Ref. Ares(2026)4464604 - 30/04/2026

CIRCUBATT

CIRCUlar economy innovations for resilient, competitive and sustainable BATTery technologies

Deliverable D1.9: Policy Recommendation Report

Project GA No	101192383
Project Name	CIRCUBATT
Work Package No	1
Lead Beneficiary	University of Greenwich
Other Participants	E-F
Version	04
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Dissemination Level	PU
Due Date	M16

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Document classification code

(D1.9-Policy Recommendation)_v4

Document History

Version	Date	Author	Modifications and comments
V1	29/03/2026	UoG	First draft issued with structure confirmed
V2	26/04/2026	UoG	Full draft issued for the consortium review
V3	28/04/2026	UoG	Minor revisions of figures, proofreading, formatting.
V4	30/04/2026	UoG	Final version

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List of Figures

Figure 1 Methodology Framework 11
Figure 2 Theoretical foundation of policy mix literature 12
Figure 3 The Temporal Trajectory of the EU Battery Maturity Score 20
Figure 4 The Supranational Gap (EU-Level Regulatory Bottlenecks) 23
Figure 5 The Transpositional Gap (Member State-level Regulatory Bottlenecks) 26
Figure 6 Cluster Diagnostics 27
Figure 7 Cross-Border Benchmarking: K-Means Clustering of Policy Gaps 29
Figure 8 Supranational Intervention Pathway for Cluster 1 and Cluster 2 30

Figure A. 1 Correlation Matrix 50
Figure A. 2 PCA Scree Chart 51

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List of Tables

Table 1 Key Policy Indicator (KPI) codebook.....13

Table A. 1 Definition and codebook of Key Policy Indicator 47
Table A. 2 PC loading-based assessment of correlated KPI pairs for double-counting risk 52
Table A. 3 Final BPMS Weight Allocation.....54
Table A. 4 Country BPMS in 2025 (Compared to EU Supranational Baseline: 2.024) 58

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List of acronyms

- Battery Energy Storage Systems (BESS)
- Battery-as-a-Service (BaaS)
- Key Policy Indicator (KPI)
- Extended Producer Responsibility (EPR)
- Distance to Frontier (DTF)
- Potential Gap Closure (PGC)
- Battery-as-a-Service Policy Maturity Score (BPMS)
- State of Health (SoH)
- End-of-Waste (EoW)

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Table of contents

Executive Summary 7
1. Introduction 8
1.1 Project Overview 8
1.2 Background and Problem Statement 8
1.2.1 The Imperative of Second-Life Electric Vehicle Batteries 8
1.2.2 The Current Policy Landscape: The Shift to Circularity 9
1.2.3 Systemic Barriers hindering the second-life BaaS Ecosystem 9
1.3 Purpose of the Deliverable (D1.9) 10
1.4 Report Structure 11
2. Methodology 11
2.1 Policy Classification Framework for Second-Life EV Batteries 12
2.2 Second-life Battery-as-a-Service Policy Maturity Score 16
2.3 Distance to Frontier Analysis 17
2.4 Cross-Border Benchmarking: Clustering of Policy Gaps 19
3. Key Findings and Policy Gap Analysis 19
3.1 The Temporal Trajectory of the EU Battery Policy (Macro View) 19
3.2 Analysis of Policy Gaps 22
3.2.1 Diagnosing the Supranational Gap (EU-Level Policy Lag) 22
3.2.2 Diagnosing the Transposition Gap (National Policy Lag) 25
3.3 Clustering Analysis for Cross-border Benchmarking 27
4. Policy Recommendation 32
5. Conclusion and Future Agenda in Year 3 42
5.1 Report Summary 42
5.2 Contributions to European Policymakers 42
5.3 Contributions to Academic Researchers 43
5.4 Future Research Agenda for Deliverable D1.10 44
Reference 45
Appendix 47
Appendix A1: Definition and codebook of Key Policy Indicator 47
Appendix A.2. Redundancy and Double-Counting Assessment 49
Appendix A.3. Mathematical Formulations 56
Appendix A4. Country Profile: Policy Maturity Assessment 58

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Executive Summary

Context and Objective

This report identifies the *regulatory* bottlenecks hindering the market implementation of Battery-as-a-Service (BaaS) – an umbrella business model developed within this project to enable the repurposing and reuse of second-life electric vehicle batteries. While the 2023 EU Battery Regulation was a massive leap forward for battery circularity and digital tracking, widespread commercialisation remains constrained by administrative delays, a lack of transparent data regarding asset health, and fragmented safety protocols.

Methodology

This study analyses a 20-year dataset to evaluate the regulatory readiness of 34 European economies for the second-life battery market. By benchmarking each nation's framework against the EU standards and clustering economies with shared legislative gaps, we develop high-yield roadmaps for the EU and laggard nations to address top-priority bottlenecks.

