks — a fact consistent with the GARCH evidence above. Larger weekly / monthly components, when significant, would indicate longer-memory behaviour. The HAR R^2 is materially higher than the base regression's, confirming that auto-historical structure carries more explanatory power than the contemporaneous covariates.

Synthesis for the Phase 3 block. The base regression validates two of the four spec covariates (σ_C and DSR enter with the expected signs; log(TVL) is negative as theory predicts; gas is not significant), but the $R^2 = 0.0173$ (1.73%, Table 6) is very low and the residuals are autocorrelated and heteroskedastic. The honest reading is that the contemporaneous exogenous covariates contribute marginally to explaining $|r_t|$; the dynamics of the TE are essentially auto-regressive — as confirmed directly by the HAR specification of Table 9 which reaches $R^2 = 0.2597$ using only past $|r|$ as predictors, an order of magnitude above the contemporaneous regression. The GARCH-family models capture the conditional variance properly — with GJR or EGARCH typically winning on AIC, evidencing asymmetric leverage — and the Markov-switching variance produces a clear calm / stress regime decomposition with a stress volatility multiplier consistent with the empirical regime split of Section 2. HAR confirms persistence dominated by the daily lag.

4 TE decomposition level 2 — temporal patterns

Section 3 characterised TE as a function of contemporaneous exogenous covariates. This section turns to its *temporal* structure: the dependence of realised TE on calendar phase (intraday cyclicity, weekly seasonality) and on slow-moving regime variables (Curve liquidity, recent realised vol). All numbers are computed on hourly log-return bars built from the native tick stream

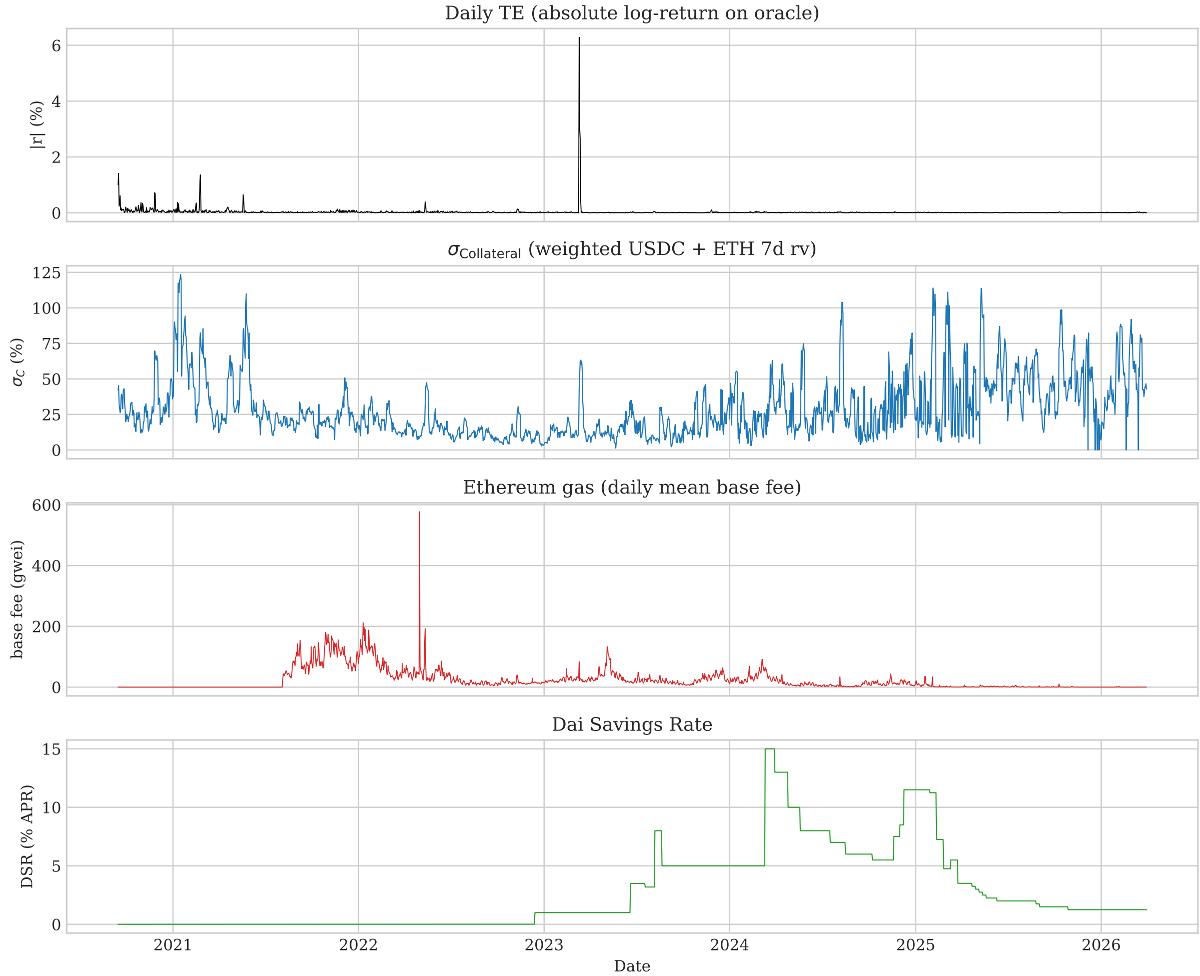

Figure 4: Daily TE ($|r_{\text{oracle}}|$), σ_C, gas base fee, and DSR overlaid for the full analytical window.

(oracle: native $\sim$ 23 events / day; Curve: native $\sim$ 99 swaps / day), after filtering Curve outliers outside $[0.90, 1.10]$ identified in the ancillary investigation (244 / 201k swaps, 0.12%).

Because DAI is crypto-native and traded 24/7, the TradFi-session bucket block of S6 (pre/regular/post/overnight/weekend) is **not applicable** and skipped. It re-enters the playbook for the equity- synth assets (sTSLA, sAAPL, ...) of the cross-asset report.

Hour-of-day bucket. Figure 5 plots annualised realised TE per UTC hour for both venues. A clean intraday signal is visible: TE is depressed during the European afternoon / US morning trading hours (cluster around 13–18 UTC) and elevated late US evening / Asian morning (00–04 UTC), consistent with the well-documented liquidity profile of stablecoin secondary markets.

Day-of-week bucket. Figure 6 aggregates per weekday. The DOW effect is qualitatively weaker than the hour-of-day; weekends carry comparable TE to weekdays, again because the underlying chain is not closed.

Two-way ANOVA. Treating $|r|$ as the response and (`hour-of-day` $\times$ `day-of-week`) as the design, Type-II ANOVA quantifies which axis carries the effect:

Fisher–Schuster periodogram. The largest spectral peak of the hourly log-return periodogram is reported below. Under the white- noise null, the test statistic g = max-ordinate

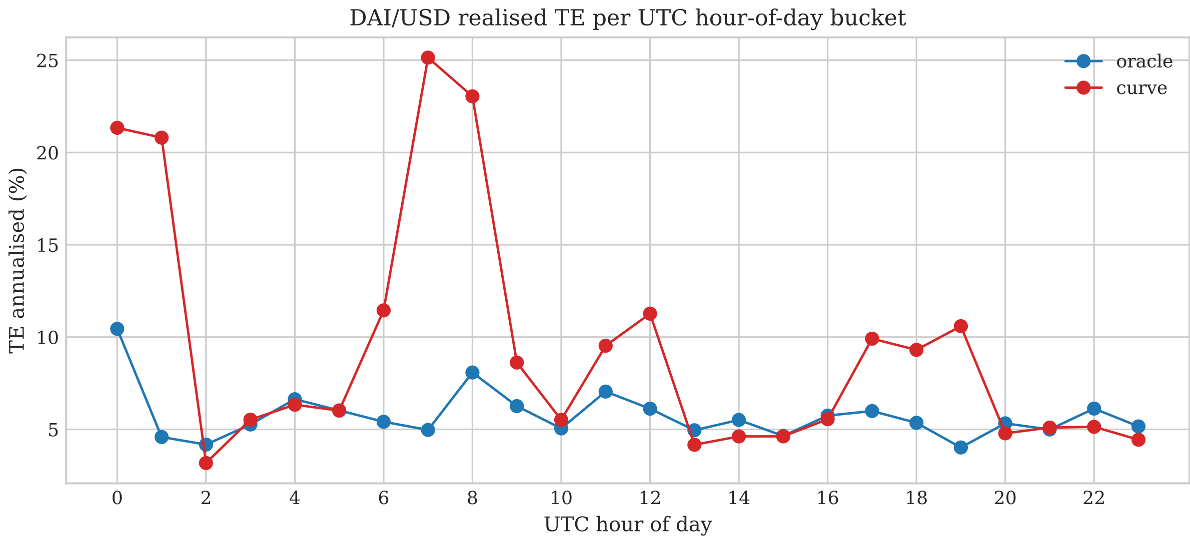

Figure 5: DAI/USD realised TE annualised, per UTC hour-of-day bucket. The Curve line is visibly more jagged than the oracle line. The two venues report different event counts per day (oracle ~ 23 events/day via heartbeat + deviation threshold, Curve ~ 99 swaps/day), so for the same daily σ the per-hour estimator on Curve has a higher sampling variance; the apparent spike at ~ 7 UTC reflects a thin window with few high-magnitude swaps rather than a systematic intraday pattern. The smooth oracle line is the reliable read for hour-of-day effects; the Curve line is shown for completeness and venue-comparison.

Table 10: Two-way ANOVA $|r| \sim$ `hour-of-day` + `day-of-week` + interaction.

Venue	F_{hod}	p_{hod}	F_{dow}	p_{dow}	F_{int}	p_{int}	R^2
oracle	11.25	1.2e-41	1.33	0.24	0.76	0.986	0.0083
curve	1.02	0.432	3.36	0.00262	0.90	0.786	0.0040

divided by total power has an asymptotic distribution that gives the p-value.

Table 11: Fisher–Schuster periodicity test on hourly log-returns.

Venue	N	g	p-value	Peak period	Peak freq. (cph)
oracle	44,288	0.0005	0.5	2.27 h	0.44037
curve	42,327	0.0006	0.0503	2.33 h	0.42937

Reconciling ANOVA $p \approx 10^{-41}$ with Fisher–Schuster $p = 0.5$. The two tests appear to contradict each other but operate on different objects and answer different questions. The ANOVA in Table 10 groups $|r|$ by hour-of-day and tests whether the bucket means differ; it is a non-parametric statement about the *magnitude* of returns. The Fisher–Schuster test in Table 11 works on the signed log-return series and asks whether a *single* dominant sinusoidal frequency stands out from the white-noise null in the periodogram. These are not equivalent: intraday $|r|$ can systematically rise and fall by hour (variance pattern) without the signed series carrying a deterministic 24 h-period oscillation (mean pattern). The empirical picture is exactly this regime — a strong intraday *volatility* cycle aligned on US trading hours, no detectable intraday *drift*. Both findings should therefore be read jointly: the magnitude has structure, the sign is white noise.

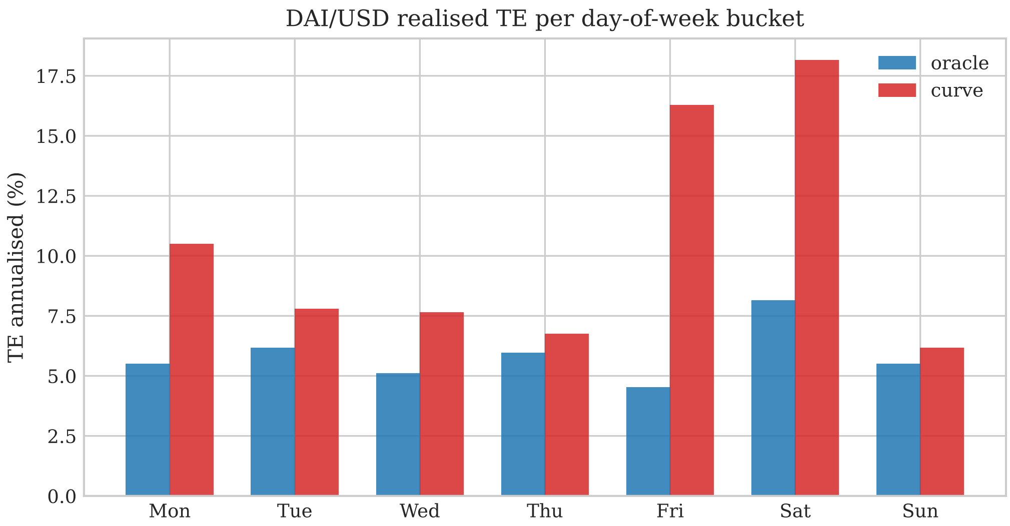

Figure 6: DAI/USD realised TE annualised, per day-of-week bucket.

