From Asset Encumbrance to Programmable Collateral: Covered Bonds, Tokenised Market Infrastructure and Bank Funding Resilience in Europe

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Abstract

This paper investigates a two-part puzzle. Why did mature European covered-bond markets preserve issuance continuity when banks moved away from extraordinary central-bank support, and why has greater digital-market-infrastructure readiness not yet translated into visibly stronger covered-bond funding outcomes? The analysis separates the established funding channel from the emerging technology layer. A country-year panel for 2015-2024, constructed from European Covered Bond Council statistics, relates ex ante market maturity to issuance intensity in the 2022-2024 funding-normalisation window. A prospective Programmable Collateral Readiness Index (PCRI) then assesses legal digital-securities readiness, wholesale settlement capacity, cover-pool disclosure and market maturity in eight jurisdictions. Mature markets maintained mean issuance intensity at 20.9%, while less mature markets declined from 28.5% to 20.6%, producing a raw difference-in-differences of about 9.1 percentage points. In country and year fixed-effects models, a one-standard-deviation higher maturity score is associated with a 4.8 percentage point relative increase in issuance intensity (clustered $p=0.130$; wild-cluster bootstrap $p=0.156$). The coefficient remains positive in every leave-one-country-out estimate. Mechanism diagnostics indicate that pre-existing benchmark access, and to a lesser extent issuer breadth, account for more of this pattern than market size alone. The PCRI pilot identifies a programmable-collateral conversion gap: technology-and-transparency readiness is not positively correlated with realised issuance continuity. The contribution is a conversion-capacity mechanism. Market depth, recurring access and investor recognition sustain the funding channel; programmability can enhance that channel through verifiable data and safe settlement, but cannot substitute for it. Asset encumbrance remains a prudential boundary condition rather than a technological problem.

Keywords: covered bonds; asset encumbrance; programmable collateral; tokenisation; bank funding; market infrastructure; financial stability

JEL classification: G21; G23; G28; E44; E52; O33

Author declaration. The views expressed in this paper are solely those of the author and do not represent the position of any employer or institution with which the author is affiliated. The empirical analysis uses public data only.

1. Introduction

European covered-bond markets present a revealing puzzle. The withdrawal of extraordinary central-bank support restored the importance of market-based bank funding, yet the adjustment was not uniform. In 2022-2024, the more mature half of the European markets examined in this paper broadly maintained the pace of gross issuance relative to their outstanding stock, while less mature markets retrenched. At the same time, the jurisdictions furthest advanced in digital-securities law and wholesale distributed-ledger settlement did not, as a group, display stronger covered-bond issuance continuity. The first pattern suggests an institutional maturity advantage. The second cautions against a technologically deterministic interpretation of tokenisation.

The question matters because two transformations are occurring simultaneously. The monetary transformation is the normalisation of bank funding after the recalibration and expiry of TLTRO III and the reduction of reinvestments under the APP and PEPP. This process increased the strategic relevance of deposits, unsecured debt, secured market funding and collateral management. The infrastructural transformation is the movement from experiments with tokenised securities towards regulated DLT market infrastructures, interoperability solutions and settlement arrangements anchored in central-bank money. The DLT Pilot Regime created a controlled legal environment, but ESMA found limited uptake and highlighted interoperability and cash-settlement frictions (ESMA, 2025). The Eurosystem subsequently developed a two-track settlement strategy and, from 30 March 2026, accepted qualifying assets issued through DLT-based CSD services as collateral under its existing framework (ECB, 2025b, 2026a).

Covered bonds connect these transformations more directly than most instruments. They are a core European source of secured term funding, based on dual recourse, a segregated and dynamically maintained cover pool, specialised supervision and preferential prudential treatment. At the end of 2024, covered bonds outstanding worldwide reached about EUR 3.3 trillion, of which roughly EUR 2.5 trillion had been issued in the European Union (ECBC, 2025; European Commission, 2025). Yet their stabilising function is inseparable from asset encumbrance. High-quality assets are reserved for secured creditors; this can lower and stabilise funding costs, but it also changes the recovery position of unsecured creditors and may reduce balance-sheet flexibility (CGFS, 2013; Ahnert et al., 2019; García-Appendini et al., 2023).

Tokenisation does not remove that economic trade-off. It may combine asset records, transfer instructions and conditional execution on a programmable platform, thereby reducing reconciliation and lifecycle friction (BIS & CPMI, 2024; BIS, 2025b). It does not create eligible mortgage collateral, legal certainty, investor demand or a safe settlement asset. Recent work on tokenised government and corporate bonds similarly stresses that potential efficiency gains depend on regulatory clarity, infrastructure integration and scale (Aldasoro et al., 2025; ECB, 2026c). For covered bonds, the

relevant unit of analysis is therefore not the digital bond certificate alone. It is the institutional chain from asset eligibility and cover-pool registration through disclosure, issuance, settlement, collateral mobilisation and supervision.

This paper calls the ability to operate that chain through reliable rule-based infrastructure programmable collateral. The concept is deliberately narrower than a general claim about smart contracts. Collateral becomes programmable when legally effective claims and sufficiently standardised data can support verifiable eligibility, controlled lifecycle actions, interoperable settlement and supervisory observability. Such capability is potentially valuable, but it is conditional on the credibility of the underlying funding channel. The central research question is therefore: why does established covered-bond market maturity support issuance continuity during funding normalisation, and under what conditions can digital infrastructure convert that analogue resilience into programmable-collateral capacity?

The research design separates what can be tested retrospectively from what can only be assessed prospectively. The retrospective component uses a harmonised panel of seventeen European covered-bond markets for 2015-2024. An ex ante maturity index, measured over 2015-2019, combines market scale, issuer breadth, benchmark access and public-market orientation. Country and year fixed-effects models test whether this maturity predicted relative issuance continuity in 2022-2024. Robustness analysis uses an alternative maturity classification, a 2023 start date, log issuance, an event-study specification, leave-one-country-out estimates and a wild-cluster bootstrap suited to the small number of clusters. The prospective component constructs an auditable pilot PCRI for eight jurisdictions from legal, settlement, disclosure and market evidence available up to early 2026. PCRI is explicitly not used as a historical treatment variable.

Three results organise the article. First, the raw maturity-group comparison yields a 9.1 percentage point relative difference in issuance intensity between the pre-normalisation and normalisation windows. The baseline fixed-effects coefficient is positive and economically material, although statistically imprecise: 0.048 with a clustered p-value of 0.130 and a wild-cluster p-value of 0.156. Its sign is positive in every leave-one-country-out estimate. Second, mechanism diagnostics indicate that benchmark access has the clearest individual association with the post-2022 continuity differential, while issuer breadth is also positive; scale alone is not. Third, the PCRI pilot shows no positive cross-sectional relationship between digital readiness and realised issuance intensity. This is interpreted as a conversion gap, not as evidence that digital infrastructure lacks value.