Key Findings

The analysis demonstrates that a generic, one-size-fits-all European law is insufficient. The market is currently stalled by two primary tiers of policy gaps:

- **The Supranational Gap:** The EU achieves an aggregate policy maturity score of 2.02 out of 3.0. Over half of this shortfall comes from just five bottlenecks: missing unified fire and building codes for battery storage, strict rules that treat functional used batteries as hazardous waste during transport, prolonged facility permitting, a shortage of trained workers, and slow patent processing for new technologies.
- **The National Implementation Gap:** A substantial bloc of 27 countries is currently falling short of meeting EU standards, categorised into two distinct clusters:
  - **Cluster 1 (14 nations):** These economies have foundational legal frameworks but lack the specialised, high-voltage workforce and government-backed market demand required to grow the market.
  - **Cluster 2 (13 nations):** These nations suffer from a profound "trust deficit" and urgently need fundamental market protections, including secure battery data-sharing networks, mandatory safety testing for second-life assets, and strong consumer warranties.

Actionable Policy Recommendations

To prioritise high-yield policies and effectively de-risk industrial investments, the European Commission (EC) and national policymakers should deploy targeted interventions:

- **Establish a Unified Physical Baseline:** The EC should mandate harmonised safety standards for battery storage via EU standardisation bodies to prevent fragmented local rules, and legally exempt functional used batteries from strict hazardous waste transport rules.
- **Resolve Waste Status and Permitting Gridlock:** The EC should establish a fast-track for factory permits and classify functional used batteries not as "hazardous waste".
- **Accelerate IP Commercialisation:** The EC should negotiate a dedicated fast-track mechanism for approving patents related to battery diagnostics and hardware.
- **Drive Market Scaling (Cluster 1 Focus):** National governments should secure a baseline of demand by committing to buy or use repurposed batteries in public projects, supported by targeted financial subsidies to stimulate market uptake.
- **Enforce Structural Safeguards (Cluster 2 Focus):** National authorities should mandate secure data-sharing networks to prevent original manufacturers from locking battery software, legally require them to disclose the battery health data, and establish safety testing protocols exclusively for second-life batteries.

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1. Introduction

1.1 Project Overview

The CIRCUBATT project (*Circular Economy Innovations for Resilient, Competitive and Sustainable Battery Technologies*) is a Horizon Europe Research and Innovation Action positioned to fundamentally redefine the EU battery value chain. By integrating AI-driven data analytics, business model innovation, and advanced material sciences, the project aims to enhance the circularity, resilience, and sustainability of the battery sector, directly aligning with the European Green Deal's decarbonisation goals.

One of the central pillars in this initiative is **Work Package 1 (WP1) - "Business models"**, led by the University of Greenwich. WP1 focuses specifically on the design, assessment, and validation of the second-life Battery-as-a-Service (BaaS) business model. By shifting the traditional market paradigm from battery ownership to a servitisation framework, BaaS disrupts linear consumption patterns and incentivises the active reuse, repurposing, and advanced lifecycle management of batteries. This service-oriented approach maximises resource efficiency, extends the operational lifecycle of battery assets, and substantially lowers the upfront costs and risks for consumers. Furthermore, it ensures that valuable end-of-life batteries are securely retained within a closed-loop European supply chain, thereby delaying energy-intensive recycling and minimising raw material extraction.

Despite its vast economic and environmental potential, the widespread deployment of the second-life BaaS model is currently hindered by significant regulatory bottlenecks, including administrative gridlock, ambiguous liability standards, and a lack of harmonised market safeguards. Therefore, this deliverable (D1.9) aims to fulfil one of the core tasks of WP1 - translating complex business model barriers into actionable policy intelligence.

1.2 Background and Problem Statement

1.2.1 The Imperative of Second-Life Electric Vehicle Batteries

While the rapid global proliferation of electric vehicles (EVs) is essential for decarbonising the transport sector and meeting international greenhouse gas emissions targets, this transition poses a profound waste management challenge. As the EV market expands, the cumulative burden of end-of-life (EoL) lithium-ion batteries (LIBs) will surge. However, because EV batteries are designed to withstand harsh operating conditions, they typically retain 70% to 80% of their electrochemical capacity upon retirement from traction applications. This residual

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capacity makes them highly viable for less demanding secondary applications, such as stationary Battery Energy Storage Systems (BESS). Aligning with the established waste management hierarchy, cascading these batteries into a "second life" via a BaaS model is both environmentally and economically preferable to immediate recycling; it delays energy-intensive materials recovery and optimises overall life-cycle impacts (Harper *et al.*, 2019).