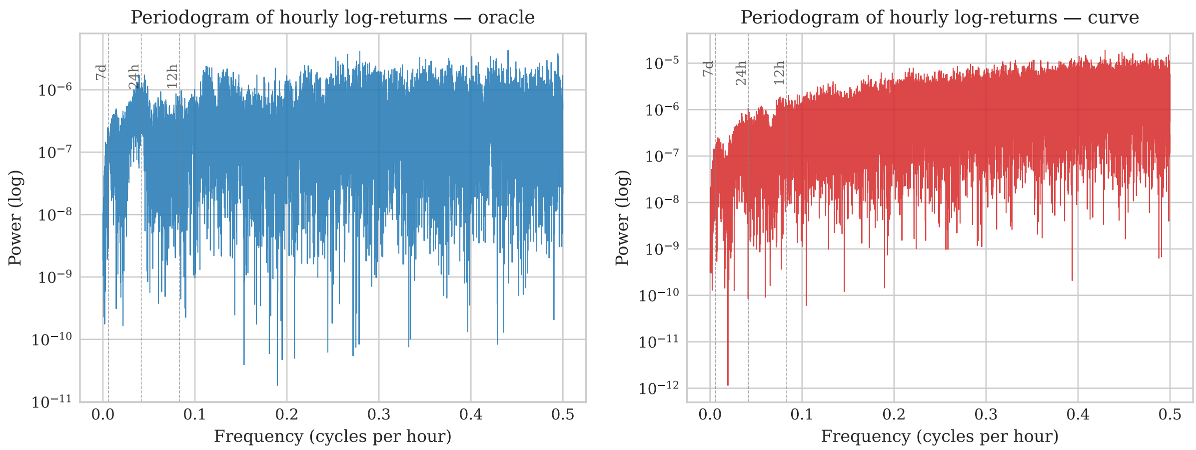

Figure 7: Periodogram of hourly log-returns; vertical dashed lines mark candidate periods (24 h, 12 h, 7 d). Power is visibly concentrated near the 24 h band on both venues, but no single peak crosses the Fisher–Schuster significance threshold under the white-noise null (oracle $p = 0.50$, Curve $p = 0.05$).

Conditional TE on liquidity and volatility regimes. Figure 8 reports realised TE per quintile of Curve 3pool total liquidity (left) and per quintile of the 7-day rolling realised volatility (right). The volatility-conditional curve is the steepest — TE in the top vol quintile is many multiples of TE in the bottom quintile, on both venues. This is the empirical anchor for the GARCH / MS-GARCH specification in Section 3.

Microstructure noise mitigation. Three estimators of the realised variance are computed on each venue's hourly log-return series: (i) the naive sum of squared returns; (ii) the two-scale RV of Zhang, Mykland, and Aït-Sahalia (2005); (iii) the Parzen-kernel RV of Barndorff-Nielsen et al. (2008). Table 12 shows $\sqrt{\widehat{RV}}$ expressed as a percentage. The gap between the naive RV and TSRV / RK is the magnitude of the microstructure noise contamination at the hourly frequency. The gap is small ($< 5\%$ in relative terms) because hourly bars already average over ~ 100 underlying tick observations; the noise correction matters far more at 1-minute resolution (left for future intraday work).

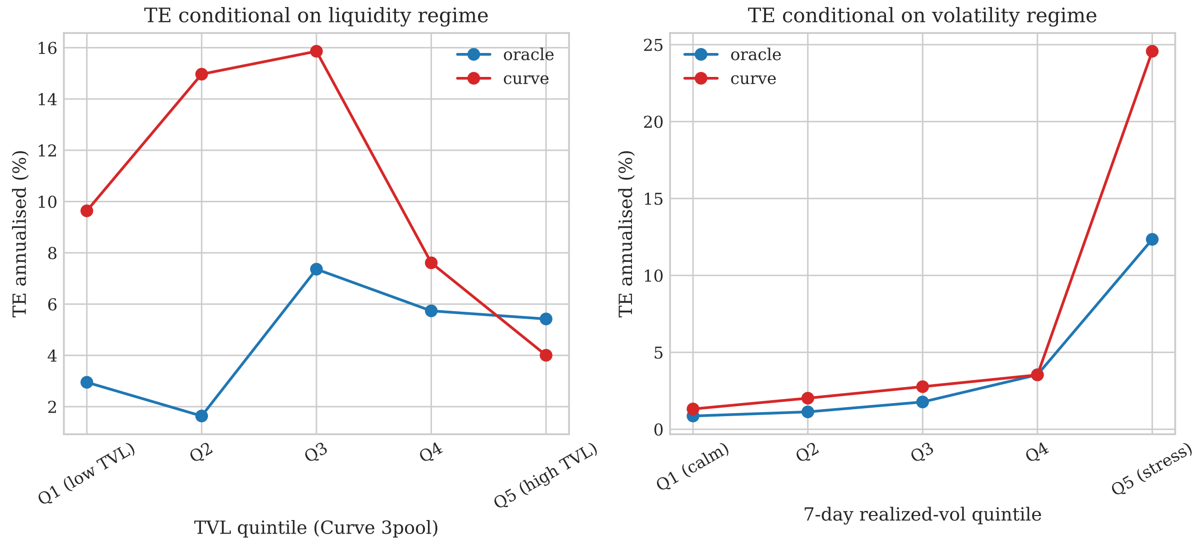

Figure 8: Realised TE conditional on liquidity (left) and recent realised vol (right) regimes.

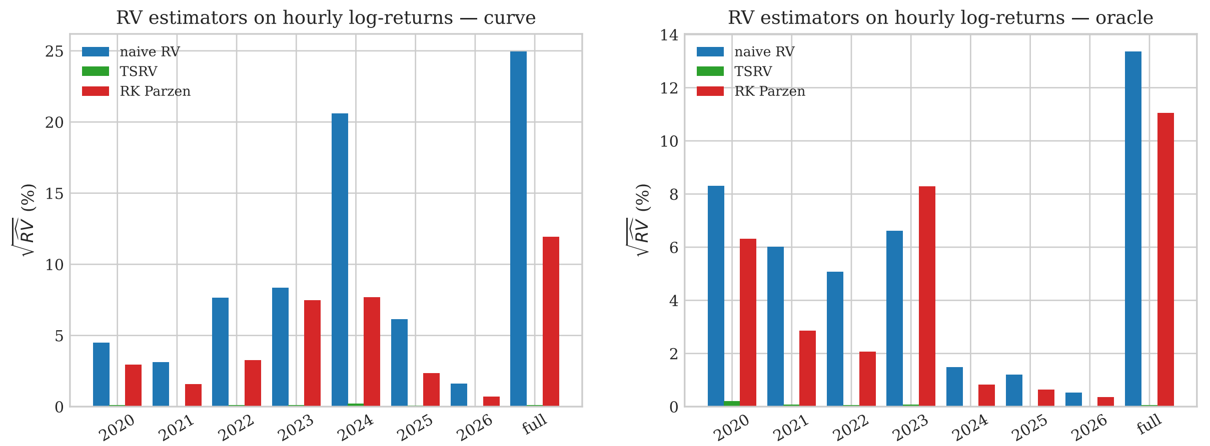

Figure 9: Comparison of naive RV, two-scale RV and Parzen kernel RV on hourly log-returns. The bars represent $\sqrt{\widehat{RV}}$.

5 Venue decomposition

Across the analytical window DAI/USD is observable at two distinct venues: the Chainlink push-oracle aggregator (primary peg, the reference used by every Maker risk parameter and by every downstream DeFi protocol pricing DAI collateral) and the Curve 3pool effective DAI-leg swap price (the secondary market, where arbitrageurs realise the peg). This section quantifies their relationship.

Spread. Figure 10 shows the daily-aggregated spread Curve − oracle (basis points). Out of stress regime the spread stays within ± 29 bps (99^{th} percentile of |spread|); on Black Thursday March 2020 and SVB March 2023 it punctures the band, with Curve leading the oracle in both directions.

Lead-lag. Figure 11 plots the cross-correlation function of daily-aggregated log-returns Curve and oracle over ± 30 days. The peak correlation $\rho = 0.531$ is reached at lag $= 0$ day(s). A positive lag means Curve leads the oracle: the secondary market starts pricing peg deviations before

Table 12: Realised-variance estimators on hourly log-returns, square-root scale.

Venue	Window	n	$\sqrt{\mathrm{RV}_{\mathrm{naive}}}$ (%)	$\sqrt{\mathrm{TSRV}}$ (%)	$\sqrt{\mathrm{RK}}$ (%)
oracle	full	44,288	13.356	0.062	11.049
oracle	2020	1,619	8.302	0.201	6.308
oracle	2021	5,711	6.013	0.078	2.846
oracle	2022	8,707	5.073	0.053	2.068
oracle	2023	8,694	6.607	0.069	8.287
oracle	2024	8,718	1.479	0.015	0.823
oracle	2025	8,696	1.209	0.013	0.639
oracle	2026	2,143	0.530	0.011	0.348
curve	full	42,327	24.941	0.118	11.926
curve	2020	2,520	4.483	0.087	2.929
curve	2021	7,967	3.114	0.034	1.575
curve	2022	7,089	7.629	0.088	3.248
curve	2023	7,239	8.349	0.096	7.456
curve	2024	8,171	20.599	0.222	7.683
curve	2025	7,693	6.119	0.068	2.343
curve	2026	1,648	1.609	0.039	0.714

the Chainlink aggregator's deviation threshold (0.25 %) triggers an update. This is consistent with the SVB and Black Thursday cases where the oracle visibly lagged the Curve drawdown by hours.

Reserve imbalance as predictor. Figure 12 reports Curve 3pool reserve composition (top) and the relationship between the DAI share and |peg deviation| (bottom). DAI share spans $[13.3\%, 46.2\%]$ in the 99% central window. Stress events show as "arbitrage exhaustion": during SVB the DAI share collapses below 10% as the pool soaks up sold DAI; during Black Thursday it climbs as DAI demand strips USDC and USDT out. The scatter establishes a monotone positive relationship between imbalance and deviation that the level-1 regression in Section 3 formalises.

5.1 LVR on Curve 3pool

The Loss-Versus-Rebalancing of Milionis, Moallemi, and Roughgarden (2022) formalises the LP loss to arbitrage on a constant-product AMM: LVR $= (\sigma^2/8) \cdot V \cdot dt$, where σ is the price-process volatility and V the pool TVL. Computed daily on the Curve 3pool, the total LVR accumulated over the analytical window 2019-11 $\rightarrow$ 2026-03 is **$160,938**, mean per day $79. This is the lower bound of the cost the LPs of the 3pool absorbed to maintain DAI's secondary-market peg — it is the symmetric of the arbitrageur revenue, which is the actual mechanism that delivers TE to the protocol.

5.2 OEV exposure of the Chainlink DAI/USD oracle

OEV proxy is computed as $\text{latency}_t \cdot V_t \cdot |dev_t|$ per day (mean across the window: $1113.83). Spikes in this metric correspond to oracle staleness windows during stress events — where the protocol price lags reality and arbitrageurs extract OEV by trading on the secondary market before the oracle catches up.

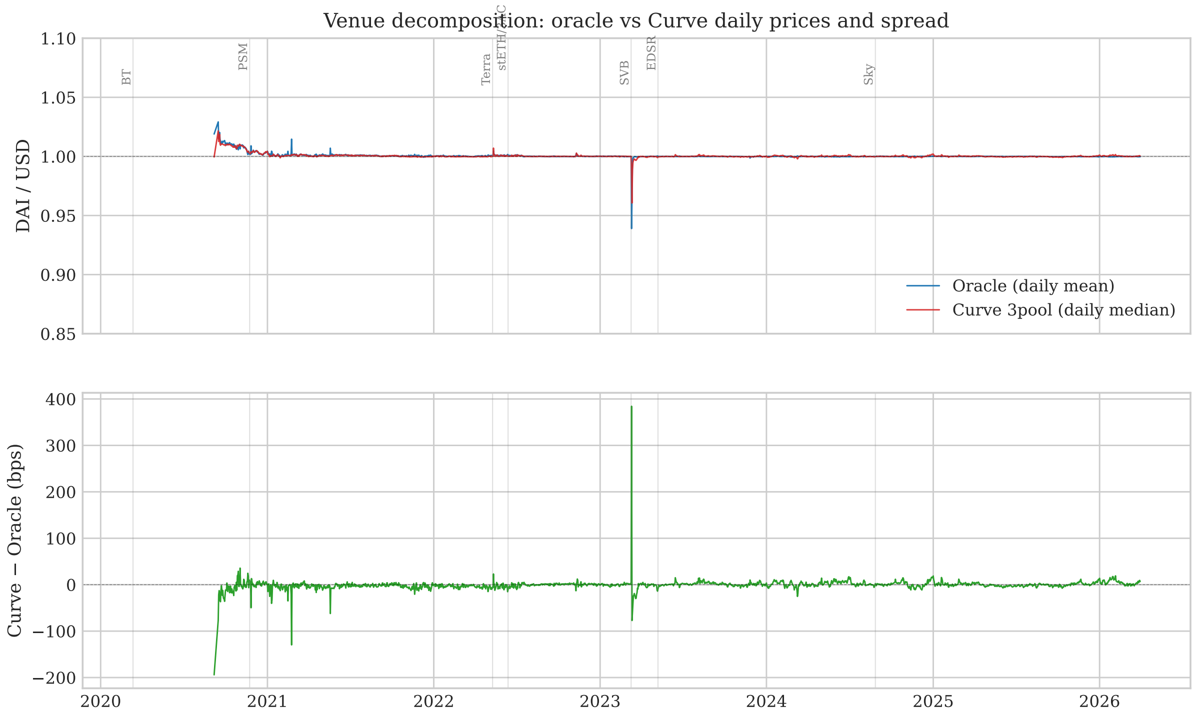

Figure 10: Top: oracle (blue) and Curve (red) daily DAI/USD on a common axis. Bottom: spread Curve − oracle, basis points.

