b-science.net

striepe-battery-consult

Connecting the dots in energy storage

Liquid Electrolyte vs. Semi-Solid vs. All-Solid Batteries

Navigating Performance, Cost, and Safety Trade-offs from Materials to EV / eVTOL Packs

Dr. Pirmin Ulmann, b-science.net LLC, Stäfa / Zurich, Switzerland, pirmin@b-science.net
Dr. Soeren Striepe, Striepe Battery Consult Inc., Mount Albert / Ontario, Canada, soeren@striepebatteryconsult.ca

1 **Takeaway: No Single Winning Electrolyte**

Each electrolyte architecture optimizes for different priorities — because the underlying physics (ionic conductivity, electrochemical stability window, interfacial contact) create inherent trade-offs. Liquid carbonate dominates on cost and maturity, semi-solid offers a promising path to higher energy density at attractive active material costs, all-solid provides the highest performance ceiling — at the highest development risk.

2 **Takeaway: Pack-Level Innovation Critical**

Solid-state packs with lithium metal or Si anode cells face combined pressure and cell expansion compliance challenges — because solid-solid interfaces demand sustained mechanical contact. Patent strategies diverge: sulfide cells require 0.5–1.0 MPa stack pressure, while semi-solid cells can probably avoid it entirely. A wider operating temperature range (up to 80-100°C) relaxes cooling requirements and opens simpler pack architectures. Integrated solutions unifying pressure, thermal management, and safety are an emerging frontier.

3 **Takeaway: Go-to-Market Matters**

Niche-first strategies (eVTOL, specialty electronics, swappable batteries) are de-risking novel chemistries before EV-scale commitment. Technology transfer will likely occur asymmetrically: eVTOL demands higher performance and safety at lower production volumes with greater cost tolerance — so advanced chemistries proven in aviation are likely to transfer to automotive, but not the reverse. CAPEX-minimizing market entry paths will determine which technologies reach EV mass-market first.

EV vs. eVTOL — Diverging Requirements Drive Technology Selection

Electric Vehicles (EV)

Energy Density
Volumetric density prioritized (pack space constraint), gradually rising — cost, fast charge, and cycle life often outweigh peak Wh/kg, favoring low-cost Si paths.

Cycle Life
Demonstrated: >1,000, to be validated: >5,000 (parity with liquid carbonate electrolytes).

Power Density
Target: SOC 10→80% in 5-10 min, 5→60% in 5 min certified (oxide/polymer semi-solid), fast discharge typically less critical (≤1 C).

Safety Standards
UN ECE R100, GB 38031 (China), thermal runaway propagation prevention, sulfide H_2S risk adds manufacturing, crash safety and recycling complexity.

Reserve Capacity
Not life-threatening in most use cases — vehicle can safely stop at roadside.

Cost Sensitivity
Highly cost-sensitive — ICE parity drives technology selection, mid- to long-term cost levers: low-cost metallurgical Si (~$2/kWh anode material, 2600–2800 mAh/g, favorable SEI formation characteristics at Si interface) and high voltage cathodes with low raw materials costs enabled by solid electrolytes.

EV Priority: Cost parity with ICE drives technology selection — because cell cost dominates pack cost, higher energy density directly reduces $/kWh. Leading programs target ≥1,000 km range with stacked prismatic designs. Semi-solid offers fastest path, all-solid sulfide targets mass production by ~2030.

vs

Electric VTOL (eVTOL)

Energy Density
500+ Wh/kg highly desirable, gravimetric density is binding range constraint.

Cycle Life
1,000+ cycles currently, 2,000–5,000 cycles desirable, high-frequency short missions, need for maintaining reserve capacity results in limited depth of discharge, accelerated range loss upon cell capacity fade.

Power Density
Very high C-rates during hover (2–4 C burst sustained), fast charging also critical for favorable aircraft utilization and vertiport pad throughput.

Safety Standard
Aviation-grade: FAA/EASA certification, catastrophic failure rate $<10^{-9}$/flight hour, multi-mechanism thermal runaway suppression.

Reserve Capacity
Mission-critical — mandatory reserve for diversion, holding patterns, emergency landing, SoC cutoff margins needed for safe landing power: ~30–40% of cell capacity!

Cost Tolerance
Higher $/kWh acceptable because gravimetric performance is binding constraint, single OEM investing $894M+ into eVTOL partner illustrates willingness to pay for performance.

eVTOL Priority: Performance and safety are non-negotiable — catastrophic failure rate requirements ($<10^{-9}$/flight hour) and mandatory reserve capacity make gravimetric energy density the binding constraint. Patent analysis reveals dedicated polymer and oxide cell tracks for eVTOL alongside sulfide EV tracks — even within single organizations. Higher cost tolerance accelerates adoption.