1.2.2 The Current Policy Landscape: The Shift to Circularity

At the macro-strategic level, the European Union (EU) has decisively shifted from a linear waste-disposal paradigm to a comprehensive circular economy model. Initiatives such as the European Green Deal, the 2020 Circular Economy Action Plan (CEAP), and policies targeting critical raw materials explicitly reframe batteries from mere consumer goods into strategic geopolitical assets. These high-level agendas strongly promote the '10R' framework, emphasising the urgent need to decouple economic growth from resource extraction by prioritising the reuse, repair, and repurposing of critical minerals.

In recent years, the transition has been anchored by the new **EU Battery Regulation 2023/1542**, a landmark legislative framework that entirely replaces the older 2006 Battery Directive and establishes harmonised rules for the entire life cycle of all battery categories (including EV, industrial, and light means of transport batteries). To decouple economic growth from virgin resource extraction, the regulation mandates aggressive sustainability targets. By 2031, industrial and EV batteries must meet minimum quotas for recycled critical minerals (e.g., 16% cobalt, 6% lithium). Furthermore, it enforces strict supply-chain due diligence, requiring large economic operators to undergo third-party audits to prevent social and environmental risks in sourcing these raw materials. Crucially for the second-life market, the regulation begins to address historical administrative gridlock by establishing clear documentation pathways for waste EV and industrial batteries to achieve End-of-Waste (EoW) status once they are tested and prepared for repurposing.

1.2.3 Systemic Barriers hindering the second-life BaaS Ecosystem

Despite the clear theoretical benefits of repurposing retired EV batteries and the EU's top-down ambition, the transition to a scaled secondary battery market remains obstructed by a confluence of regulatory and technical challenges. The literature identifies four primary systemic bottlenecks:

- *Administrative Gridlock and Waste Classification:* A major hurdle for repurposing operations is the ambiguous legal classification of retired batteries,

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which are often treated as hazardous waste rather than viable secondary assets (Harper *et al.*, 2019). Without standardised End-of-Waste (EoW) frameworks, administrative friction severely hinders cross-border logistics and scale.

- *Information Asymmetry and Trust Deficits:* The economic viability of battery refurbishment depends heavily on the accurate assessment of the degradation and State of Health (SoH) of retired batteries (Akram and Abdul-Kader, 2024). There is a critical need for comprehensive service-life databases (e.g., a digital battery passport) to record the entire service life of each battery cell, thereby resolving the information asymmetry that paralyses market trust (Zhu et al., 2021).

- *Lack of Standardised Testing and Certification:* The heterogeneity of battery cell form factors and degradation histories complicates the application of secondary safety regulations. Without bespoke national safety standards for second-life batteries, markets are forced to rely on inadequate legacy frameworks, hindering commercial insurance and consumer protection (Christensen, 2023).

- *Missing Demand Signals:* Without explicit market interventions, emerging battery technologies often struggle to achieve the economies of scale needed to compete. Studies demonstrate that successful market deployment relies heavily on public policy to overcome initial economic hurdles, specifically pointing to the necessity of binding public procurement mandates and targeted financial incentives to establish a guaranteed demand baseline and drive market uptake (Petropoulos and Wanner, 2024).

1.3 Purpose of the Deliverable (D1.9)

The primary purpose of this deliverable (D1.9) is to provide targeted, data-driven policy recommendations designed to de-risk industrial investments, establish harmonised regulatory frameworks, and proactively facilitate market entry for the innovative second-life BaaS models developed within the CIRCUBATT project.

Given that policy frameworks and market conditions are highly dynamic, evaluating policy-market maturity requires a rigorous, two-phase methodological approach:

Phase 1 - Deliverable D1.9 (Current - Year 2): This deliverable systematically develops a comprehensive policy classification framework to assess policy maturity across the European regulatory landscape. It tracks legislative momentum in the targeted Member States and EU supranational level to diagnose and quantify

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the immediate, high-priority policy gaps that currently obstruct the scalable deployment of circular BaaS business models.

Phase 2 - Deliverable D1.10 (Future - Year 3): This deliverable will move from diagnosis to impact assessment. By ingesting market effectiveness data on second-life EV batteries, the study will develop interpretable predictive models to assess the effectiveness and causal impact of EU government intervention policies on the maturity/readiness of the second-life BaaS market.

This phased approach ensures that the European Commission (EC) and Member States' policymakers are equipped not only with an immediate, calibrated legislative roadmap but also with the longitudinal intelligence required to continuously adapt policy instruments to the rapidly evolving second-life BaaS ecosystem.