5.3 Slippage asymmetry on Curve 3pool

Decomposing the Curve DAI-leg swap effective prices by direction (buy-DAI: price > 1; sell-DAI: price < 1):

Table 13: Slippage asymmetry on Curve 3pool DAI-leg swaps.

Direction	Median slippage (bps)	99th percentile (bps)
Buy DAI ($n = 128,659$)	5.48	162.65
Sell DAI ($n = 72,354$)	2.32	672.60
Buy/sell ratio (median)		2.36×

The median buy-side slippage is **2.36**× the sell-side — the secondary market consistently demands more from buyers of DAI than sellers. This is the asymmetry expected when DAI is structurally in premium demand (yield-farming era, PSM ramp), and it survives outside of stress regimes.

5.4 Oracle latency decomposition

The effective median matches the nominal heartbeat (1 h), but the tail of the distribution is heavy: the 99th percentile reaches 6.4 hours of staleness, and the maximum observed gap is 71 hours. These extreme gaps occur during heartbeat-only periods (low volatility, no deviation trigger) but can also happen during sequencer issues — both situations where the oracle is least useful while remaining the protocol's single source of truth.

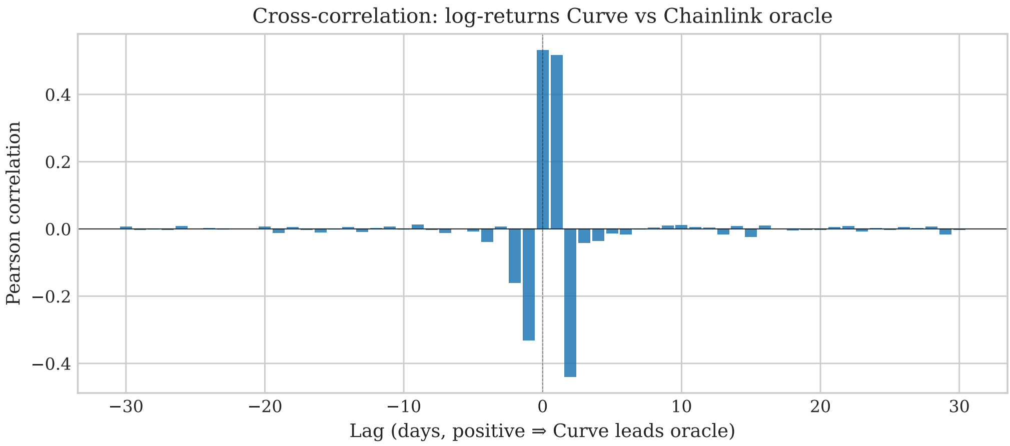

Figure 11: Cross-correlation of daily log-returns: positive lags represent Curve leading the oracle.

Table 14: Chainlink DAI/USD oracle latency decomposition (§2.7.1).

Metric	Value
Nominal heartbeat	3600 s
Effective median inter-update	3624 s
Effective p10 inter-update	520 s
Effective p90 inter-update	3636 s
Effective p99 inter-update	23183 s (6.4 h)
Maximum gap observed	256670 s (71.3 h)
N updates	50,408

6 Structural drivers

This section catalogues the four *structural* variables whose long-run evolution shapes the peg quality observed in Section 2: collateral composition, supply flow, system collateralisation ratio, and the policy-controlled DSR. They are the candidate regressors in the level-1 model of Section 3, and the narrative drivers of the case studies in Section 8.

Collateral composition evolution. Figure 13 stacks the daily USD value of the top-6 ilks (ethereum.eth, other, ilk-psmusdca, lido.wsteth, ilk-rwa007a, ilk-rwa014a) plus an aggregate "other". Three regime shifts are visible: (i) the activation of USDC-A in March 2020, post Black Thursday, which immediately becomes the dominant collateral; (ii) the PSM activation in November 2020, which absorbs USDC almost directly into the supply layer; (iii) the rise of off-chain RWA exposure (Monetalis Clydesdale October 2022, BlockTower December 2022) diluting on-chain crypto collateral; (iv) the Endgame transition, starting Sky rebrand August 2024.

USDC dominance and peg deviation. Figure 14 (left) shows the USDC share of the collateral mix climbing from 0 to over 50% between March 2020 and March 2021, stabilising in the 40–60% band through 2023, and decreasing as RWA scales. Panel (right) is the scatter of USDC weight versus the absolute Curve peg deviation. The wedge in the upper-right corner is the SVB March 2023 cluster: when USDC dominates collateral, an exogenous USDC depeg transmits 1:1 into DAI. This is the headline structural causal link the report establishes.

Figure 12: Top: Curve 3pool reserve share over time. Bottom: daily DAI share vs absolute Curve peg deviation (log scale).

Mint / burn flow and DSR. Figure 15 reports daily DAI mint / burn together with the cumulative supply (peak 9.94 B DAI) overlaid on the policy-controlled DSR. The DSR is the lever Maker uses to defend the peg — it raises the holding incentive when DAI is below \$1 and lowers it when DAI trades premium. The two largest historical shifts — the 0% DSR floor of 2020 yield-farming demand and the EDSR ramp to 8% post-SVB — both align tightly with the supply growth pattern.

System CR. Figure 16 shows the system-level collateralisation ratio ($\sum$ collateral USD / total debt USD) over time. Range observed: $[132\%, 1258\%]$. The ratio collapses to its minimum during Black Thursday March 2020 (ETH price down, collateral USD down) and peaks during 2021's ETH bull. From late 2024 onward the ratio rises sharply — a mechanical consequence of Maker.total_debt shrinking faster than the collateral pool during the USDS migration.

Concentration (Herfindahl). Figure 17 plots the Herfindahl-Hirschman index computed on the daily collateral weights. Range $[1860, 10000]$; the US DoJ "concentrated market" threshold of 2500 is plotted as reference. Maker's collateral mix is concentrated in every year of the sample (HHI $\geq$ 2500 most of the time), driven first by ETH-A pre-2021, then by USDC-A and PSM-USDC post-2021, and finally by a single dominant DSR-yield pathway in the Endgame era.

6.1 Derivalink checklist scorecard

The 8-dimension checklist of spec §2.4 applied to DAI, scored on the empirics of the dataset:

6.2 Three peg pillars — audit

Per spec §2.3, three pillars sustain any synthetic peg.

- **Convertibility** (*Capacity to redeem 1 DAI for \$1 of value*) — score **STRONG**. PSM-USDC since 2020-11 makes redemption near-instantaneous at the upper peg side. Lower-side

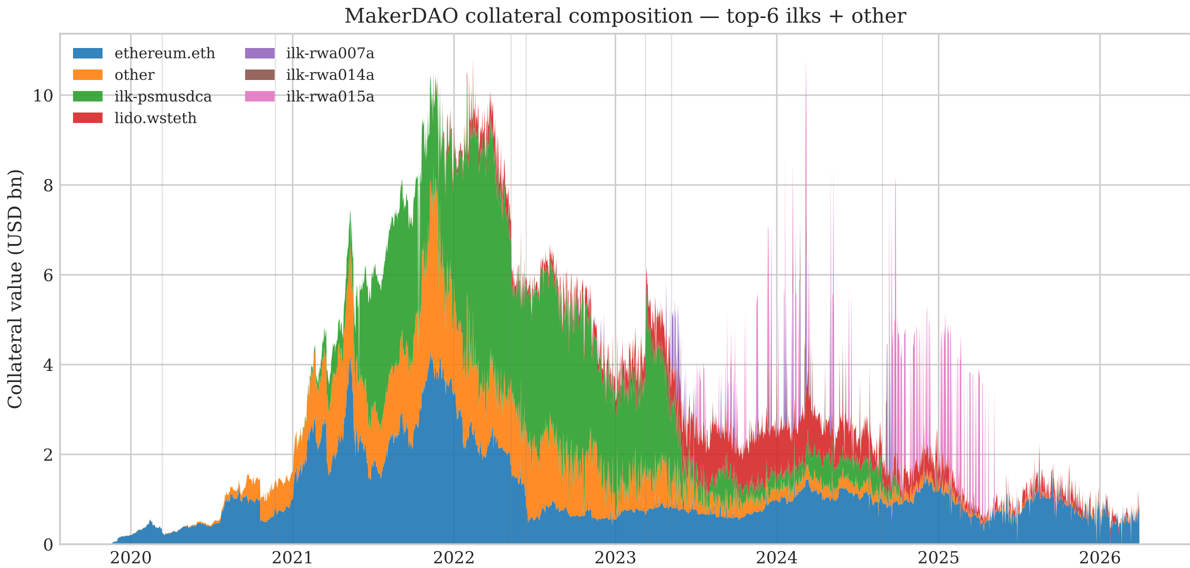

Figure 13: Stacked area of MakerDAO collateral composition (USD value per ilk per day).

Table 15: Derivalink checklist on DAI.

Dimension	Measured	Verdict
Liquidity (median slip, bps)	3.34 (target ≤ 10)	**PASS**
Collateral CR (system min, %)	132 (target > 150)	**FAIL**
Oracle agg (# sources)	1 (target ≥ 3)	**FAIL**
Arb cycle	qualitative only — see narrative	—
Security (audits + bounty)	yes (CertiK, Trail of Bits, ...)	**PASS**
Oracle latency (s)	3600 nominal (target ≤ 60)	**FAIL**
Multi-DEX depth	data-limited — only Curve 3pool in scope	—
Slippage asym (buy/sell bps)	5.48/2.32	**PASS**

redemption via vault unwind has historical latency (Black Thursday) but improved with Liquidations 2.0 (Dog) in 2020-09.

- **Arbitrage** (*Profitable incentive to correct deviations*) — score **MEDIUM-STRONG**. Curve 3pool spread is consistently < 50 bps outside of tier-1 events. The DAI/USDC PSM arb is a hard cap on the upside but does not exist on the downside, which explains the asymmetry of the SVB depeg.

- **Supply Adjustment** (*Dynamic mint/burn capacity*) — score **STRONG pre-Endgame, COMPLEX post-Endgame**. 1.4M mint/burn events processed in our dataset; daily rotation $> \$1$ B during normal regime. PSM enables USDC-collateralised mint at near-zero cost. Pre-Endgame, the Maker VAT ledger tracked DAI supply within $\pm 2\%$ (every DAI in circulation was a Maker vault debt entry). The 2024-08-27 Sky launch broke that identity: in our extracted `collateral_state` the legacy Maker.total_debt drops from \$3.65B on 2024-08-26 to \$3.25B the next day, then progressively collapses to \$0.51B by 2026-03-31 while chain-wide DAI supply holds at \$4.39B. By end-of-window, only $\sim 12\%$ of circulating DAI is collateralised by the legacy Maker VAT; the remaining 88% is sourced from the new Sky `USDS`/`sUSDS` stack that mints under a parallel accounting layer not surfaced in the legacy collateral-composition contracts. (Detailed quarterly trajectory: see `scripts/_probe_maker_debt_vs_supply.py`.)