Both markets drive solid-state innovation — from opposite ends.
EV: cost-down pressure pushes incremental adoption (semi-solid first, all-solid sulfide by ~2030) · eVTOL: performance ceiling pulls breakthrough chemistries (>500 Wh/kg, Li metal or close to 100% Si anodes, high-Ni NMC) · Patent analysis reveals dual-track product development within leading organizations.

Cell-Level Performance Comparison

Parameter	Liquid Carbonate-Based graphite / SiO_x / Si-carbon composite	Semi-Solid Type 1 Si anode	Semi-Solid Type 2 Li metal anode	All-Solid Polymer / Oligomer Li metal anode	All-Solid Sulfide Si / Li metal anode
Energy Density (gravimetric)	**300 Wh/kg (GWh-scale)** **500 Wh/kg (eVTOL)**	320 Wh/kg (GWh-scale) 400 Wh/kg (next-gen)	300 Wh/kg (next-gen)	**500 Wh/kg (pilot / aviation)**	400 Wh/kg (next-gen)
Energy Density (volumetric)	**700 Wh/L (GWh-scale)** **1,150+ Wh/L (eVTOL)**	810+ Wh/L (GWh-scale) 950+ Wh/L (next-gen)	800–1,000 Wh/L (next-gen)	**1,000+ Wh/L (est., pilot / aviation)**	900 Wh/L (next-gen)
Upper Voltage (long-term estimate)	~5 V	~5 V	~5 V	**>5 V**	**>5 V**
Charging Rate (10 → 70% SoC)	**10 C / 6 min**	5 C / 9 min	4 C / 12–15 min	4 C / 12–15 min	>4 C / 12 min
Cycle Life (25 °C)	**5k+**	1–5k	1–5k	1k+	1–5k
Operating Temp.	–20 to +60 °C	**–20 to +85 °C+**	**–20 to +85 °C+**	**–20 to +85 °C+**	**–20 to +85 °C+**
Form Factor	Cyl. / Prism. / Pouch	Prism. / Pouch	Prism. / Pouch	Prism. / Pouch	Prism. / Pouch
Stack Pressure	**~0 MPa**	**~0 MPa**	0.1–0.5 MPa	0.1–0.5 MPa	0.5–1.0 MPa

Ranges are directional estimates based on patent analysis and public statements. Actual performance varies by cell design and manufacturer.

Key Electrolyte Architectures

Liquid Carbonate-Based Electrolyte

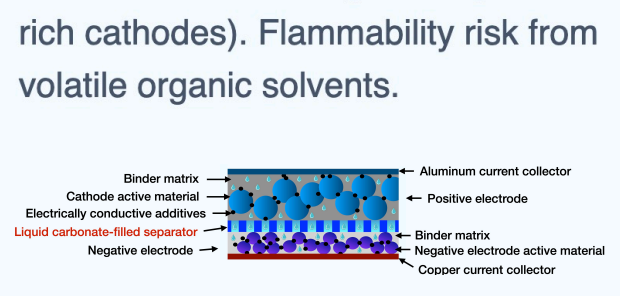
Electrolyte	Liquid carbonate
Separator	Porous PP / PE
Anode	Graphite / SiO_x / Si-based
Cathode	NMC, LFP, others

STRENGTHS

Mature technology with proven energy/power density. Established global manufacturing and supply chain with economies of scale.

LIMITATIONS

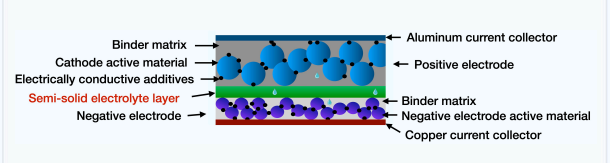
Electrolyte stability prevents use of next-gen active materials (low cost Si & Li metal anodes, high-voltage Mn-rich cathodes). Flammability risk from volatile organic solvents.



Semi-Solid Electrolyte

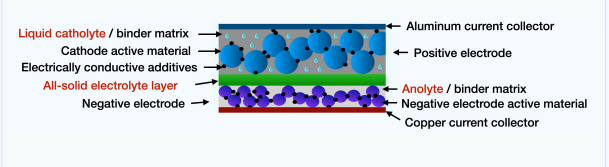
Type 1: Semi-solid layer

<10 mass% liquids / oxide / polymer · Si / SiO_x / graphite anode · Leverages existing Li-ion supply chain with adapted process steps.