1.4 Report Structure

Section 1 introduces the study, presenting its background, problems and purpose. Section 2, the Methodology, details the classification framework for key policy indicators (KPIs) that assess government interventions in the EU battery sector. It also covers the development and measurement of the second-life Battery Policy Maturity Score (BPMS) and describes the data analysis approach. Section 3 examines the results and discusses key findings, which lead to actionable policy recommendations in Section 4. The report concludes in Section 5 with a summary and outlines the research agenda for Deliverable D1.10.

2. Methodology

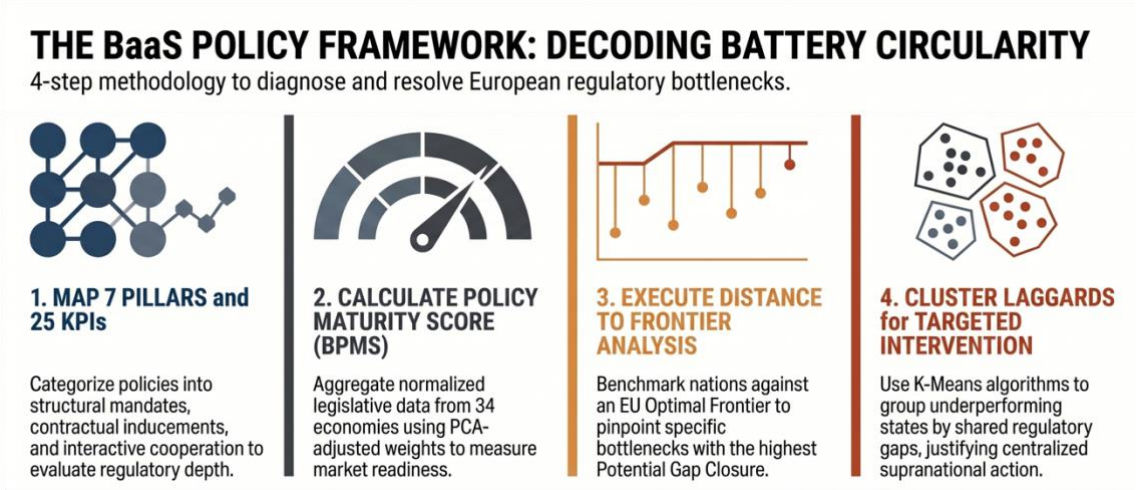


Figure 1 Methodology Framework

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To translate the complex regulatory environment of the second-life BaaS ecosystem into actionable policy intelligence, this study employs a rigorous, multi-stage quantitative methodology. The approach is designed not only to measure current legislative readiness but also to mathematically identify the specific bottlenecks that hinder market scalability at both the EU supranational and national levels. The methodology is structured around four key steps, as shown in Figure 1.

2.1 Policy Classification Framework for Second-Life EV Batteries

To systematically track and evaluate government interventions in the rapidly evolving battery landscape, there is a critical need for an analytical framework to measure and benchmark policy maturity across borders (Howlett and Ramesh, 2002). Indeed, the transition to a circular battery economy requires a well-coordinated "policy mix", as Rogge and Reichardt (2016) affirmed that single policy instruments are insufficient for complex sustainability transitions. Instead, a successful transition requires a holistic policy approach characterised by highly interactive *governance modes* (regulatory, economic, informational), a clear *policy strategy* (objectives and targeted action), and defined *design features* to evaluate the scope, depth, and maturity of government intervention, as shown in Figure 2.