The paper contributes in three ways. It first reframes covered-bond resilience as a conversion-capacity mechanism: recurrent market access, issuer breadth and investor recognition reduce the fixed and coordination costs of returning to market under changing conditions. Second, it disciplines the tokenisation debate by treating programmability as an option-enhancing layer rather than a substitute

for institutional market depth. Third, it distinguishes the empirical question of funding-channel continuity from the prudential question of asset encumbrance. The available country-market data can examine the former, but they cannot credibly identify an encumbrance threshold; that requires bank-level encumbrance ratios and unsecured funding prices. This boundary is made explicit rather than approximated by a weak proxy.

The remainder of the paper develops the mechanism, derives the testable implication, presents the data and methods, reports the panel and PCRI results, discusses Central and Eastern Europe and Poland, and concludes with implications for covered-bond policy and European digital-market infrastructure.

2. Mechanism and related literature

2.1. Covered-bond maturity as conversion capacity

Covered bonds solve a funding problem through institutional design. Dual recourse and segregation of the cover pool protect investors; programme supervision and disclosure reduce information asymmetry; regulatory treatment supports a broad institutional investor base. These features can improve liquidity and pricing, as documented around covered-bond purchase programmes and across government and covered-bond markets (Beirne et al., 2011; Dick-Nielsen et al., 2012). The instrument has also become institutionally embedded as a European alternative to mortgage securitisation (Skyrman, 2024).

However, the existence of covered-bond legislation is not equivalent to a resilient funding channel. Issuance requires a stock of eligible assets, a functioning programme, legal and operational documentation, internal governance, ratings, hedging, investor communication and access to settlement and dealer networks. Many of these costs are fixed or quasi-fixed. A market with recurring issuers and benchmark transactions repeatedly pays and learns those costs; investors maintain credit lines and analytical coverage; intermediaries preserve distribution capacity. A market that issues only sporadically must rebuild much of this coordination when conditions change.

This logic defines conversion capacity: the ability to convert eligible balance-sheet assets into marketable term funding at the time the issuer needs it. Four pre-existing market characteristics support that ability. Scale increases the asset and issuance base. Issuer breadth prevents the market from depending on one programme. Benchmark access signals that issues can reach a broad public investor base. Public-market orientation preserves price discovery and observable transaction standards. Together, they make covered bonds a repeatable funding technology rather than an occasional legal possibility.

The mechanism predicts resilience as continuity, not necessarily growth. A mature market may maintain a stable outstanding stock while refinancing redemptions; a small market can show high

percentage growth from a low base. Gross issuance relative to lagged outstanding stock is therefore the primary outcome. It measures whether the channel remains active relative to the funding stock that must ultimately be refinanced. It is not a comprehensive measure of bank resilience, but it is closely aligned with the institutional mechanism studied here.

2.2. Asset encumbrance as a prudential boundary condition

Secured funding reallocates claims on the bank balance sheet. Theoretical work shows that encumbrance can improve funding capacity in normal states while increasing fragility or unsecured-creditor subordination in stress (Ahnert et al., 2019). European disclosure evidence and bank-level studies likewise identify heterogeneous risk effects depending on funding structure, business model and the use of covered bonds (Banal-Estañol et al., 2021; García-Appendini et al., 2023). The Norwegian introduction of covered bonds affected bank behaviour and the distribution of funding and assets, illustrating that legal access to the instrument can have real balance-sheet consequences (Cao et al., 2025).

Encumbrance is therefore a boundary condition on conversion capacity. A system should be able to mobilise collateral without treating every eligible asset as costless funding capacity. Prudential analysis must retain visibility over the assets committed to cover pools, central-bank operations, repo, derivatives and other secured claims. Recent EBA risk assessments report an increase in the aggregate asset-encumbrance ratio and substantial cross-country dispersion, reinforcing the importance of this constraint (EBA, 2025b, 2026).

The distinction has a methodological consequence. Market maturity is not an encumbrance ratio. A large and liquid covered-bond market may coexist with conservative overcollateralisation and strong balance-sheet capacity, while a smaller bank may be highly encumbered. This article therefore does not infer an encumbrance turning point from the square of a market-maturity index. It uses the encumbrance literature to define the prudential boundary and reserves empirical threshold analysis for future bank-level work.

2.3. Programmability and the conversion gap

Tokenisation can compress functions that are separated in conventional infrastructure. A programmable platform may combine asset representation, transfer, conditional execution and settlement, reducing manual reconciliation and allowing atomic delivery-versus-payment (BIS & CPMI, 2024; BIS, 2025a, 2025b). The monetary anchor is central. Tokenised central-bank money or interoperable access to central-bank settlement preserves finality and the singleness of money, whereas fragmented private settlement assets may create additional credit, liquidity and redemption risks.

Europe is moving towards that infrastructure, but the transition remains incomplete. ESMA reported only three authorised infrastructures and minimal live activity by mid-2025, identifying legal uncertainty, thresholds, interoperability and access to central-bank money as obstacles (ESMA, 2025).

The authorised set subsequently expanded, but scale remains modest (ESMA, 2026). The Eurosystem's 2024 trials settled almost EUR 1.6 billion across more than fifty experiments and trials, and the Pontes/Appia programme aims to connect DLT transactions to central-bank money and a more integrated digital asset ecosystem (ECB, 2025a, 2025b, 2026b).

For covered bonds, digital form can generate value at several points: the liability can be issued and transferred digitally; cover-pool data can be standardised and verified; eligibility and concentration rules can be monitored more rapidly; settlement and collateral mobilisation can be synchronised. Yet these functions become economically relevant only when linked to an investable and recurrent market. A live DLT venue without a broad investor base does not create benchmark funding. Conversely, a mature analogue market can remain resilient without DLT, although it may forgo future process efficiencies.

This yields the paper's second concept: the programmable-collateral conversion gap. The gap is the distance between possessing digital legal or settlement capability and converting that capability into observable funding outcomes. It should be widest where infrastructure is advanced but issuance remains small or irregular, and also where a deep analogue market has not yet integrated digital settlement. The gap is expected during transition and does not imply technological failure.

3. Testable implication and analytical propositions

H1. During the 2022-2024 funding-normalisation window, countries with higher ex ante covered-bond market maturity experience a smaller decline or a larger increase in issuance intensity than less mature markets.

H1 is a relative prediction. It does not imply that mature markets always issue more relative to their stock, or that the 2022-2024 window is an exogenous treatment. It predicts that a recurrent, institutionally recognised market can keep converting assets into term funding when extraordinary central-bank support is reduced and funding conditions change.

The mechanism also yields a diagnostic expectation. If conversion capacity is the relevant channel, benchmark access and issuer breadth should explain more of the post-window differential than scale alone. Benchmark issuance proxies broad investor access and repeatable public execution; issuer breadth proxies organisational depth and reduces dependence on a single programme. These component tests are exploratory because the four maturity dimensions are correlated.