Type 2: Solid separator + liquid catholyte

Li metal anode · Solid oxide separator enables high-voltage operation · Some process steps can be skipped.



STRENGTHS

Very high Si content with low-cost material, or Li metal anode. Fastest path to higher energy density via existing manufacturing.

LIMITATIONS

GWh-scale ramp-up at competitive cost & quality remains challenging. Initial process cost disadvantage may be hard to avoid.

All-Solid Electrolyte

Halide · Oxide · Sulfide · Polymer · Oligomer

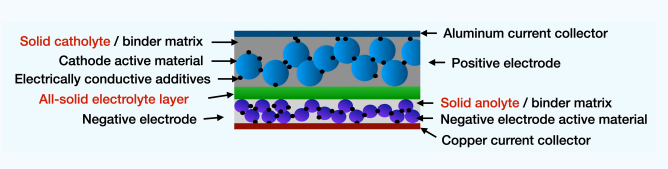
Anode	Si-based, Li metal
Cathode	NMC, LRLO, others

STRENGTHS

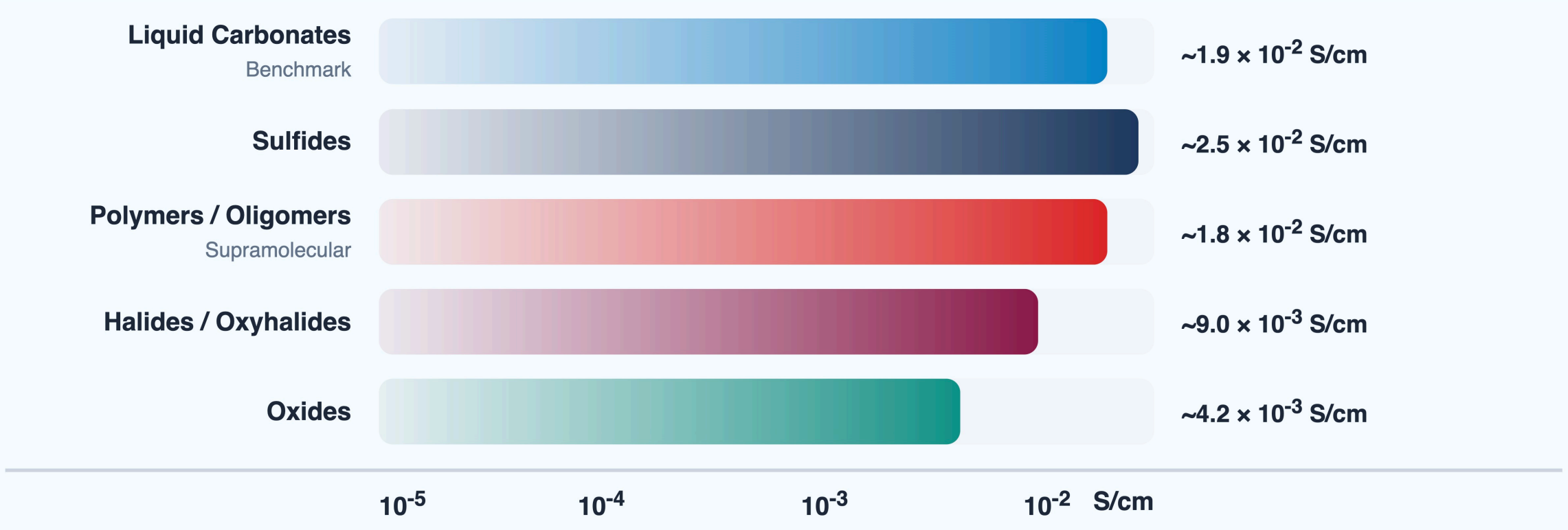
Multi-layer bipolar cell designs enabling higher-voltage cathodes from abundant raw materials. Path to >500 Wh/kg. Improved thermal stability. No flammable liquid.

LIMITATIONS

Interfacial resistance from crack formation, stack pressure up to 1 MPa, challenging scale-up of novel processes (oxides) or supply chains (sulfides).



Ionic Conductivity Landscape



Highest ionic conductivities identified in patent filings.

Key insight: Supramolecular ion channels in oligomers — patented by key industrial players — have driven ionic conductivity beyond 10^{-2} S/cm, rivalling liquid electrolytes. This design principle likely transfers to polymers. Progress has also been made with sulfides, halides / oxyhalides and oxides.