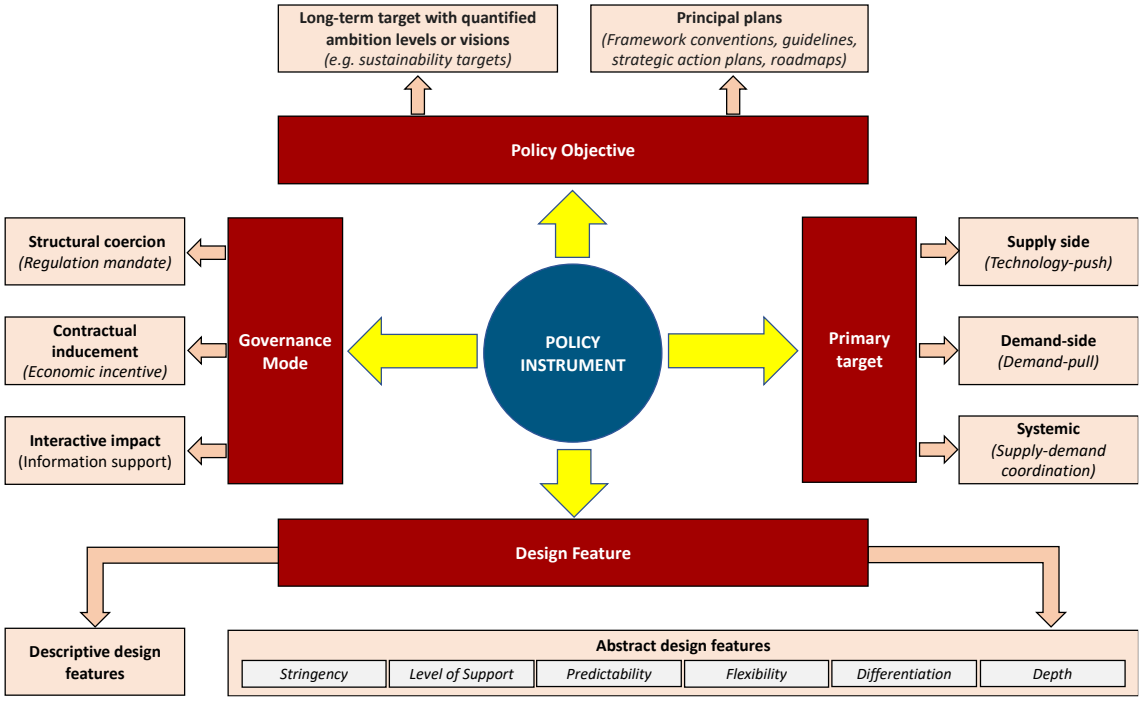


Figure 2 Theoretical foundation of policy mix literature

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Drawing on key literature on policy tool interactions (e.g., Yi and Feiock, 2012) and behavioural assumptions in policy design (e.g., Hille et al., 2020; Mercier et al., 2016), we systematically map the multidimensional landscape of the second-life EV battery market onto a 7-pillar classification framework (Table 1), which includes 25 distinct Key Policy Indicators (KPIs).

The list of KPIs in our framework is presented in Table 1 below, while the full KPI codebook with definitions is provided in Appendix A1.

Table 1 Key Policy Indicator (KPI) codebook

Main Index	KPI Code	KPI name
PA. Regulatory & Legal Framework *(Measures enacted regulations, legal definitions, and liability frameworks)*	PA1	Legal Classification
	PA2	End-of-Waste (EoW) Status
	PA3	EPR Coverage
	PA4	Liability Framework
	PA5	Logistics & Transport Rules
PB. Safety & Standards *(Measures established safety, testing, and performance standards)*	PB1	Reuse/Repurposing Safety Standards
	PB2	Battery Testing & Certification
	PB3	Modernised Safety & Building Codes
PC. Incentives & Economic Enablement *(Measures financial, fiscal, and market support mechanisms)*	PC1	Financial Incentives
	PC2	Market Participation & Access
	PC3	Public Procurement Programs
PD. Data & Information Transparency *(Measures mandates for transparency and digital standards for battery lifecycle data)*	PD1	Battery Passport or Tracking Mandate
	PD2	Data Access Rules
	PD3	Data Interoperability and Security
PE. Circular Economy Integration *(Measures integration into broader circular economy and waste management policies)*	PE1	Reuse Prioritisation
	PE2	Landfill Bans
	PE3	Permitting Streamlining
PF. Institutional Capacity & Governance *(Measures government capacity to enforce, coordinate, and foster innovation)*	PF1	Dedicated Institutional Coordination/Governance
	PF2	R&D Grants & Innovation Support
	PF3	Skills Development Programs
	PF4	IP Fast-tracking
PG. Consumer & Environmental Protection *(Measures safeguards and public information policies)*	PG1	Warranty and Consumer Protection
	PG2	Environmental Impact Monitoring
	PG3	Consumer Awareness/Labelling
	PG4	Operational Risk Mitigation & Financial Compliance

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Governance Mode

We operationalise the 7-pillar framework by categorising the governance modes into three mutually exclusive and non-overlapping domains of government interventions:

- *Structural Mandatory Instruments (Administrative Regulation)*

These instruments rely on the coercive force of government authority to mandate specific actions and are subdivided into laws, regulations, and goal programming. (Yan *et al.*, 2024) note that structural mandates - such as redefining "waste" status and enforcing Extended Producer Responsibility (EPR) - are the primary catalysts for secondary battery markets. Furthermore, strict regulatory institutions are necessary to overcome entrenched linear economic interests (Hughes and Urpelainen, 2015). This domain comprises three indices: the Regulatory and Legal Framework Index (**PA**), the Safety & Standards Index (**PB**), and the Circular Economy Integration Index (**PE**).

- *Contractual Inducement Instruments (Economic Contract)*

These instruments are implemented through economic means to alter the cost-benefit calculus of market actors. Ossenbrink et al., (2019) argue that government policies should move beyond basic regulation to actively stimulate market demand. By measuring these mechanisms, our framework captures how the state utilises contractual inducements to bridge the financial "valley of death" for emerging BaaS models (Hille *et al.*, 2020). Our framework encompasses 2 pillars within this domain: the Incentives and Economic Enablement Index (**PC**) and the Institutional Capacity and Governance Index (**PF**).