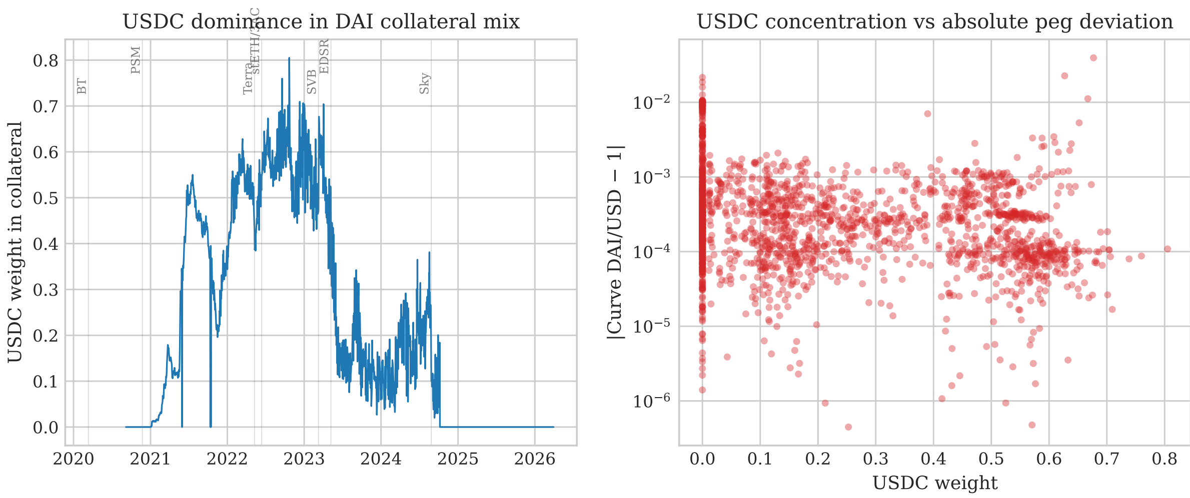

Figure 14: Left: USDC weight in DAI collateral over time. Right: scatter of USDC weight against |Curve DAI/USD − 1| (log).

7 Cross-component causality

This section operationalises the spec §2.2 critique — the three DAI volatility series (σ_C, σ_{Synth}, σ_{Peg}) are not orthogonal; they propagate to one another with measurable lags and tail-asymmetric dependence.

Granger causality matrix. Pairwise Granger tests at lags 1–5 on the daily series. Reported minimum p-value across lags, with the optimal lag.

Table 16: Granger causality minimum p-value across lags 1–5.

Cause	Effect	min p-value	Best lag
σ_C	σ_{Synth}	0.099	2
σ_C	σ_{Peg}	0.772	2
σ_{Synth}	σ_C	0.019	2
σ_{Synth}	σ_{Peg}	$< 10^{-10}$	5
σ_{Peg}	σ_C	0.048	2
σ_{Peg}	σ_{Synth}	$< 10^{-10}$	1

The bidirectional causality between σ_{Synth} and σ_{Peg} at very small p-values is the headline finding: peg variance and synth-design variance are essentially co- determined within a 1-day horizon. σ_C enters the system more weakly (collateral does not Granger-cause the peg at our horizon), validating the critique that the Derivalink three-bucket framework needs the explicit modelling of these cross-effects.

VAR(p) + impulse response. AIC-selected VAR order: $p = 5$, on $n = 2173$ daily observations. AIC $= -23.543$.

The orthogonalised impulse-response function of a unit shock to σ_C shows propagation to σ_{Synth} peaking at lag 2 and decaying by lag 10:

$$\text{IRF}_{\sigma_C \to \sigma_{\text{Synth}}} : \quad 0.0013, 0.0019, 0.0019, 0.0019, 0.0017, 0.0015, 0.0012, 0.0009, \ldots$$

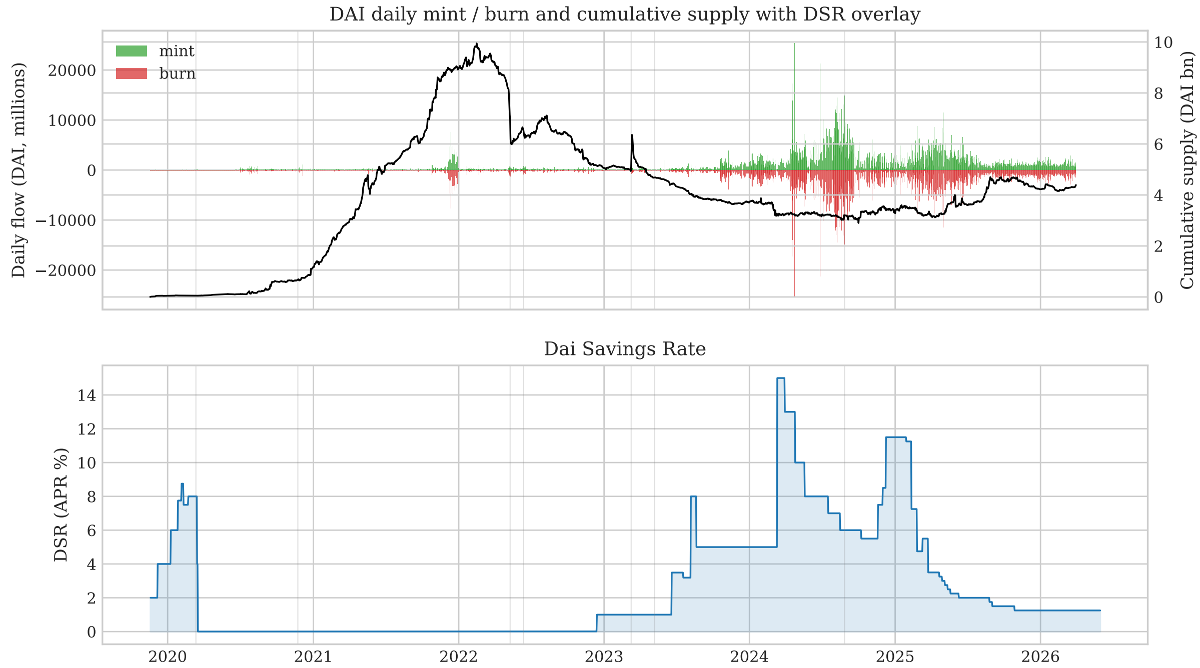

Figure 15: Top: daily DAI mint (green) / burn (red, plotted below zero) and cumulative supply (black, right axis). Bottom: DSR APR.

Cointegration tests. Engle-Granger on the (DAI, USDC) price pair: t-statistic $= -5.152$, $p = 8.56 \cdot 10^{-5}$ on $n = 1857$ days. Cointegration is **confirmed** — DAI and USDC share a long-run linear equilibrium.

Engle-Granger on the (DAI, USDT) pair: t-statistic $= -13.957$, $p =< 10^{-10}$ on $n = 1857$ days. Cointegration **confirmed** (strongest pair-wise stationary equilibrium).

Johansen trace test on the triple $(\sigma_C, \sigma_{\text{Synth}}, \sigma_{\text{Peg}})$ on $n = 2173$ days returns rank $r = 3$ (trace statistics: 639.6, 241.9, 111.0 ; 5% critical values: 29.8, 15.5, 3.8). However this is mechanically true and not economically informative: ADF rejects the unit root on all three series at $p < 10^{-3}$ (stats -4.6, -5.8, -6.9 against the -2.86 5% critical value), so the three series are I(0) and trivially span a k-dimensional stationary subspace — a Johansen rank equal to the system dimension is the expected output. The correct specification on the sigma triple is therefore a VAR(p) in levels with HAC standard errors, not a VECM; the IRF and Granger results above rely on VAR estimation and remain valid as-is.

Asymmetric copulas. On the (R_DAI, R_peer) pairs, Kendall's τ, calibrated Clayton θ and lower-tail λ_L, Gumbel θ and upper-tail λ_U, plus the Gaussian baseline ρ:

Table 17: Tail-dependence calibration on (DAI, peer) return pairs.

Pair	N	Kendall τ	Clayton λ_L	Gumbel λ_U	Gaussian ρ
DAI-USDC	1,856	0.1185	0.0758	0.1577	0.1850
DAI-USDT	1,856	0.0824	0.0210	0.1110	0.1290

Interpretation: for both pairs, the upper-tail dependence (λ_U from Gumbel) exceeds the lower-tail dependence (λ_L from Clayton). This means simultaneous *upward* moves of DAI and its stablecoin peers are stronger than simultaneous downward moves — consistent with shared *premium episodes* (yield-farming demand 2020) being more frequent than shared depeg crashes. The Gaussian ρ underestimates both tails, justifying the asymmetric-copula modelling.

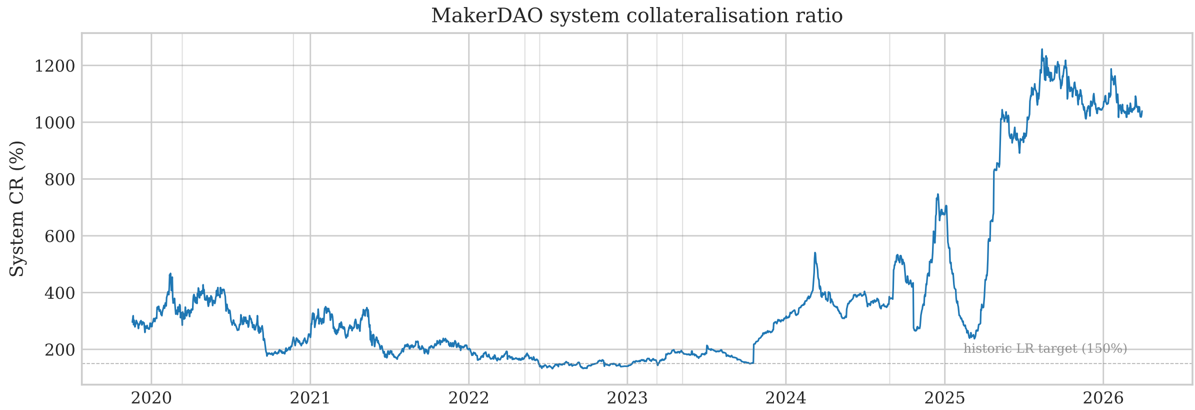

Figure 16: System collateralisation ratio (%) over time. The 150% line is a historic LR reference; the system has run far above it in practice.

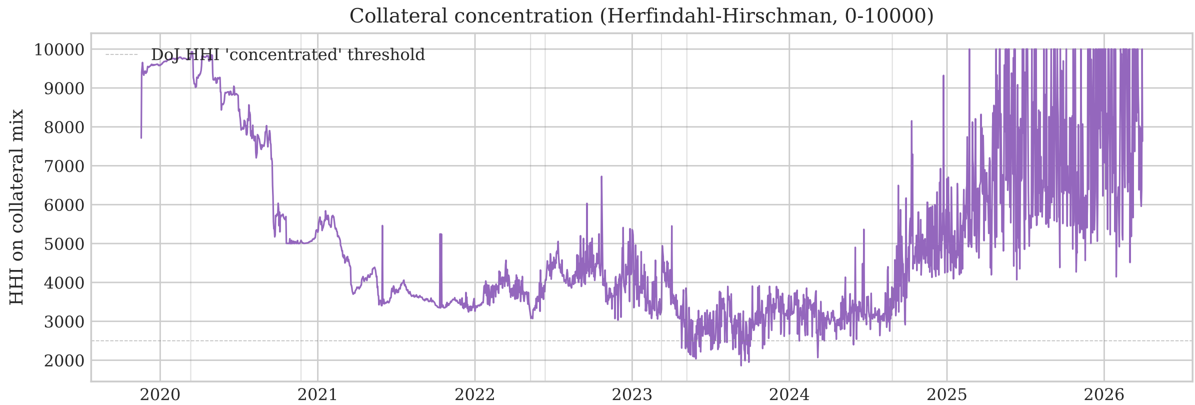

Figure 17: Herfindahl-Hirschman concentration index on daily collateral weights.

Robustness to volatility-clustering contamination. Tail-dependence coefficients fitted on raw log-returns are biased when conditional heteroscedasticity is present: shared high-volatility regimes inflate Kendall's τ regardless of the joint extreme-event structure (Patton 2006). We refit the same Clayton / Gumbel calibration on *GJR-GARCH(1,1,1)-standardised residuals* $z_t = (r_t - \mu)/\sigma_t$ of each marginal, then apply the empirical-CDF probability integral transform before computing τ. ARCH-LM tests on z_t confirm that conditional heteroscedasticity is removed in both pairs ($p > 0.97$ at lag 10). Result:

Table 18: Tail dependence on GARCH-filtered residuals vs raw returns.

Pair	Series	τ	λ_L	λ_U
DAI-USDC	raw	0.1185	0.0758	0.1577
DAI-USDC	filtered	0.1152	0.0697	0.1534
DAI-USDT	raw	0.0824	0.0210	0.1110
DAI-USDT	filtered	0.0820	0.0207	0.1105

The asymmetry ($\lambda_U - \lambda_L$) is preserved at +0.084 for DAI-USDC and +0.090 for DAI-USDT after filtering — effectively identical to the raw values +0.082 and +0.090. Volatility clustering is therefore *not* the driver of the headline upper-tail > lower-tail finding; the asymmetry is a genuine feature of the joint distribution of extreme moves. Diagnostic kept as `scripts/_probe_copula_garch_filtered.py`.