Finally, the conceptual framework yields two prospective propositions. First, legal or settlement readiness alone need not correlate with current covered-bond issuance, because digital capacity is not yet a mature funding technology. Second, the long-run value of programmability should be complementary to market maturity: digital infrastructure is most likely to affect funding when it connects a recurrent instrument, standardised collateral data and safe settlement. The PCRI analysis diagnoses these propositions; it does not causally test them.

4. Data and empirical design

4.1. Covered-bond panel and outcome variables

The primary dataset is manually harmonised from the statistical chapter of the European Covered Bond Fact Book 2025, which reports market statistics through the end of 2024 (ECBC, 2025). The descriptive sample covers Austria, Belgium, Czechia, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, the Netherlands, Norway, Poland, Slovakia, Spain and Sweden. Romania is excluded because the extracted series records only a one-off issue and does not provide a continuous market. Estonia is retained in descriptive analysis but excluded from specifications requiring a 2015-2019 maturity score.

The raw series include year-end covered bonds outstanding, annual gross issuance, benchmark and other public issuance, private placements, programme and issuer counts, and mortgage or public-sector composition. All reported amounts follow the ECBC EUR million convention. The main dependent variable is issuance intensity, defined as gross issuance divided by lagged outstanding stock. Secondary outcomes are annual stock growth, benchmark share, private-placement share and the logarithm of gross issuance. Issuance intensity and stock growth are winsorised at the first and ninety-ninth percentiles in regression analysis to reduce the influence of very small denominators and transcription anomalies.

The funding-normalisation indicator equals one for 2022-2024. October 2022 marked the recalibration of TLTRO III terms; APP reinvestments ended in June 2023 and PEPP reinvestments were discontinued at the end of 2024 (ECB, 2022, 2023, 2024). The indicator is a regime marker, not a treatment assignment. It coincides with rate increases, inflation, mortgage-market changes and geopolitical shocks. Year fixed effects absorb common shocks, but country-specific exposures remain a source of confounding.

Table 1. Variables and measurement

Variable	Definition	Unit	Source
Outstanding	Year-end covered bonds outstanding	EUR million	ECBC Fact Book 2025
Gross issuance	Annual covered-bond issuance	EUR million	ECBC Fact Book 2025
Issuance intensity	Gross issuance / lagged outstanding	Ratio	Author calculations
Outstanding growth	Annual change in outstanding stock	Ratio	Author calculations

Variable	Definition	Unit	Source
Benchmark share	EUR benchmark issuance / gross issuance	Ratio	Author calculations
Private share	Private placements / gross issuance	Ratio	Author calculations
Maturity index	Mean z-score of scale, issuers, benchmark share and public share, measured in 2015-2019	Standardised	Author calculations
Normalisation window	One for 2022-2024	Binary	ECB policy chronology
PCRI	Legal + settlement + disclosure + market maturity	0-12	Official EU/national sources and ECBC

Note. The market panel contains no confidential or proprietary bank-level information.

4.2. Ex ante market-maturity index

Market maturity is measured before the normalisation window to avoid using the outcomes being explained in the classification. Four country characteristics are averaged over 2015-2019: log covered bonds outstanding, log number of issuers, benchmark issuance share and public issuance share. Each component is standardised across countries and the index is their unweighted mean. Equal weights avoid optimising the index to the post-2022 outcome. A binary mature-market indicator identifies the top half of the distribution for transparent group comparisons.

The index is an institutional proxy rather than a structural model. Scale captures the market base; issuer breadth captures organisational capacity; benchmark share captures access to broad public placement; and public share distinguishes observable market issuance from private funding. Appendix A reports all scores. Germany, Norway, Sweden and Denmark rank highest; Hungary, Czechia, Slovakia and Ireland rank lowest. Poland is below the sample mean despite a well-developed specialist legal model, reflecting smaller scale and less recurrent benchmark access.

4.3. Econometric specification and inference

The baseline country and year fixed-effects model is:

$$Y_{it} = \alpha_i + \lambda_t + \beta(Maturity_i \times Normalisation_t) + \gamma\, ln(Outstanding_{i,t-1}) + \varepsilon_{it}$$

Country fixed effects absorb the time-invariant maturity level; year fixed effects absorb common market shocks. The coefficient β captures whether countries with higher pre-period maturity experienced relatively different outcomes in 2022-2024, conditional on lagged market size. Standard errors are clustered by country. Because the analysis uses only sixteen incumbent-market clusters, conventional cluster inference can be unreliable. The paper therefore reports a restricted wild-cluster bootstrap-t p-value for the main coefficient.

Robustness tests replace the continuous score with a top-half indicator, move the window start to 2023, use log gross issuance as the outcome, and estimate year-specific maturity interactions with 2021 omitted. Leave-one-country-out estimates assess whether the result is driven by a single market. Mechanism diagnostics interact each pre-period maturity component separately with the normalisation window. A joint component model is reported in Appendix D but interpreted cautiously because the components are correlated and the sample is small.

4.4. Programmable Collateral Readiness Index

The PCRI is a prospective institutional diagnostic for Austria, Czechia, Denmark, France, Germany, Italy, Poland and Spain. The selection captures mature and catch-up markets, specialist and universal-bank settings, and different forms of digital-market participation. Evidence is current to early 2026 and is not back-cast into the panel.

Four pillars are scored from zero to three. Legal readiness reflects the clarity and operational use of rules for digitally represented securities beyond the minimum EU baseline. Settlement readiness reflects authorised DLT infrastructure, an operational national route or participation as a Eurosystem solution provider. Disclosure readiness reflects the standardisation and accessibility of programme-level cover-pool information; it does not assert that data are fully machine executable. Market maturity reflects recurrent issuance, issuer breadth, benchmark orientation and investor access. The first three pillars form a technology-and-transparency sub-index from zero to nine; the total PCRI ranges from zero to twelve.

Scoring follows an evidence hierarchy: enacted law, authorisation or live infrastructure ranks above consultation, experimentation or policy intent. Appendix C records the evidence used. The index is transparent but remains an expert coding exercise. Leave-one-pillar-out and alternative-weight checks produce rank correlations of approximately 0.91-0.99 with the baseline ranking; these diagnostics indicate ordinal stability, not measurement precision. With eight countries, correlations with market outcomes are descriptive.

5. Results

5.1. Market growth and descriptive evidence

Across the selected markets, covered bonds outstanding increased from approximately EUR 2.05 trillion in 2015 to EUR 2.60 trillion in 2024. Gross issuance was cyclical: it declined through 2017, recovered before the pandemic, and increased sharply in 2022 and 2023 before moderating in 2024. This pattern is consistent with a renewed need for market refinancing, but it also reflects redemptions, mortgage origination, interest rates, currency translation and national issuance strategies. The aggregate series cannot identify a monetary-policy effect.