- *Interactive Impact Instruments (Voluntary Cooperation & Information)*

These instruments operate on the basis of multi-party interaction, transparency, and information support. Villamayor-Tomas et al. (2019) highlight the critical role of the state in facilitating cooperation through information-sharing, which is vital for resolving the SoH information asymmetry in battery markets. The pillars of our framework in this domain are the Data & Information Transparency Index (**PD**) and Consumer & Environmental Protection Index (**PG**).

Primary target

Based on established innovation policy literature (e.g., Rogge and Reichardt, 2016), the 25 KPIs can be classified into three fundamental instruments:

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- *Technology-Push (Supply-Side Interventions)*

These instruments (PF2, PF3, and PF4) aim to generate new knowledge, reduce the early-stage financial risks of Research and Development (R&D), and build the foundational human and intellectual capital required to supply the market with circular innovations.

- *Market-Pull (Demand-Side Interventions)*

These instruments (PC1, PC2, PC3, PE2) alter the economic cost-benefit calculus to artificially stimulate, subsidise, or legally compel market demand for second-life BaaS applications.

- *Systemic Coordination (Information, Regulatory & Network Interventions)*

The remaining KPIs in our framework are coordination instruments designed to address systemic market failures - such as legal ambiguity, information asymmetry, institutional inefficiency, and consumer trust issues - thereby ensuring seamless interaction between supply (Push) and demand (Pull) within the ecosystem.

Scoring Logic of Policy Design Features

As comparable quantitative data on nascent circular markets are scarce, our policy framework operationalises qualitative "soft" data derived from legislative reviews (OECD, 2008). To ensure cross-country comparability, each KPI is scored using a discrete ordinal scale from 0 to 3: **Score 0** denotes the complete absence of a policy; **Score 1** indicates basic guidelines; **Score 2** represents a restricted framework; and **Score 3** signifies a clear, operational legal framework.

While ***descriptive design features*** of a policy outline its basic administrative details, our 0–3 scoring scale enables quantitative evaluation of ***abstract design features*** that drive true market impact, including: *Stringency* - the strictness of the mandate (e.g., progressing from Score 1 - Voluntary guidelines to Score 3 - Fully enforced laws); *Depth* - the policy's comprehensiveness (e.g., extending producer obligations across the entire BaaS value chain); *Predictability* - the regulatory certainty required for long-term investment (e.g., clear, harmonised nationwide frameworks); Level of Support - the magnitude of state incentives (e.g., financial mechanisms explicitly tailored for second-life systems).

To illustrate how this scale evaluates abstract policy design, consider the **End-of-Waste (EoW)** Status of used batteries in the legislative framework:

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- **Score 0** *(Complete absence of policy):* No legal pathway exists; all used batteries are automatically classified and treated strictly as hazardous waste.
- **Score 1** (*Basic guidelines):* The government acknowledges the concept of EoW for batteries in strategic documents or voluntary roadmaps, but no formal, binding legal mechanisms are enforced.
- **Score 2** *(Restricted framework):* A legal pathway exists but is highly complex, requiring burdensome, case-by-case environmental assessments to prove a battery is no longer waste.
- **Score 3** *(Clear operational legal framework):* A standardised, harmonised legal pathway is fully operational, automatically decoupling functional secondary batteries from hazardous waste classifications (e.g., by utilising verified SoH diagnostics).

It is noteworthy that the KPI score evaluates *only policy design, not policy outcomes*; i.e., it measures how many relevant policy types a government has enacted and to what extent, but does not assess on-the-ground implementation effectiveness or the administrative enforcement of those policies.

Synthesis: The Necessity of Policy Interaction

Ultimately, individual KPI scores are aggregated to calculate the final ***second-life Battery-as-a-Service Policy Maturity Score (BPMS)***, designed for comparative analysis of policy mix maturity and to reveal policy gaps.

As Yi and Feiock (2012) conclude, interactions among policy tools are critical; for example, a structural mandate (e.g., a recycling target) will fail without the simultaneous deployment of an interactive impact instrument (e.g., a data-tracking passport) and a contractual inducement (e.g., an infrastructure subsidy). Our policy framework effectively captures this theoretical interdependence.

2.2 Second-life Battery-as-a-Service Policy Maturity Score

As explained above, an individual KPI score quantifies the extent to which a government has implemented a specific policy intervention. By aggregating these scores, we derive the ***BPMS*** *- a comprehensive score that measures the maturity (i.e., how ready and supportive) of a country's policy system for the second-life BaaS market.*

The construction of the BPMS rigorously adheres to the internationally recognised OECD (2008) methodological framework for Constructing Composite Indicators,

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which includes the redundancy/double-counting assessment and the normalisation and aggregation approach, as described in Appendix A2 and Appendix A3.1, respectively.