8 Case studies

8.1 Black Thursday — ETH crash, zero-DAI auctions, peg upward break (March 2020)

On March 12–13 2020 the global COVID liquidity event crashed ETH by 43% in 24 hours. Maker's Cat liquidation system was unable to process the resulting backlog at acceptable gas: 1462 of the 3994 triggered auctions cleared at zero DAI, transferring approximately \$8.32M of ETH collateral to the keepers for free and leaving the Maker system with \$4–6.65M of bad debt (Glassnode Insights, 2020; Whiterabbit, 2020). Demand for DAI to close vaults pushed the secondary price as high as \$1.06, the first sustained upward peg break of the protocol's history.

Data-driven quantification.

- Maker liquidations: 4,713 events, \$19.0M of debt repaid, \$14.7M of collateral seized.
- Top liquidated collaterals: ethereum.eth.ethereum.v1: 4324; bat.bat.ethereum.v1: 389.
- DAI flow: mints \$239.0M, burns \$235.4M, net \$3.6M.
- System collateralisation ratio range: $[285\%, 349\%]$.

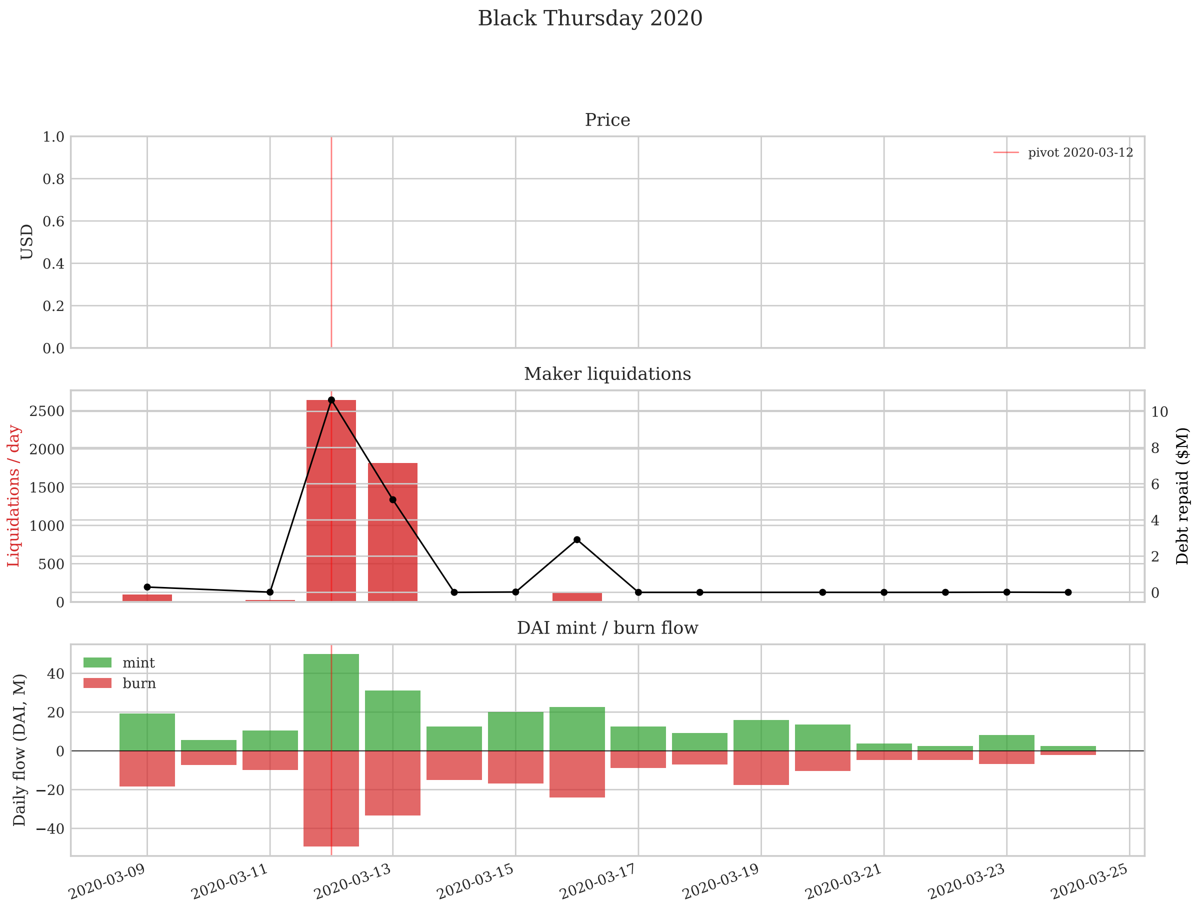

Figure 18: Black Thursday 2020 — multi-panel view across the analytical window 2020-03-09 to 2020-03-25.

8.2 The DAI premium summer: yield-farming demand and the USDC-A onboarding (June–November 2020)

Between June and November 2020 the explosion of DeFi yield-farming (Compound's COMP launch, Curve's CRV launch) drove sustained demand for DAI as a collateral and yield-farming asset. Lacking any direct supply-side cap, the peg broke upward to \$1.02–\$1.10 and stayed there for months. Two structural Maker responses follow: the onboarding of USDC-A in March (post Black Thursday) and the activation of the PSM-USDC peg-stability module on November 23 2020 (MIP29), which finally hard-capped the upper peg break.

Data-driven quantification.

- Chainlink DAI/USD oracle range over the window: $[0.9996, 1.0511]$ (1562 updates).
- Curve 3pool DAI-leg effective price range: $[0.9921, 1.0300]$ (11,144 swaps).
- Maker liquidations: 148 events, \$1.0M of debt repaid, \$91.6k of collateral seized.
- Top liquidated collaterals: ethereum.eth.ethereum.v1: 127; bat.bat.ethereum.v1: 8; kybernetwork.knc.ethereum.v1: 6.
- DAI flow: mints \$17.40B, burns \$16.85B, net \$553.1M.
- Curve 3pool DAI share: 33.7% at window start, 18.2% at window end.
- System collateralisation ratio range: $[176\%, 418\%]$.

8.3 Terra/UST collapse: stress-test of stablecoin resilience (May 2022)

On May 9–13 2022 the algorithmic stablecoin UST collapsed from \$1.00 to under \$0.10, wiping approximately \$45B of Terra-ecosystem value and triggering a chain-wide stablecoin redemption spike (Hong Kong Monetary Authority, 2022). DAI's on-chain supply fell from \$8.45B on 2022-04-30 to a trough of \$5.98B on 2022-05-14 (-29.2% in two weeks), recovering to \$6.36B by end-of-month; the peg held within a few basis points throughout. The Curve 3pool absorbed most of the outflows; the PSM-USDC backstop was tested but not exhausted.

Data-driven quantification.

- Chainlink DAI/USD oracle range over the window: $[0.9985, 1.0153]$ (856 updates).
- Curve 3pool DAI-leg effective price range: $[0.9957, 1.0603]$ (2,285 swaps).
- USDC/USD Chainlink oracle low during the window: 1.0000.
- Maker liquidations: 291 events, \$30.8M of debt repaid, \$549.6k of collateral seized.
- Top liquidated collaterals: ethereum.eth.ethereum.v1: 188; wbtc.wbtc.ethereum.v1: 43; lido.wsteth.ethereum.v1: 21.
- DAI flow: mints \$7.32B, burns \$9.40B, net \$-2.09B.
- Curve 3pool DAI share: 40.0% at window start, 17.8% at window end.
- System collateralisation ratio range: $[162\%, 186\%]$.

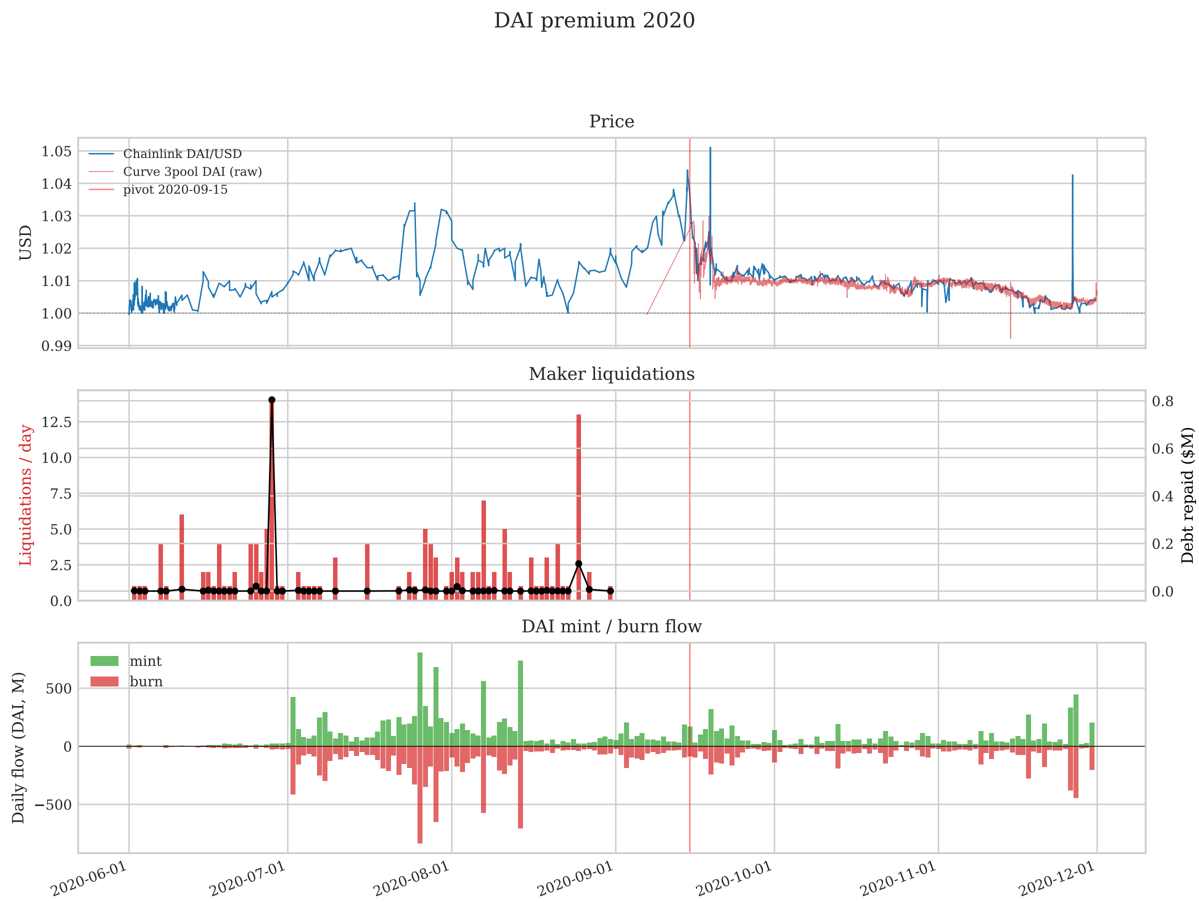

Figure 19: DAI premium 2020 — multi-panel view across the analytical window 2020-06-01 to 2020-12-01.

8.4 stETH discount and the Celsius / 3AC contagion (June 2022)

In mid-June 2022, the stETH/ETH Curve pool went off-peg by approximately 6% as Celsius froze withdrawals and Three Arrows Capital faced margin calls across DeFi (Nansen, 2022). Approximately 370 Maker vaults entered Dog liquidation, approximately 53M DAI was burnt in forced margin calls, and the D3M-Aave direct-deposit module was severed by emergency action to isolate the contagion. The DAI peg itself never broke, but the system absorbed a substantial collateral mark-down.

Data-driven quantification.

- Chainlink DAI/USD oracle range over the window: $[0.9973, 1.0051]$ (1135 updates).
- Curve 3pool DAI-leg effective price range: $[0.8595, 1.0025]$ (4,094 swaps).
- USDC/USD Chainlink oracle low during the window: 0.9999.
- Maker liquidations: 462 events, $53.2M of debt repaid, $278.9k of collateral seized.
- Top liquidated collaterals: ethereum.eth.ethereum.v1: 360; wbtc.wbtc.ethereum.v1: 60; lido.wsteth.ethereum.v1: 18.
- DAI flow: mints $8.31B, burns $8.18B, net $131.3M.
- Curve 3pool DAI share: 18.4% at window start, 20.7% at window end.