The analysis sample is highly heterogeneous. Average outstanding stock is EUR 137.6 billion, but observations range from less than EUR 1 billion to more than EUR 500 billion. The mean issuance intensity is 0.229 and the standard deviation is 0.152. Benchmark and private shares each average about 43%, illustrating that public benchmark funding and private placements are both important parts of the European market.

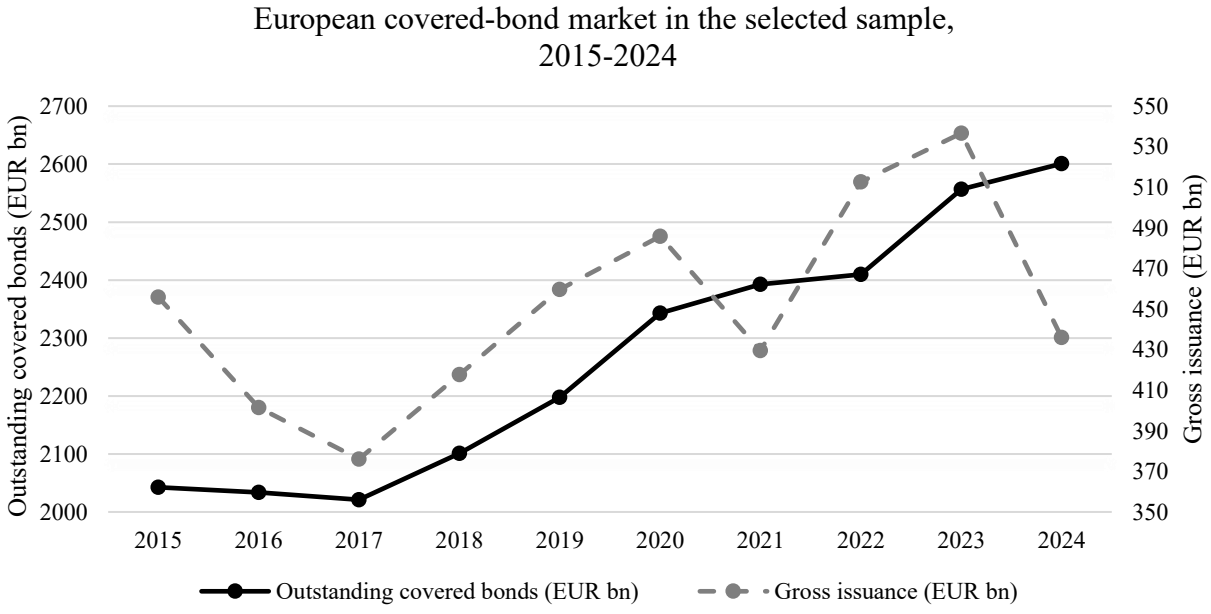

Figure 1. Covered bonds outstanding and gross issuance in the selected European sample, 2015-2024.

Source: author calculations based on ECBC (2025).

Table 2. Descriptive statistics

Variable	N	Mean	Std. dev.	Min.	Max.
Outstanding (EUR mn)	165	137,573	143,710	850	501,609

Variable	N	Mean	Std. dev.	Min.	Max.
Gross issuance (EUR mn)	161	28,020	35,742	22	173,298
Issuance intensity	144	0.229	0.152	0.056	0.900
Outstanding growth	148	0.065	0.165	-0.262	0.770
Benchmark issuance share	161	0.434	0.305	0.000	1.000
Private-placement share	161	0.430	0.347	0.000	1.000
Number of issuers	165	15.2	18.2	2	84

Note. Winsorised issuance intensity and stock growth are used in regressions. The table reports the corresponding analysis-sample ranges.

5.2. Market maturity and issuance continuity

The raw comparison provides the most intuitive evidence. In the mature half of the sample, mean issuance intensity was 19.7% in 2016-2021 and 20.9% in 2022-2024. In less mature markets it fell from 28.5% to 20.6%. The implied relative difference is about 9.1 percentage points. Mature markets did not have a higher issuance ratio before normalisation; they preserved the channel while the less mature group reduced issuance relative to its stock.

The same comparison clarifies why growth is not the primary resilience measure. Less mature markets grew faster from a smaller base in both periods. Mature markets were more benchmark-oriented and less dependent on private placements. The evidence is consistent with recurring public-market access as an institutional shock absorber, although the group split is descriptive and does not control for country-specific shocks.

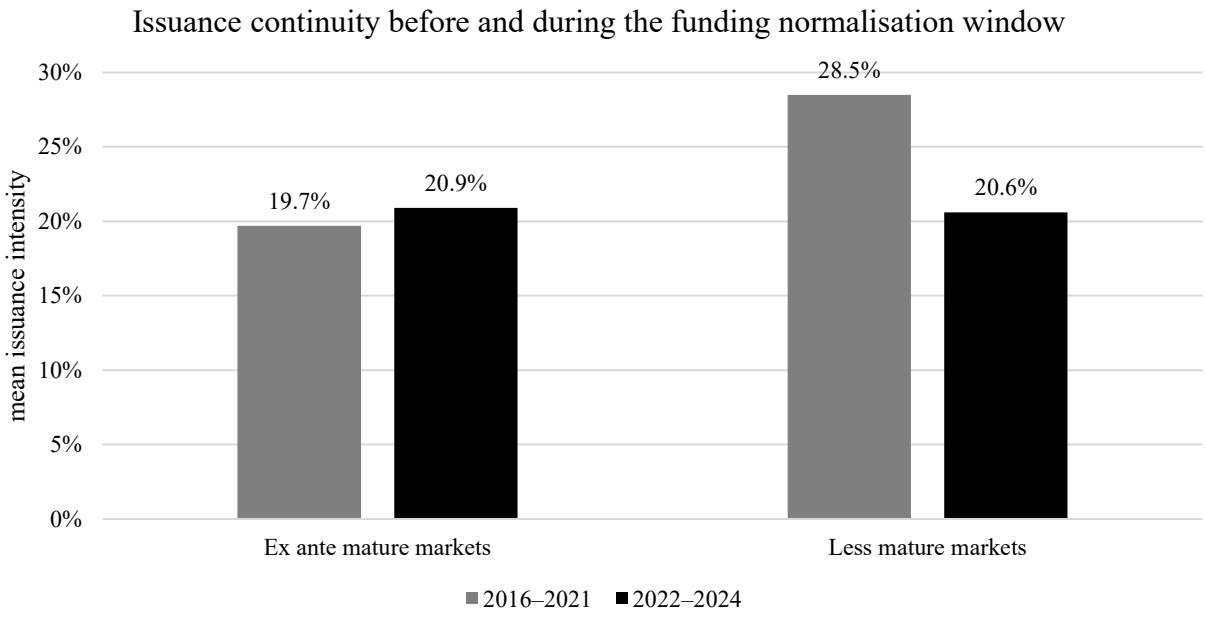

Figure 2. Issuance intensity before and during the funding-normalisation window.