Data Collection

To systematically assess the maturity of BaaS policy ecosystems, the CIRCUBATT project recorded and evaluated policy data across all 27 European Union Member States, as well as selected European Economic Area (EEA) nations and the United Kingdom. This generated a comprehensive database tracking the regulatory frameworks necessary for the circular management of second-life EV batteries. Our dataset covers the period from 2006, when the EU introduced its first major framework governing batteries (Battery Directive 2006/66/EC), to 2025.

To assemble this highly specialised legislative dataset, we relied on a coordinated team of policy analysts and regulation researchers in the international CIRCUBATT consortium. The research team systematically collected data from publicly available legislative repositories, including EUR-Lex for supranational EU directives, national government websites, official news reports, and well-established policy databases such as IEA (Döme et al., 2025). These researchers, with deep knowledge of European environmental law and national energy frameworks, were trained to apply the KPI codebook and scoring logic methodology described above.

To ensure methodological rigour, each country was assigned to at least two researchers who independently collected legislative data and evaluated the KPI scores. Afterwards, they compared their results, discussed any discrepancies, and agreed on the final scores to ensure accuracy and consensus.

2.3 Distance to Frontier Analysis

While the aggregated BPMS provides a macro-level diagnostic of a Member State's circularity status, it often masks specific regulatory bottlenecks. We thus employ a Distance to Frontier (DTF) analysis to deconstruct the composite indicators (BPMS) and identify the specific legislative bottlenecks preventing a Member State from achieving the optimal policy environment, thereby enabling the formulation of calibrated policy recommendations. Our approach adapts the structural logic of The World Bank's 2017 Doing Business report and the OECD (2008)'s "Distance to a reference" and "Back to the details" frameworks.

In our study, *the DTF analysis measures how far a country's current policy landscape is from the "ideal" or optimal policy situation*. By calculating this

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distance, we can pinpoint exactly *which missing regulations are causing the biggest roadblocks in a specific country*.

The analysis is conducted through the following 3-step approach:

Step 1: Defining the Frontier (Optimal Frontier vs. Supranational Baseline)

To accurately diagnose the source of regulatory bottlenecks, we establish two distinct reference points:

- *The EU Optimal Frontier (The Theoretical Target):*

Unlike The World Bank (2017), which evaluates countries against the best real-world performer, our analysis measures them against a perfect, theoretical ideal called the "***EU Optimal Frontier***". Because we grade every policy on a fixed 0-3 scale, this optimal frontier is simply set at the maximum score of 3 for every single indicator

Using this theoretical frontier allows us to show exactly how much work a country still needs to do to achieve ideal legislation. This prevents the "moving goalpost" problem. If we compared countries only to the current best-performing nation, the policy gap would appear artificially small, which could mislead policymakers into believing that their country is "at the frontier", even though, in reality, no country has yet achieved a fully mature policy framework.

- *The EU Supranational Baseline (The Institutional Baseline):*

Along with the country-level data, we treat the European Union as a single entity and calculate an independent BPMS based solely on the EC's supranational policy documents (e.g., the Battery Directive 2006/66/EC, the EU Battery Regulation 2023/1542). We define this calculation as the "***EU Supranational Baseline"***. By comparing each country's BPMS score against this baseline, we can measure how far a nation's regulatory framework exceeds or falls short of the European standard, thereby identifying the frontrunners and laggards.

Step 2: Mathematical Decomposition of the Policy Gap

To calculate exactly how many policy steps a country needs to take to reach the optimal frontier, we measure its "Weighted Gap" by taking the difference between a country's actual score and the perfect maximum score of 3. This difference is then standardised so all policies are comparable, and adjusted to ensure that overlapping policies are not counted twice.

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Step 3: Identification of Top-Priority Regulatory Bottlenecks

Finally, we calculate the Potential Gap Closure (PGC). This metric measures exactly how much of a country's overall policy gap would be solved if just one specific regulation were upgraded to the EU Optimal Frontier. By ranking the policy interventions from highest to lowest PGC, we enable policymakers to recognise the top-priority bottlenecks and identify the exact legislative fixes that will deliver the highest **"return on compliance"** with the least administrative effort.

The exact mathematical formulations of the weighted policy gap and PGC are provided in Appendix A3.2.

2.4 Cross-Border Benchmarking: Clustering of Policy Gaps

While the DTF analysis allows us to explicitly identify regulatory bottlenecks in each nation, we further employ cluster analysis as a diagnostic tool for cross-border benchmarking and to evaluate where the EU collectively falls short in establishing a comprehensive second-life BaaS framework.