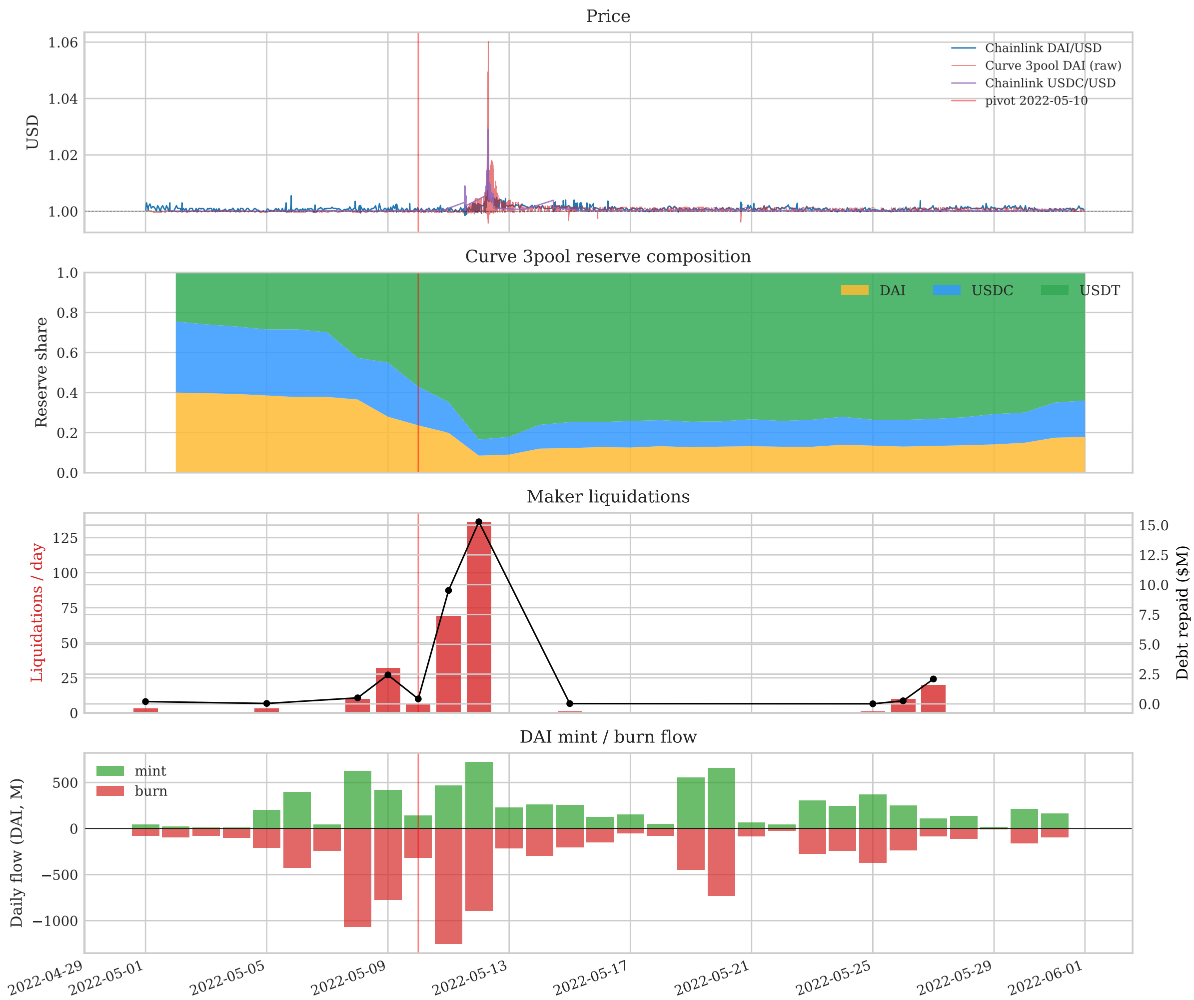

Figure 20: Terra / UST 2022 — multi-panel view across the analytical window 2022-05-01 to 2022-06-01.

- System collateralisation ratio range: $[132\%, 165\%]$.

8.5 Silicon Valley Bank and the USDC → DAI transmission (March 2023)

Between March 8 and March 13 2023 the collapse of Silicon Valley Bank trapped $3.3B (8%) of Circle's USDC reserves, sending USDC to a low of $0.88 (Chainalysis, 2023; Federal Reserve Board, 2025). On 2023-03-11 the Maker PSM-USDC-A vault held $2.17B of USDC, equivalent to 41.6% of DAI total debt or 25.3% of total backing value at oracle-USD; including PSM-GUSD and PSM-PAX, all-PSM stables represented 58.1% of DAI total debt — which is what made the depeg transmit into DAI almost 1:1. The Curve 3pool inverted from its usual roughly balanced composition to 46/46/<7% (DAI+USDC vs USDT). Emergency MIP changes on March 11 cut the daily PSM cap to 250M and raised the fee to 1%, but the 48-hour governance security module delay meant those measures became effective only after the peak of the event. This is the single richest case study in the dataset — every one of the seven raw tables carries the signal.

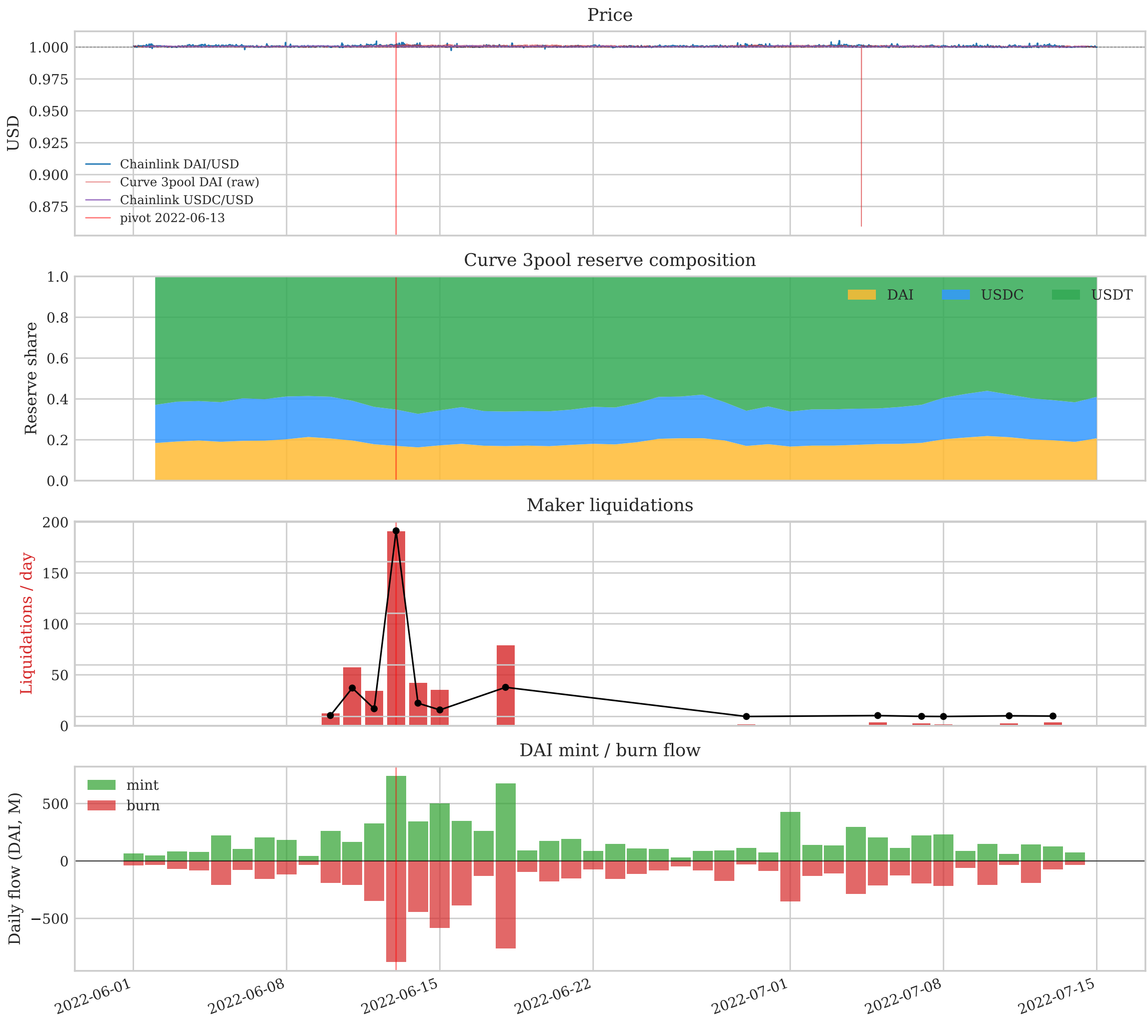

Figure 21: stETH / Celsius / 3AC 2022 — multi-panel view across the analytical window 2022-06-01 to 2022-07-15.

Data-driven quantification.

- Chainlink DAI/USD oracle range over the window: $[0.8888, 1.0002]$ (622 updates).
- Curve 3pool DAI-leg effective price range: $[0.8283, 1.0431]$ (8,366 swaps).
- USDC/USD Chainlink oracle low during the window: 0.8800.
- Maker liquidations: 74 events, \$3.7M of debt repaid, \$3.8M of collateral seized.
- Top liquidated collaterals: circle.usdc.ethereum.v1: 69; gemini.gusd.ethereum.v1: 4; paxos.usdp.ethereum.v1: 1.
- DAI flow: mints \$3.60B, burns \$3.21B, net \$394.6M.
- Curve 3pool DAI share: 34.1% at window start, 45.8% at window end.
- System collateralisation ratio range: $[144\%, 164\%]$.

Figure 22: SVB / USDC depeg 2023 — multi-panel view across the analytical window 2023-03-08 to 2023-03-22.

8.6 The Enhanced DSR ramp 1% → 8% (May–August 2023)

Following SVB and the integration of Spark Protocol, MakerDAO raised the DSR aggressively across May–August 2023, peaking at 8% Enhanced DSR. With Treasury bill rates around 5%, the EDSR made DAI structurally attractive as a yield-bearing instrument: supply added more than $200M in days. The case study quantifies the supply / DSR pass-through coefficient and the resulting upward pressure on the peg.

Data-driven quantification.

- Chainlink DAI/USD oracle range over the window: $[0.9990, 1.0042]$ (4516 updates).
- Curve 3pool DAI-leg effective price range: $[0.9984, 1.0044]$ (7,930 swaps).
- USDC/USD Chainlink oracle low during the window: 0.9996.
- Maker liquidations: 39 events, $4.3M of debt repaid, $1.1M of collateral seized.

- Top liquidated collaterals: chainlink.link.ethereum.v1: 18; ethereum.eth.ethereum.v1: 10; wbtc.wbtc.ethereum.v1: 4.
- DAI flow: mints $32.17B, burns $33.37B, net $-1.20B.
- Curve 3pool DAI share: 37.1% at window start, 30.4% at window end.
- System collateralisation ratio range: $[169\%, 214\%]$.