Source: author calculations based on ECBC (2025). Mature markets are the top half of the 2015-2019 maturity distribution.

Table 3. Market outcomes by ex ante maturity group

Group	Period	Issuance intensity	Stock growth	Benchmark share	Private share
Less mature	2016-2021	0.285	0.120	0.246	0.598
Less mature	2022-2024	0.206	0.059	0.350	0.543
Mature	2016-2021	0.197	0.032	0.560	0.309
Mature	2022-2024	0.209	0.028	0.620	0.255

Note. Values are unweighted country-year means. Growth rates are sensitive to small starting stocks.

5.3. Fixed-effects estimates and robustness

The baseline maturity-by-normalisation coefficient is 0.048. A one-standard-deviation higher ex ante maturity score is therefore associated with an approximately 4.8 percentage point relative increase in issuance intensity in 2022-2024, conditional on country and year fixed effects and lagged market size. The country-clustered p-value is 0.130; the wild-cluster bootstrap-t p-value is 0.156. H1 receives economically meaningful but statistically qualified support.

The conclusion is stable in sign across alternative designs. The binary top-half specification produces a 6.7 percentage point coefficient; starting the window in 2023 gives 4.7 percentage points. The log-issuance specification is also positive but imprecise. More importantly, the baseline coefficient

remains positive when each country is excluded in turn, ranging from 3.1 to 7.0 percentage points. Omitting Poland produces 5.2 percentage points, indicating that the regional case is not driving the result.

The event-study coefficients show no systematic maturity-related differential before 2022. Individual pre-period estimates fluctuate around zero and are imprecise. Post-2021 coefficients are positive in each year, but their confidence intervals are wide. The figure supports the timing of the aggregate pattern while also displaying the central limitation: the sample cannot sharply distinguish a persistent maturity effect from heterogeneous shocks.

Table 4. Main estimate and robustness checks

Specification	Maturity effect	Cluster SE	Cluster p	Additional inference	N	R^2
Continuous maturity; 2022-2024	0.0481	0.0300	0.130	Wild-cluster p=0.156	141	0.390
Top-half indicator; 2022-2024	0.0669	0.0410	0.124	-	141	0.389
Continuous maturity; 2023-2024	0.0467	0.0355	0.209	-	141	0.387
Log gross issuance; 2022-2024	0.1174	0.1636	0.484	-	141	0.903

Note. All models include country and year fixed effects and lagged log outstanding stock. Standard errors are clustered by country. The wild-cluster p-value is based on 4,999 restricted bootstrap draws.

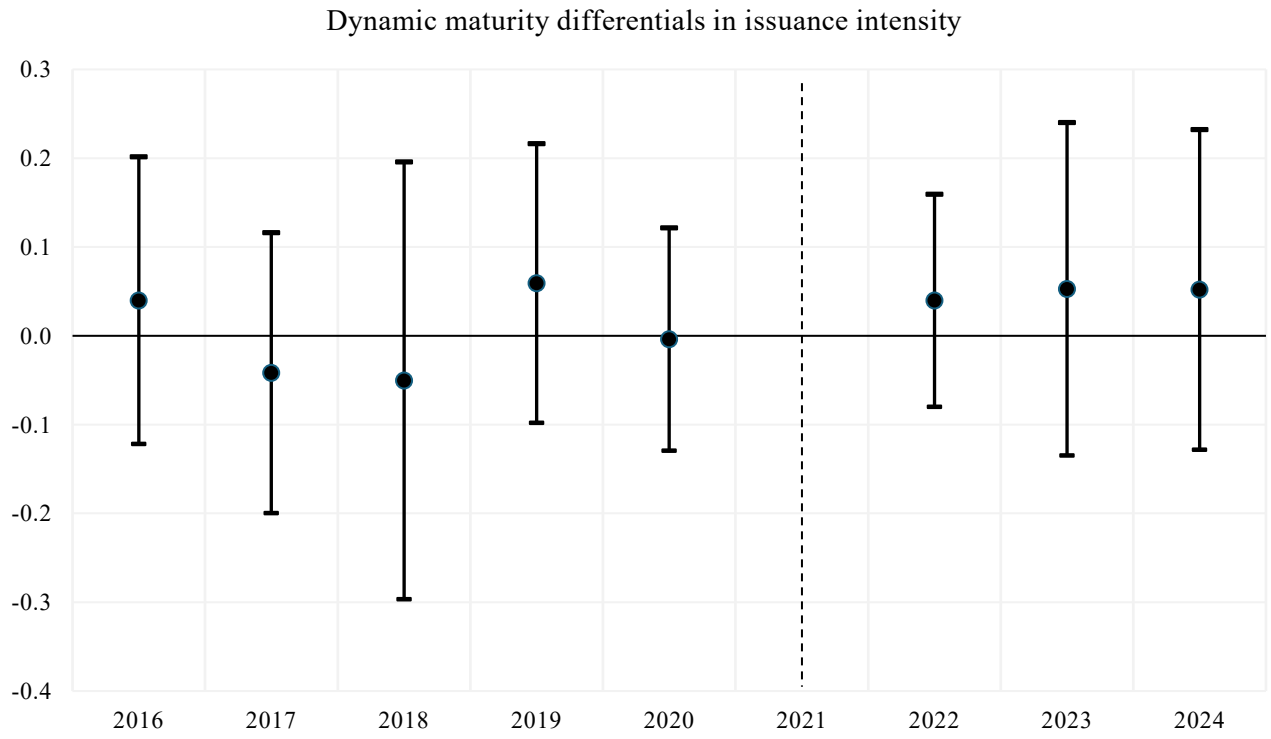

Figure 3. Dynamic maturity differentials in issuance intensity.

Note. Points are year-specific interactions between ex ante maturity and year indicators; 2021 is omitted. Bars show 95% confidence intervals using country-clustered standard errors.

5.4. Which component of maturity matters?

The component diagnostics provide evidence on the proposed mechanism. When each pre-period component is interacted separately with the normalisation window, benchmark share has the largest and most precisely estimated coefficient: 0.0438 with a clustered p-value of 0.031. Issuer breadth is positive at 0.0279, with p=0.104. Market scale and the overall public share are smaller and imprecise.

This pattern is consistent with conversion capacity rather than size alone. Benchmark access indicates that issuers can return to a public, broadly distributed format; issuer breadth indicates that the market infrastructure is used by more than one or two institutions. A large stock can remain outstanding without generating recurring issuance, and the public share can include smaller transactions that do not provide benchmark liquidity. The diagnostics are not independent hypothesis tests, however. The components are correlated, multiple comparisons are present and the joint model is unstable in a small sample. They should be read as mechanism evidence that motivates security-level and issuer-level research.