Cost Perspective

Short-to-Medium Term

Liquid carbonate retains cost advantage via established TWh-scale supply chain and economies of scale — because 1) process maturity reduces yield losses, 2) advanced CAPEX amortization. Semi-solid Type 1 probably is leading among next-gen electrolyte cells on the path to cost competitiveness by reusing existing Li-ion equipment while employing low-cost Si anodes.

Long Term

All-solid cells are fervently pursued because of prospective performance + safety + cost advantages upon overcoming initial production scale disadvantages: 1) higher operating voltage unlocks Mn-rich LRLO cathodes from earth-abundant raw materials, 2) SEI stabilization enables use of low-cost metallurgical Si and Li metal anodes, 3) elimination of flammable liquid permits simpler pack designs with reduced cooling and safety systems.

Pack-Level Innovation & Stack Pressure

The Stack Pressure Challenge: All-solid cells likely require external stack pressure (0.1–1.0 MPa) to maintain interfacial contact. Si anodes swell ~300% at full lithiation, and Li-metal anodes undergo full plating/stripping every cycle — vs. ~10% volume change for graphite — creating new pack-level challenges. Patent analysis reveals three distinct approaches:

1 Compliant Material Components

Compliant layers (e.g. polyurethane) between cells deform while transmitting pressure. Thermal management via potting material.

EXAMPLE PATENTS
Compliant layers (yellow) accommodating up to 20% vol. expansion, blade battery configuration.

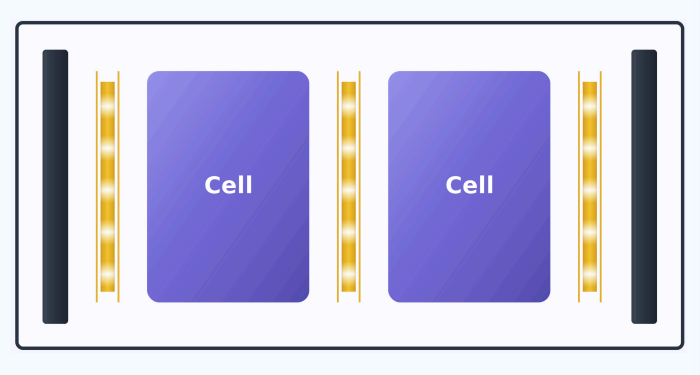
Passive · Low complexity

2 Mechanical Spring-Loaded Devices

Elastic members with stamped tabs provide passive mechanical pressure and accommodate expansion/contraction throughout lifecycle. No external pressure systems or manual adjustments needed.

EXAMPLE PATENTS
Elastic tab system (yellow) for SSB cells, open-frame with elastic deformation.

Passive · Maintenance-free · Lifecycle-adaptive

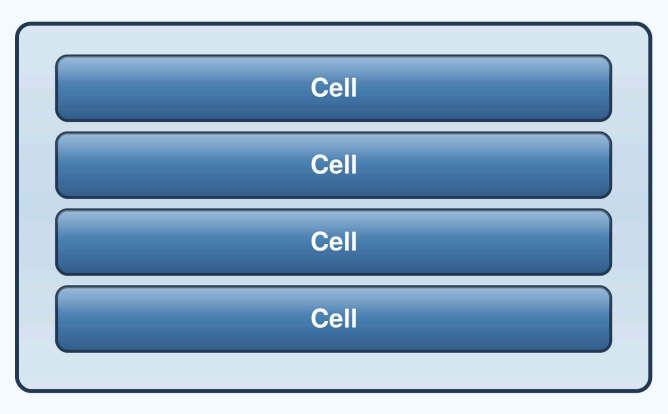


3 Fluid-Based Pressurization

Hydraulic/pneumatic fluid provides isostatic pressure with dual thermal management function. Dynamic adjustment based on cell state via sensors, diagnostics, and algorithms.

EXAMPLE PATENTS
Isostatic pressure for anodeless SSB, fluid-based module with thermal integration.

Active · Dynamic pressure · Dual-function thermal



Supply Chain & Manufacturing Scale

Scale	Technology	Status
TWh	**Liquid Carbonate** Graphite / SiO_x / Si-C anodes	**TWh-scale global production.** Continuous improvements — including at active materials level, but liquid carbonate electrolytes tend to exhibit chemical stability limitations that prevent the use of low-cost, high energy active materials. Mature supply chain with full economies of scale.
GWh	**Semi-Solid Type 1** Si anodes	**GWh-scale achieved.** Leverages existing Li-ion supply chain with adapted process steps (e.g. two-layer deposition).
GWh	**All-Solid Polymer** Li metal anodes	**GWh-scale achieved.** Need to demonstrate successful battery operation at room temperature and below.
Pre-comm.	**Semi-Solid Type 2** Li metal anodes	**Pre-commercial.** Oxide separator requires substantial process development. High energy density potential.
Pre-comm.	**All-Solid Sulfide** Si / Li metal anodes	**Pre-commercial (exception: microscale cells (<10 mAh)).** Extensive resources needed for entire EV-scale supply chain including raw chemicals (e.g. Li_2S). High CAPEX risk, high performance ceiling.