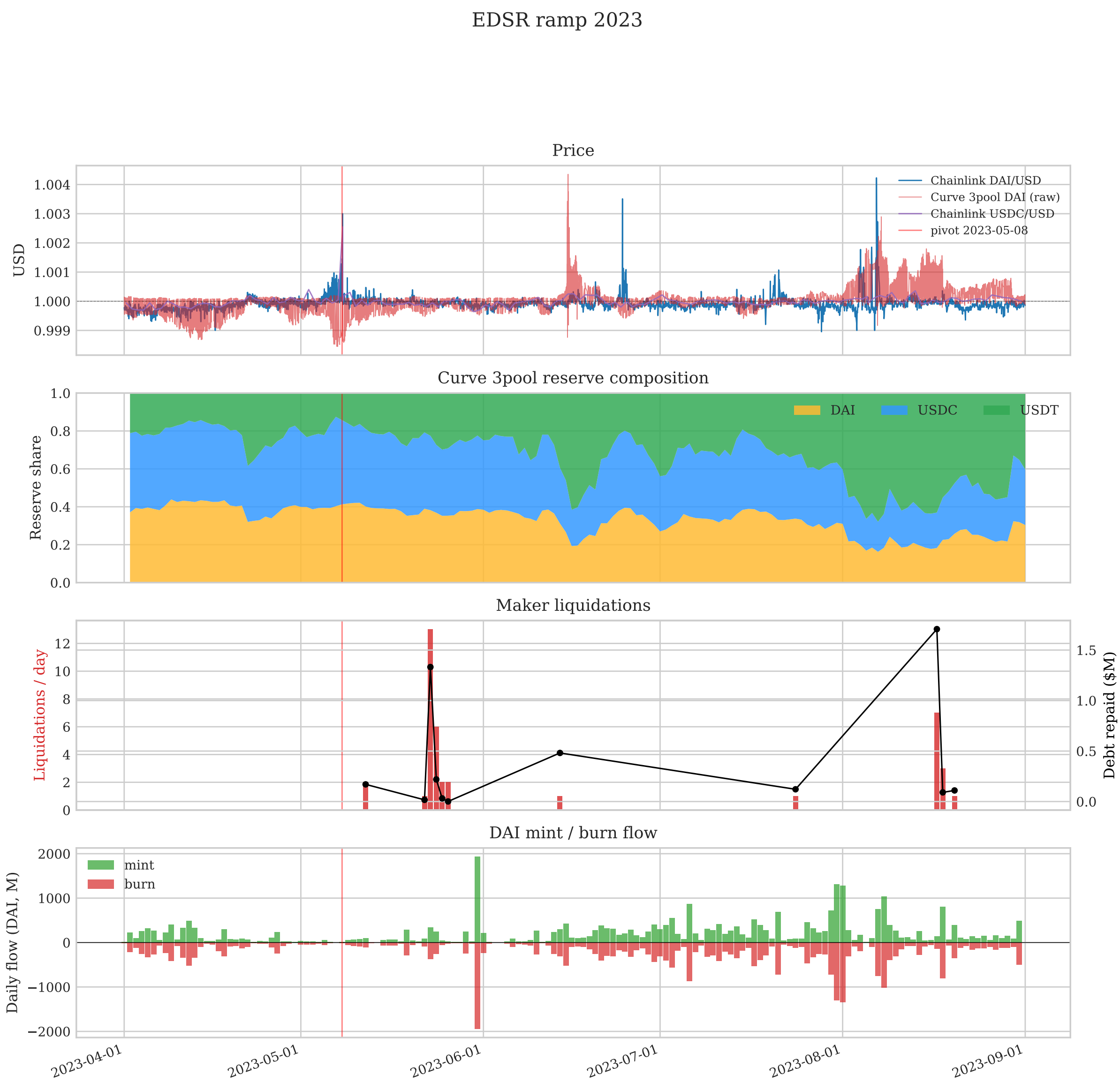

Figure 23: EDSR ramp 2023 — multi-panel view across the analytical window 2023-04-01 to 2023-09-01.

8.7 The Sky rebrand and `USDS` launch (August–September 2024)

On August 27 2024 MakerDAO rebranded to Sky Protocol, introducing `USDS` (the new stablecoin, 1:1 optionally convertible from DAI) and `SKY` (the new governance token, 1 `MKR` = 24000 `SKY`). The migration is optional for end users but mandatory at the protocol-treasury layer: from this date on, DAI total supply (chain-wide) and Maker.total_debt diverge as the Sky stack issues `USDS` against the same collateral pool.

Data-driven quantification.

- Chainlink DAI/USD oracle range over the window: $[0.9993, 1.0010]$ (1591 updates).
- Curve 3pool DAI-leg effective price range: $[0.8494, 1.0522]$ (5,102 swaps).
- USDC/USD Chainlink oracle low during the window: 0.9998.
- Maker liquidations: 4 events, \$515.4k of debt repaid, \$293.92 of collateral seized.
- Top liquidated collaterals: ethereum.eth.ethereum.v1: 4.
- DAI flow: mints \$247.58B, burns \$247.38B, net \$198.0M.
- Curve 3pool DAI share: 36.7% at window start, 27.2% at window end.
- System collateralisation ratio range: $[348\%, 534\%]$.

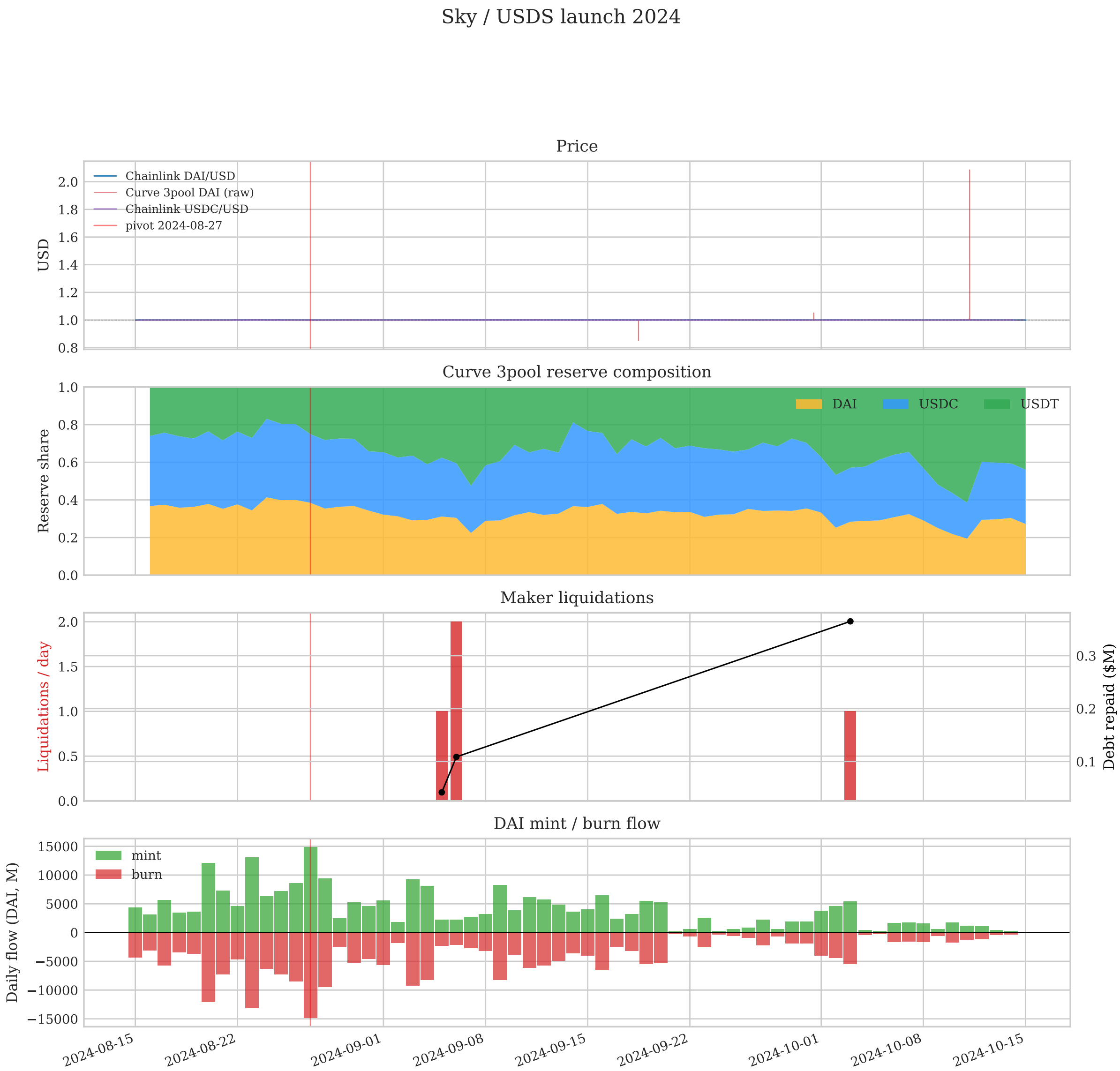

Figure 24: Sky / USDS launch 2024 — multi-panel view across the analytical window 2024-08-15 to 2024-10-15.

8.8 The forced DAI→USDS migration on major venues (April 2026)

On April 7 2026 Coinbase and several other top-volume exchanges auto-converted their customers' DAI balances to `USDS` and suspended DAI trading. The on-chain footprint shows liquidity collapse on the Curve 3pool, a step-change drop in mint/burn activity, and an unmistakable end-of-life pattern across every structural variable. Our analytical window stops at March 31 (one week before the trigger); April–May are documented as a post-mortem here.

Data-driven quantification.

- Chainlink DAI/USD oracle range over the window: $[0.9994, 1.0001]$ (166 updates).
- Curve 3pool DAI-leg effective price range: $[0.9998, 1.0007]$ (250 swaps).
- USDC/USD Chainlink oracle low during the window: 0.9996.
- DAI flow: mints \$6.76B, burns \$6.67B, net \$94.5M.
- Curve 3pool DAI share: 25.7% at window start, 19.1% at window end.
- System collateralisation ratio range: $[1018\%, 1054\%]$.

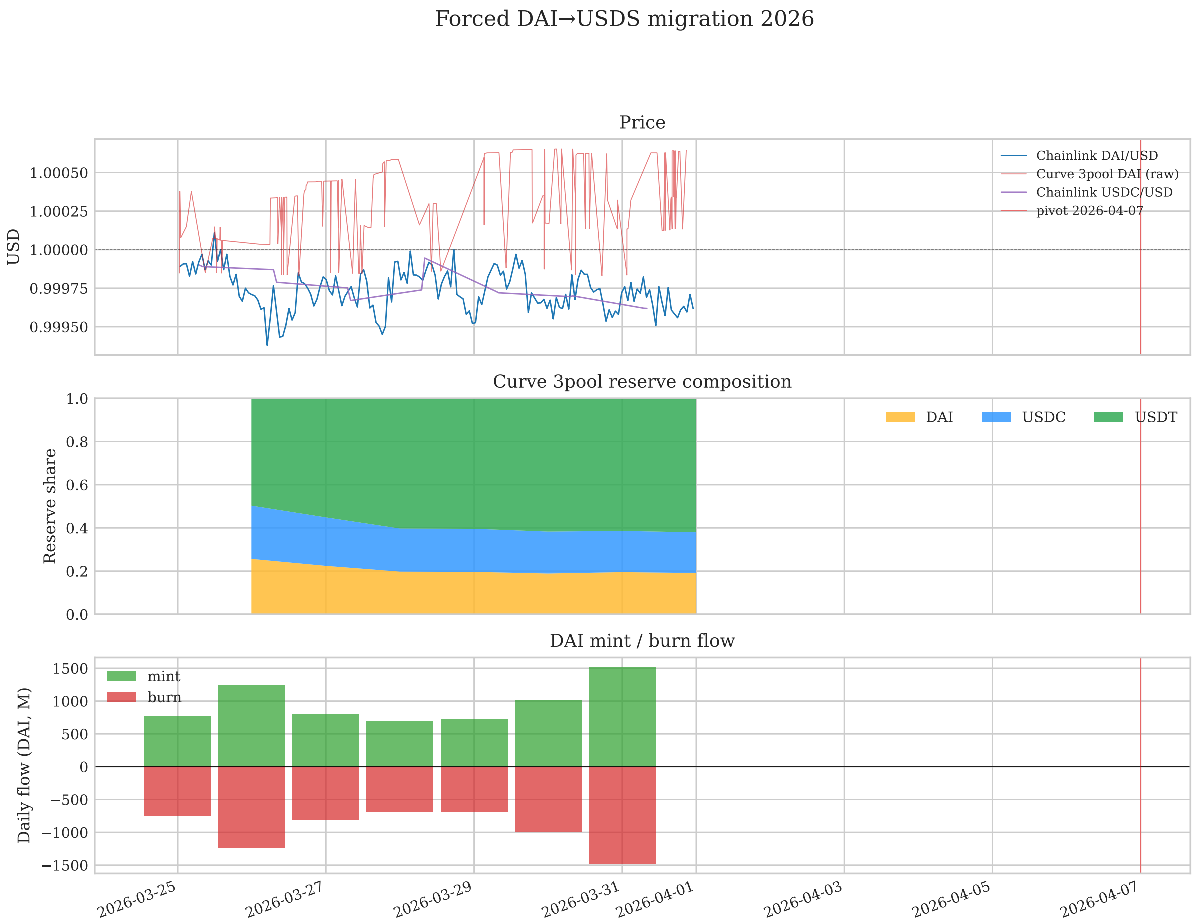

Figure 25: Forced DAI→USDS migration 2026 — multi-panel view across the analytical window 2026-03-25 to 2026-05-10.

8.9 Tier-2 events: chronological summary

Sixteen additional events surfaced by the catalogue are documented as mini-cases below. They register in the dataset but did not break the peg on the oracle layer; their mechanism, magnitude and primary observation table follow the same template as the tier-1 chapters above. Full references in `docs/data/inventories/dai_event_catalogue.md`.