Table 5. Maturity-component diagnostics

Pre-period component × normalisation	Coefficient	Cluster SE	p-value	Mechanism interpretation
Market scale	0.0209	0.0247	0.412	Stock alone does not ensure recurring access
Issuer breadth	0.0279	0.0161	0.104	Broader organisational use supports continuity
Benchmark issuance share	0.0438	0.0184	0.031	Broad public access is the clearest channel
Public issuance share	0.0147	0.0283	0.611	Public format without benchmark depth is insufficient

Note. Each row comes from a separate model with country and year fixed effects and lagged log outstanding stock. Results are diagnostic and not adjusted for multiple testing.

5.5. PCRI and the programmable-collateral conversion gap

Germany and France receive the highest pilot scores because mature covered-bond markets coexist with developed digital-securities frameworks, authorised infrastructure and Eurosystem settlement participation. Italy and Spain have strong legal and settlement readiness but weaker recent issuance intensity. Denmark is the key counterexample: it has exceptional covered-bond maturity and the highest normalisation-window issuance intensity in the pilot, but a lower technology score because no comparable domestic DLT market infrastructure or Eurosystem solution-provider role was identified. Czechia combines an operational DLT settlement route with a much smaller covered-bond market.

The exploratory relationship does not show that digital readiness has already strengthened the funding channel. The Pearson correlation between the technology-and-transparency sub-index and 2022-2024 issuance intensity is -0.313 (p=0.450); the Spearman correlation is -0.284 (p=0.495). For the total PCRI, the Pearson correlation is -0.047. With eight observations, these statistics are

descriptive. Their value is conceptual: current digital capacity is not a substitute for recurring issuance, mortgage asset supply or investor demand.

The result identifies a conversion gap. Digital law and settlement infrastructure reduce the distance to tokenised issuance and collateral mobilisation, but realised benefits require an instrument that is already investable at scale. Conversely, mature analogue markets can be resilient before they digitalise. The relevant policy task is to connect the two states through interoperable data and settlement, rather than ranking countries on a single technological ladder.

Table 6. Programmable Collateral Readiness Index: pilot application

Country	Legal	Settlement	Disclosure	Market	PCRI	2022-24 issuance intensity
Germany	3	3	3	3	12	0.173
France	3	3	3	3	12	0.236
Italy	2	3	3	2	10	0.140
Spain	3	2	3	2	10	0.107
Denmark	1	1	3	3	8	0.287
Austria	1	2	2	2	7	0.200
Czechia	2	2	2	1	7	0.116
Poland	1	1	3	1	6	0.201

Note. Pillars are scored 0-3 using evidence available up to early 2026. PCRI is prospective and is not used as a historical causal regressor.

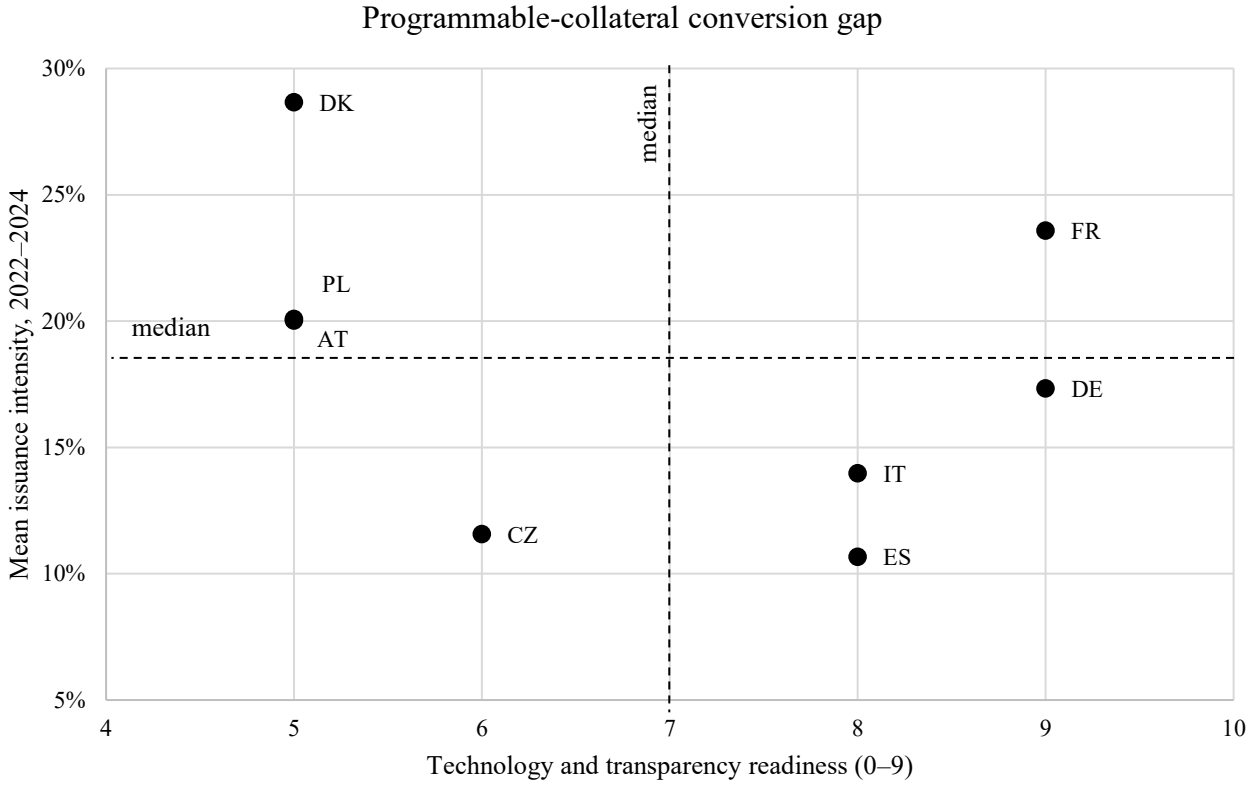

Figure 4. The programmable-collateral conversion gap.

Note. Technology and transparency readiness is the sum of legal, settlement and disclosure pillars. Country codes: AT, CZ, DE, DK, ES, FR, IT, PL.

6. Central and Eastern Europe and the Polish sequencing problem

The CEE markets in the panel - Czechia, Estonia, Hungary, Poland and Slovakia - demonstrate why activity must be separated from depth. In 2022-2024, their average covered-bond stock was approximately EUR 8.2 billion, compared with EUR 206.8 billion in the non-CEE group. CEE issuance intensity and stock growth were higher, but benchmark issuance represented 36.2% of gross issuance compared with 53.0% outside CEE, while private placements represented 47.7% compared with 37.4%. A small market can issue actively without providing the broad benchmark access associated with a resilient cross-cycle funding channel.

The region is not homogeneous. Slovakia expanded its stock strongly and achieved a high benchmark share. Estonia entered from a very low base. Hungary relied more heavily on private placements. Czechia developed an operational DLT settlement infrastructure under the EU Pilot Regime while maintaining a smaller covered-bond market. These combinations support the paper's two-dimensional view: analogue market maturity and digital readiness follow different paths.