Case Study — Sulfide All-Solid (EV)

Sulfide All-Solid Pathway — EV

Cost-down at scale · argyrodite electrolyte · Si-based anode

PATENT EVIDENCE HIGH

TARGETS

≥1,000 km Vehicle range target with stacked prismatic cells.	**<10 min** SOC 10→80% charging enabled by $>10^{-3}$ S/cm conductivity.
450–500 Wh/kg Target energy density >90% retention after 2k cycles.	**495 patent families** Published since 2022 largest portfolio in class.

KEY MATERIAL CONCEPTS

1. **High-conductivity sulfide via solution synthesis**
   4.1×10^{-3} S/cm ionic conductivity with moisture-resistant ether-modifier surface coatings (10–30 nm).
2. **Dual-layer cathode-electrolyte interface**
   Oxide inner layer (50–200 nm) + sulfide conductive outer layer (1–5 µm), or halide coatings with >5.0 V electrochemical stability.
3. **Si-tolerant current collector system**
   Resin current collectors with carbon fiber networks for flexible stress absorption during Si anode expansion/contraction.

CRITICAL RISK

Toxic H_2S gas emissions when sulfide electrolytes contact water or moisture — mitigated through multiple complementary pathways across materials, cells, packs.

TIMELINE (PUBLICLY DISCLOSED)

2025	2027	2028	2030
Pilot line	Premium EV	Supply chain scale	Mass production

Multi-partner supply chain
Sulfide electrolyte producer, cathode material supplier, binder specialist.

Vertical integration
Battery material → cell → vehicle production under one organizational umbrella.

Case Study — Oxide All-Solid (eVTOL)

Oxide All-Solid Pathway — eVTOL

Performance ceiling · garnet LLZO · Li metal anode

PATENT EVIDENCE THIN

TARGETS

Max Wh/kg Gravimetric density is binding constraint for eVTOL range & payload.	**4–8 C burst** High-rate discharging required for hover phases & takeoff.
$894M+ Investment into eVTOL partner illustrating cost tolerance.	**FAA cert.** Aviation-grade certification path catastrophic failure rate $<10^{-9}$/flight hour.

KEY MATERIAL CONCEPTS

1. **Garnet LLZO via flux-mediated synthesis**
   Ca/Nb-doped $Li_7La_3Zr_2O_{12}$ at 700–900°C (vs. conventional 900–1100°C), reduced sintering temperature.
2. **Compact-porous bilayer architecture**
   95%/61% relative density via chemical sintering using H-substituted garnet, monolithic integration reduces delamination.
3. **Bipolar cells with through-hole current collectors**
   ≤1 µm diameter holes provide stress relief for Li metal deposition, critical for eVTOL high-rate charging.

CRITICAL RISK

Current density (~0.7 mA/cm²) and ionic conductivity (2.4×10^{-4} S/cm) observed in recent patent filings require significant improvement for eVTOL power demands.

TIMELINE (PUBLICLY DISCLOSED)

2025–27	2027–29	2029+
Bilayer optimization & current density improvement	Prototype eVTOL cells (plant adaptation by 2027)	Pilot production

eVTOL airframe partnership
$894M+ investment illustrating commitment to aviation-grade solid-state cells.

Shared R&D platform
Decades of hybrid-era battery expertise channeled into oxide solid-state for aviation.

Methodology — AI-Based Patent Analysis to Improve Technical Decisions

1 Basic Filter

Patents with 'battery' in title/abstract or battery IPC/CPC codes. Published since 2022.

~115,000 patent documents

2 AI Relevance Screening

AI-based 'prospective commercial relevance' assessment filters to high-impact patent families.

PDF analysis of >4k patent families

3 Classification & Clustering

AI-based classification by electrolyte type (7 categories), development focus (18 categories), patent level (6 levels, materials to packs).

Structured taxonomy

4 Expert Analysis

Review for technical accuracy, cluster analysis, cross-company benchmarking, comparison vs. public statements, white-space mapping.

Validated insights

Data source: European Patent Office (covers >100 patent offices globally).