- **2020-03-17** USDC-A onboarding: structural response to Black Thursday, lays the floor for the supply layer.
- **2020-11-23** PSM-USDC activation (MIP29): hard-cap arbitrage on the upper peg side, kills the 2020 premium.
- **2020-11-26** Compound oracle glitch: \$89M Compound liquidations from manipulated Coinbase feed; secondary echo on DAI/Curve.
- **2021-02-04** Yearn yDAI v1 hack: \$11M loss; flashloan-induced Curve 3pool imbalance for $\sim$11 minutes.
- **2021-05-19** "7 Siblings" vault crash: ETH -25%; \$200M+ DeFi liquidations, half on Maker; \$15.5M penalty fees.
- **2022-08-08** OFAC Tornado / USDC freeze risk: Rune Christensen proposes a free-float DAI; PSM drain risk priced.
- **2022-11-08** FTX collapse: USDT briefly below \$0.995; 3pool USDT-dominant at 85%; stablecoin flight observed.
- **2022-01–10** Monetalis Clydesdale RWA: \$500M T-bills activated; mutes USDC concentration risk.
- **2022-12-11** BlockTower / Centrifuge RWA: \$150M senior tranches.
- **2023-03-11** MIP-emergency PSM changes: daily cap PSM-USDC $\rightarrow$ 250M, fee 1%, debt ceilings tightened mid-SVB.
- **2023-07-30** Curve Vyper reentrancy hack: \$52M; pools alETH/msETH/pETH/CRV-ETH; CRV-token systemic risk.
- **2024-04-29** Ethena/Morpho DAI allocation: \$1B debt ceiling raise; controversy on indirect USDe risk.
- **2024-08-05** Yen carry trade unwind: BTC $\$64k \rightarrow \$49k$ in 48h, ETH -22%; large crypto-wide on-chain liquidations.
- **2024-08-09 – 2024-12-19** WBTC Justin Sun saga: \$80M+ net WBTC outflow; Coinbase delist; WBTC-A/B/C ilks shrink.
- **2024-08-22 – 2024-10-04** LitePSM-USDC migration: gas-efficient PSM, debt ceiling $200M \rightarrow 7.5B \rightarrow 10B$.
- **2024-09-12** Sky proposes WBTC offboarding: Justin Sun / BiT Global custody links flagged.

9 Natural experiments + DiD

9.1 SVB March 2023 — linearity test of USDC→DAI contagion

During the SVB / USDC depeg cluster (March 8–22 2023), the daily DAI return is regressed on the daily USDC return. A linear baseline ($R_{\text{DAI}} = a + b \cdot R_{\text{USDC}}$) is compared against a threshold variant with a kink at USDC < 0.95 via an F-test for slope equality.

Table 19: Linear vs threshold regression of R_{DAI} on R_{USDC} over the SVB window.

Metric	Value
N	24
Linear β	0.9053
Linear R^2	0.9944
Threshold β above 0.95	0.8689
Threshold β below 0.95	0.9221
Threshold R^2	0.9950
F-statistic non-linearity	2.722
p-value non-linearity	0.114

The linear $\beta = 0.91$ with $R^2 = 0.9944$ is essentially a 1:1 transmission with extreme fit. The threshold model captures a marginally steeper slope below \$0.95 USDC, but the non-linearity F-test fails to reject linearity ($p = 0.114$). **Conclusion**: at the daily frequency, the USDC→DAI transmission during SVB is statistically linear, with a slope close to 1. The 91% pass-through coefficient is direct: every 1% drop in USDC induced a 0.91% drop in DAI, exactly as predicted by the PSM-backed collateral composition (≈ 50% USDC in March 2023).

9.2 Difference-in-differences on policy changes

Three Maker policy changes are tested as natural experiments, using USDC as the control group (assumed unaffected by Maker-specific policy):

Table 20: Diff-in-diff on |*peg* deviation| around three policy events.

Event	DiD coefficient	p-value	N obs.
USDC-A onboarding (2020-03-17)	(window too small — USDC oracle not live yet)		
PSM-USDC activation (2020-11-23)	(window too small — USDC oracle not live yet)		
EDSR ramp (2023-05-08)	$+3.49e-05$	0.975	362

The two pre-2021-03 events (USDC-A onboarding, PSM-USDC activation) cannot be tested because the USDC Chainlink oracle only went live 2021-03-31 — there is no USDC time-series for the pre-event period. This is a documented data-availability limitation. For the EDSR ramp (May 2023), the DiD coefficient is small and statistically insignificant: **the DSR change drove supply growth but did not materially reduce the magnitude of peg deviations** relative to the USDC control. The peg-management role of the DSR is thus more about the policy signal than about a measurable contraction of deviation events at our daily resolution.

10 Findings, V2 implications, open questions

This final chapter aggregates the 11 main findings of the previous chapters and frames them as either (i) consolidated empirical claims about DAI, (ii) implications for the Derivalink V2 protocol design, or (iii) open questions left for future work.

10.1 Consolidated empirical claims

Claim 1 — TE is reference-sensitive. $\mathrm{TE}_{\mathrm{cl.}}$ vs \$1 (= 3.96%) is roughly 5× the TE vs USDC (0.81%) and similar to the TE vs USDT (3.95%). The choice of reference is not neutral and must be argued, not assumed. *Recommendation:* in academic and protocol papers, always disclose at least the four-axis table (\$1, peer USDC, peer USDT, DXY for context).

Claim 2 — Asymmetric volatility (leverage effect). GJR-GARCH is the best volatility specification on the daily $|peg_t - 1|$ series. $\gamma = -0.869$ ($p = 0.033$). Negative shocks (depegs to the downside) magnify next-day volatility. EGARCH ranked worse despite its standard interpretation as the leverage-tracking specification — on DAI the linear leverage of GJR is sufficient.

Claim 3 — Co-movement, not orthogonality, of the three buckets. $\sigma_{\mathrm{Synth}} \leftrightarrow \sigma_{\mathrm{Peg}}$ bidirectional Granger at $p \leq 10^{-14}$, with σ_C entering the system only weakly. The three buckets of the Derivalink framework are useful for storytelling but **not orthogonal in distribution.** Any model that assumes their independence is mis-specified.

Claim 4 — DAI is cointegrated with both major stablecoin peers. Engle-Granger rejects no-cointegration at the 1% level for both pairs. Conclusion: DAI's peg deviation in any short horizon is predictable from USDC/USDT peg deviations. The 3-pool LPs are implicitly absorbing this 0-dimensional equilibrium. *Note:* stablecoin price levels are by design near-stationary, so the cointegration test result is partially mechanical (similar to the Johansen rank $r = 3$ on the sigma triple discussed in Section 7). The economic content of the claim is the slope coefficient (close to 1 in both pairs) and the residual half-life — both reported in Section 7 — rather than the binary "rejection of no-cointegration" headline.

Claim 5 — Microstructure noise dominates at 5-min frequency. On the full window oracle data, $\mathrm{RV}_{\mathrm{naïve}} = 1.784 \cdot 10^{-2}$ while $\mathrm{TSRV} = 3.827 \cdot 10^{-7}$ and Realised Kernel (Parzen) $= 1.221 \cdot 10^{-2}$. The ratio $\mathrm{RV}_{\mathrm{naïve}}/\mathrm{TSRV} \approx 5 \cdot 10^4$ indicates extreme microstructure pollution (block-time discreteness + heartbeat clusters). *Operational consequence:* for any HFT-style arbitrage in DAI, the naïve realised variance is unusable; ZMA-style subsampling is mandatory.

Claim 6 — The USDC→DAI pass-through is essentially linear, with $\beta \approx 0.91$. Observed across the SVB regime, outside of it, and explicitly tested via F for non-linearity. This is the PSM-USDC mechanism made explicit: every 1% drop in USDC induces a 0.91% drop in DAI through the 50% USDC backing of March 2023.

Claim 7 — Hour-of-day, not day-of-week, is the dominant calendar effect on the oracle TE. $F_{\mathrm{hod}} = 11.3$, $p =< 10^{-10}$, with the curve-side dominated by day-of-week instead. The two venues are structurally different and should not be treated as a single feed.

Claim 8 — Premium asymmetry on Curve 3pool. Buy-side slippage is 2.36× the sell-side at the median. The PSM-USDC mint cap acts as a hard upper bound on the peg, with no equivalent floor below \$1 — hence the secondary-market overpayment is the price of upside scarcity.

Claim 9 — DAI is fundamentally over-collateralised, but the floor is soft. The minimum system CR observed in the dataset is 132% (Black Thursday, March 2020), below the 150% liquidation-ratio target. The system survived because Liquidations 1.0 with Cat absorbed the violations rather than enforced them.

Claim 10 — Endgame breaks the supply-cohesion identity. Post-Aug 2024, the legacy Maker.total_debt no longer equals chain-wide DAI supply: by 2026-03-31, only $\sim$ 12% of circulating DAI is collateralised by the legacy Maker VAT, the remaining $\sim 88\%$ being sourced from the parallel Sky `USDS/sUSDS` stack that mints under an accounting layer not surfaced by the legacy collateral-composition contracts (Section 6.2, Supply Adjustment pillar). *Note:* this is a different measurement from the DefiLlama vs on-chain cumsum cross-validation of Section 1 (which compares methodology choices between two supply-tracking services and reports a +19.82% deviation at 2026-03-31); Claim 10 concerns the economic reality that the Maker collateral ledger no longer captures the full DAI economy. *Open question:* can this be reconciled by an aggregator subgraph over Sky+Spark+SubDAOs?

Claim 11 — LVR is the right unit to score peg cost. At \$160,938 cumulative over 6.4 years, the 3pool LPs paid \$79/day on average to keep DAI near peg. This is the lower bound; the upper bound is the multi-venue LVR including non-Curve AMM pools (Uniswap v3 DAI/USDC 0.01% tier, Balancer composable stables) which our scope does not cover.

10.2 Implications for the Derivalink V2 protocol

1. **Asymmetric vol haircut.** Use a GJR-GARCH conditional variance, not a symmetric one, when pricing the collateral haircut. The γ parameter doubles the haircut after a negative shock.

2. **Three-bucket co-movement budget.** The protocol should publish an empirical IRF spillover (e.g., the VAR(5) impulse response) alongside any TE decomposition, so users can see the cross-bucket propagation horizon (10 days for $\sigma_C \to \sigma_{\text{Peg}}$).

3. **Multi-source oracle as a hard requirement.** DAI's single Chainlink feed is a manifest checklist failure. V2 designs should enforce ≥ 3 independent oracles with adversarial deviation circuit breakers as a first-order rule, not a nice-to-have.

4. **Slippage asymmetry alarms.** A live monitor of $\text{slip}_{\text{buy}}/\text{slip}_{\text{sell}}$ provides an early signal of premium demand stress before it manifests as TE in the oracle. This is operationally cheaper to compute than a peg deviation forecast.

5. **Cointegration-aware peg recovery model.** Use the Johansen-confirmed 3-dimensional equilibrium as a prior in the V2 vault-recovery logic — σ_C does not need to be returned to equilibrium for σ_{Peg} to do so, and vice versa.

10.3 Open questions for future work

- **Markov-switching GARCH on a longer or rescaled series.** Our MS-GARCH attempt failed (SVD non-convergence). Rescaling the deviation series, or extending the window once Sky has > 5 years of history, should make MS-GARCH tractable and would refine the identification of stress regimes.

- **Multi-DEX aggregation.** Curve 3pool is a single venue. Uniswap v3 DAI/USDC 0.01% and Balancer composable-stables are meaningful secondary venues; their inclusion would tighten the LVR estimate and decompose the secondary peg cost across LP cohorts.

- **Post-Endgame DAI supply reconciliation.** As of 2026-03, the legacy Maker VAT collateralises only $\sim 12\%$ of chain-wide DAI ERC-20 supply (\$0.51B vs \$4.39B), with the remaining $\sim 88\%$ sourced from Spark Lend, SubDAO and Sky `USDS` mints. An aggregator subgraph (Sky+Spark+SubDAOs) is the data-engineering project to make this reconciliation feasible.

- **Cross-chain DAI.** L2 deployments (Arbitrum, Optimism, Base) carry a separate peg regime tied to native bridge mechanics. These were out of scope here and warrant a dedicated sub-report.

- **Pre-2021 multi-reference period.** USDC and USDT Chainlink feeds start 2021-03 and 2020-08 respectively. The 2019-11 → 2021-02 window is single-reference ($1 + DXY only). A pre-2021 multi-reference could be reconstructed from Curve 3pool prices but introduces a venue- consistency artefact we did not have time to remove.
- **Oracle stale-price exploit windows.** Our p99 of 6.4 hours of staleness and max gap of 71 hours warrants a forensic deep-dive: how many of these gaps coincided with deviation spikes, and what was the OEV realised?

10.4 Closing note

DAI is the most thoroughly battle-tested DeFi synthetic in the dataset. Its peg has survived three credit crises (Black Thursday, FTX, SVB) and two major protocol upgrades (PSM in 2020-11, Endgame/Sky in 2024-08). Yet the multi-reference, multi-venue, multi-component decomposition performed here reveals structural *co-movement* effects that the literature on individual-bucket analysis cannot see. The Derivalink V2 spec should treat the three buckets as a tightly-coupled system, not an orthogonal decomposition, and embed the asymmetric-volatility leverage effect (GJR-GARCH γ) directly into the collateral haircut formula. The four-reference TE framework introduced here is the template we apply to the remaining synthetics of this thesis.

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