Poland is especially instructive. It combines a specialist mortgage-bank model, statutory cover-pool segregation and strong programme disclosure with limited scale and lower benchmark continuity. Outstanding covered bonds declined from EUR 6.18 billion in 2019 to EUR 4.19 billion in 2024; 2022-

2024 issuance intensity averaged 0.201 and benchmark issuance represented about 25.6% of gross issuance. Five issuers were active in 2024. Legal and operational capacity therefore exists, but the market has not yet achieved the scale and recurrent international access of the largest European systems.

The binding constraints are predominantly economic and institutional: the volume and transferability of eligible mortgage assets, the frequency with which issuers can reach the market, relative pricing against government and unsecured debt, currency and interest-rate structures, investor breadth and the economics of a specialist mortgage bank. Digital issuance cannot remove these constraints. It can reduce process friction only after the asset-to-cover-pool-to-issuance chain is sufficiently standardised and recurrent.

The sequencing implication is clear. First, strengthen the analogue channel through predictable asset supply, standardised cover-pool data, repeat issuance, investor development and access to public benchmark formats. Second, make the legal and operational chain compatible with common European digital infrastructure and central-bank-money settlement. This sequence treats tokenisation as an infrastructure investment in a functioning market, not as a substitute for market formation.

Table 7. Selected market benchmarks, 2024 and normalisation-window averages

Country	Outstanding EUR bn	2024 issuance EUR bn	2022-24 intensity	Benchmark share	Private share	PCRI
Poland	4.2	1.4	0.201	0.256	0.172	6
Czechia	15.0	1.3	0.116	0.504	0.496	7
Slovakia	15.0	1.5	0.276	0.730	0.270	n/a
Germany	399.5	57.3	0.173	0.573	0.344	12
Denmark	459.7	121.6	0.287	0.654	0.000	8
France	501.6	68.4	0.236	0.532	0.460	12

Note. Market figures are based on ECBC (2025). PCRI is calculated only for the pilot jurisdictions.

7. Discussion and policy implications

7.1. The object of policy is conversion capacity

The main empirical pattern is not that larger covered-bond markets always issue more. It is that institutionally mature markets were better able to preserve issuance relative to their outstanding stock during the funding-normalisation window. The mechanism evidence points to benchmark access and

issuer breadth, not scale alone. This supports a view of covered bonds as infrastructure: the resilient asset is not only the legal claim, but the network of issuers, investors, intermediaries, data and operating routines that makes the claim repeatedly fundable.

The finding has implications for the review of the EU covered-bond framework. The EBA has recommended greater harmonisation, legal clarity and transparency while preserving the instrument's successful national foundations (EBA, 2025a). Harmonisation should be judged partly by whether it lowers cross-border analytical and execution costs and strengthens recurring investor access. A formally aligned regime that remains small and privately placed may improve legal quality without yet creating conversion capacity.

7.2. Programmability should target the collateral chain, not the digital wrapper

Tokenising the bond liability is the most visible step, but not necessarily the most valuable. Covered-bond operations contain repeated data and control tasks: asset eligibility, valuation, concentration limits, cover tests, substitution, liquidity buffers, hedging and investor reporting. Standardised, machine-readable data could reduce reconciliation and improve timeliness across this chain. The potential gain is an auditable path from eligible mortgage exposure to cover-pool registration, issuance and settlement.

That path requires governance. Automated rules can propagate incorrect valuations or legal classifications faster. Programmability therefore includes change control, human override, cybersecurity, operational resilience and an allocation of legal responsibility. The DLT Pilot experience confirms that infrastructure innovation and regulatory integration must progress together (ESMA, 2025).

The Eurosystem can serve as an adoption anchor. Settlement in central-bank money and collateral eligibility connect digital assets to trusted public infrastructure rather than a separate private liquidity pool. The 2026 eligibility decision is important precisely because qualifying DLT-based assets remain subject to the existing collateral framework and T2S reachability requirements (ECB, 2026a). This is institutional integration, not technological exceptionalism.

7.3. Asset encumbrance remains the limiting constraint

More efficient collateral mobilisation can increase the attractiveness of secured funding. That is beneficial when it diversifies term funding and improves market access, but it can also encourage greater use of encumberable assets. The prudential objective is not maximum collateral velocity. It is efficient mobilisation subject to creditor protection, resolution feasibility and balance-sheet optionality.

Programmability can improve system-wide visibility if data on cover pools, central-bank collateral, repo and derivatives collateral are consistently mapped. It can worsen risk if it only accelerates

pledging within fragmented infrastructures. Supervisors therefore need consolidated encumbrance views and the ability to intervene when automated eligibility or substitution logic produces excessive concentration. The current paper cannot test this threshold; it identifies the information architecture required to test and manage it.

7.4. Financial sovereignty through interoperability

For smaller European economies, financial sovereignty is best understood as reliable access to diversified, market-based long-term funding and common European infrastructure. It is not technological autarky. A domestic proprietary ledger with few investors can deepen fragmentation and vendor dependence. Interoperability with European settlement, legal and data standards is more likely to strengthen the capacity of domestic issuers to mobilise high-quality assets across borders.

The combination of a harmonised covered-bond framework, interoperable digital-market infrastructure and central-bank-money settlement can therefore support the Savings and Investments Union. The policy sequence remains important: market credibility and asset quality first, infrastructure integration second, and automation only where it improves the economic function of the instrument.

8. Limitations and research agenda

First, issuance intensity is a proxy for resilience of the covered-bond funding channel, not resilience of a bank or banking system. Deposits, unsecured debt, intra-group funding, capital, liquidity buffers and central-bank facilities remain outside the outcome. The terminology in the paper is accordingly channel-specific.

Second, the design is associative. The normalisation window coincides with rapid rate increases, inflation, national mortgage-market developments and geopolitical shocks. Country and year fixed effects, ex ante classification and event-study diagnostics reduce but do not eliminate confounding. Sixteen clusters and a short post-window limit statistical power. The positive coefficient is directionally stable, but neither conventional nor wild-cluster inference reaches standard significance thresholds.

Third, ECBC data are country-market aggregates. They cannot identify issuer heterogeneity, changes in overcollateralisation, bank-level asset encumbrance, unsecured funding costs or lending outcomes. Security-level data from commercial databases and supervisory bank-level disclosures would permit a more credible test of the conversion-capacity mechanism and the encumbrance boundary.

Fourth, the maturity index is intentionally simple and ex ante. Equal weighting improves transparency but does not establish that the four components contribute equally. The component analysis suggests a stronger role for benchmark access and issuer breadth, but this should be validated in a larger issuer-level sample.

Fifth, PCRI is a pilot expert-coded index. The evidence hierarchy and scoring rubric improve auditability, and the ordinal ranking is stable to simple weighting changes, but independent coding and a wider jurisdiction sample are necessary. Disclosure readiness is not equivalent to executable collateral data, and authorised infrastructure does not imply meaningful transaction volume.

Sixth, the paper cannot estimate the effect of tokenised covered bonds on spreads, issuance costs, liquidity or collateral mobilisation. A future design should match tokenised and conventional securities, measure underwriting and settlement costs, track investor participation and exploit the Eurosystem's new collateral eligibility as an event. The ECB's emerging security-level evidence on tokenised bonds provides a useful methodological direction (ECB, 2026c).

9. Conclusion

The paper began with a puzzle. Mature covered-bond markets preserved issuance continuity when European bank funding moved away from extraordinary central-bank support, but digital-market readiness did not yet correspond to stronger covered-bond outcomes. The evidence points to an institutional answer. Scale is not sufficient. The ability to return to market depends on recurring benchmark access, issuer breadth, investor recognition and operational routines - the elements of conversion capacity.

The panel results are intentionally interpreted with restraint. The raw maturity-group comparison implies a 9.1 percentage point relative difference in issuance intensity. Fixed-effects estimates are positive, economically meaningful and robust in sign across country exclusions, but imprecise under both clustered and wild-cluster inference. Benchmark access emerges as the clearest diagnostic channel. These findings support, rather than prove, the proposition that mature market infrastructure stabilises the covered-bond funding channel.

The PCRI adds a second discipline. Europe is building legal and settlement foundations for tokenised finance, yet those foundations have not automatically converted into covered-bond issuance resilience. Programmability is an option-enhancing layer. It can make collateral data more verifiable, processes more synchronised and settlement safer, but it cannot substitute for asset supply, investor depth or legal credibility. The transition from asset encumbrance to programmable collateral is therefore institutional conversion, not technological substitution.

This conclusion also clarifies the role of asset encumbrance. Digital infrastructure can improve mobilisation and visibility, but it does not change the fact that secured funding reserves assets for particular creditors. A credible programmable-collateral regime must preserve balance-sheet optionality, consolidated supervisory visibility and safe settlement. For CEE and Poland, the practical route is sequential: deepen and standardise the covered-bond market, connect it to common European infrastructure, and automate only where that automation strengthens a functioning funding channel.

Data availability and replication

The market panel was constructed from statistical tables in the European Covered Bond Fact Book 2025. Derived variables, maturity classifications, PCRI evidence logs, regression code and robustness outputs form a replication package accompanying this paper. No confidential or proprietary bank data were used.

Funding and conflicts of interest

The author received no external funding for this study and declares no conflict of interest. The views expressed are personal and do not represent any employer or affiliated institution.

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Appendix A. Ex ante market-maturity scores

Country	Maturity index
Germany	1.133
Norway	0.917
Sweden	0.884
Denmark	0.820
France	0.625
Finland	0.562
Austria	0.244
Spain	0.215
Netherlands	-0.039
Belgium	-0.089
Italy	-0.235
Poland	-0.455
Ireland	-0.620
Slovakia	-0.758
Czechia	-1.017
Hungary	-1.343

Note. Index calculated from 2015-2019 averages of log outstanding stock, log issuer count, benchmark issuance share and public issuance share. Estonia has no pre-period score.

Appendix B. PCRI scoring rubric

Pillar	0	1	2	3
Legal digital-securities readiness	No identifiable pathway beyond general law	EU baseline or exploratory guidance	Operational national legal pathway	Comprehensive framework with live authorisation or use

Pillar	0	1	2	3
Settlement readiness	No identified activity	Experiments or indirect participation	Live infrastructure or operational national pathway	Authorised infrastructure plus central-bank interoperability role
Cover-pool disclosure readiness	Limited or non-standard public disclosure	Basic recurring issuer disclosure	Standardised and accessible programme disclosure	Broad standardisation and high transparency across active programmes
Covered-bond market maturity	No active market	Small or irregular market	Developed recurring market	Deep benchmark market with broad investor access

Note. The rubric is a pilot framework. It should be independently coded before use as a formal ranking.

Appendix C. PCRI evidence summary

Country	Evidence supporting the pilot coding
Germany	Electronic Securities Act; authorised DLT market infrastructures; Bundesbank solution-provider role; deep and recurrent covered-bond benchmark market.
France	National DLT securities framework; authorised DLT trading and settlement system; Banque de France solution-provider role; deep covered-bond market.
Italy	National framework for digital financial instruments under Decree-Law 25/2023; Banca d'Italia settlement solution; broad labelled issuer base.

Country	Evidence supporting the pilot coding
Spain	Law 6/2023 recognises DLT representation of negotiable securities; authorised DLT trading and settlement system; developed covered-bond market.
Denmark	Exceptionally mature covered-bond market and strong disclosure; no comparable domestic authorised DLT infrastructure or Eurosystem solution-provider role identified at the coding date.
Austria	EU legal baseline; DELPHI and Eurosystem experimentation; sizeable but less benchmark-oriented covered-bond market.
Czechia	CSD Prague DLT settlement system authorised under the Pilot Regime; smaller covered-bond market and less extensive disclosure than the mature benchmark systems.
Poland	EU legal baseline; specialist mortgage-bank model and strong programme disclosure; shallow market and no live domestic DLT market infrastructure identified at the coding date.

Sources include national legislation, ESMA authorisation materials, ECB/Eurosystem experiment documentation, the Covered Bond Label and ECBC (2025). The evidence log is included in the replication package.

Appendix D. Additional econometric diagnostics

Table D1. Secondary outcomes

Outcome	Maturity × normalisation	Cluster SE	p-value	Lagged log outstanding	N	R^2
Outstanding-stock growth	0.0274	0.0447	0.550	-0.2518**	141	0.404
Benchmark issuance share	-0.1042	0.0616	0.111	0.0021	141	0.661
Private-placement share	0.0515	0.0782	0.520	-0.1221	141	0.719

*Note. ** p<0.05. All models include country and year fixed effects. These outcomes do not show a uniform maturity-related shift in placement format.*

Table D2. Joint maturity-component model

Component × normalisation	Coefficient	Cluster SE	p-value
Market scale	-0.0645	0.0460	0.182
Issuer breadth	0.0529	0.0248	0.050
Benchmark issuance share	0.1712	0.0680	0.024
Public issuance share	-0.1193	0.0631	0.078

Note. Components are correlated; coefficients are unstable relative to the separate-component models. The table is reported for transparency and not used as the primary mechanism test.

Table D3. Leave-one-country-out range

Diagnostic	Result
Coefficient range	0.0308 to 0.0702

Diagnostic	Result
Number of exclusions with positive coefficient	16 of 16
Coefficient when Poland is excluded	0.0518 (p=0.063)
Smallest coefficient	0.0308 when Czechia is excluded
Largest coefficient	0.0702 when Slovakia is excluded