To achieve this, a K-Means clustering algorithm is used exclusively for underperforming Member States. Frontrunner economies are deliberately excluded from this modelling because they are largely aligned with the EU Optimal Frontier. Including their minimal gap scores would distort the statistical variance and obscure structural similarities among struggling nations.

This clustering analysis provides critical intelligence for EU-level intervention. If multiple Member States fall into a single cluster characterised by a severe maturity deficit in the same KPI (e.g., Data Access Rules or End-of-Waste Status), this constitutes strong statistical evidence that the supranational directive is failing to prompt adequate transposition. This signals to the EC that a centralised, harmonised EU-level Implementing Act is required to overcome the shared institutional lag, rather than disjointed national corrections.

The K-Means clustering algorithm is mathematically described in Appendix A3.3.

3. Key Findings and Policy Gap Analysis

3.1 The Temporal Trajectory of the EU Battery Policy (Macro View)

This section evaluates the evolution of government interventions in the second-life EV battery market across the EU over a 20-year panel (2006–2025), as depicted in Figure 3. Because the BPMS uses a time-adjusted Min-Max normalisation with fixed theoretical bounds (0 to 3) and unchanging weights, any temporal shifts in the final

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score reflect only actual legislative changes rather than methodological fluctuation. Importantly, plotting the actual EU Supranational BPMS data shows that policy maturity does not evolve in a smooth, continuous curve. Instead, the real trajectory is highly "staircase-like", accurately reflecting how institutional policy change occurs, i.e., through prolonged periods of stagnation punctuated by discrete, transformative legislative shocks. The data clearly traces three transitional phases of European battery policy.

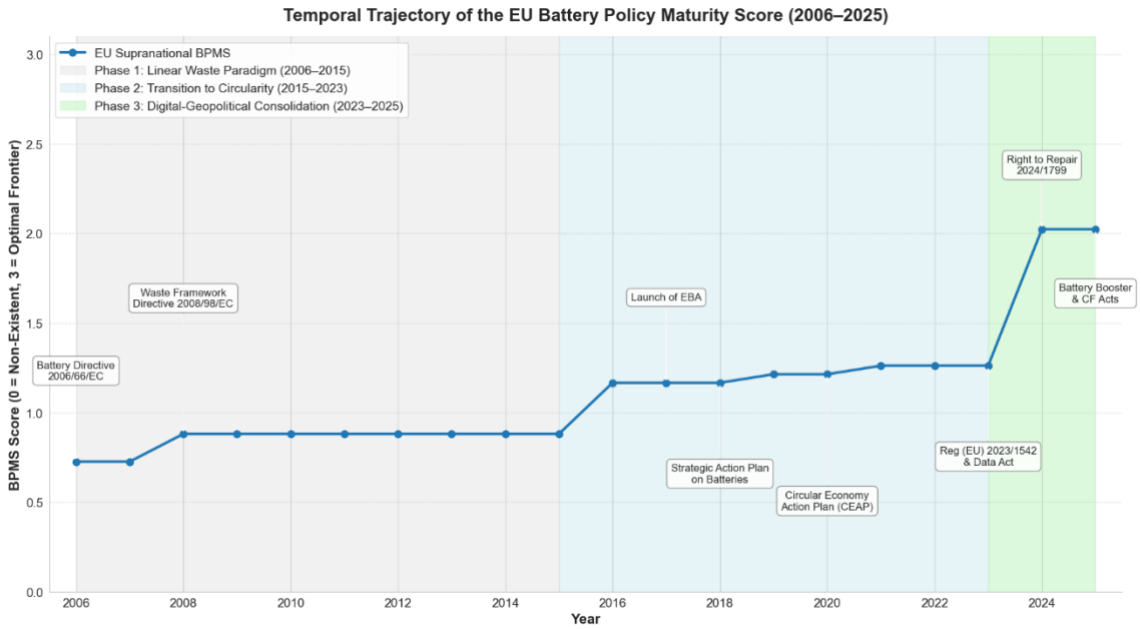


Figure 3 The Temporal Trajectory of the EU Battery Maturity Score

Phase 1: The Foundational Era and Linear Waste Paradigm (2006–2015)

During the first decade of the panel, the BPMS was genuinely stagnant, hovering tightly and flatly between **0.73 and 0.88**. This suppressed plateau mathematically confirms the severe limitations of the "Linear Waste Paradigm". During this era, the regulatory architecture was entirely dominated by the **EU Battery Directive (2006/66/EC)**. While environmentally progressive in its attempt to mitigate heavy metal toxicity—restricting mercury to 0.0005% and cadmium to 0.002% by weight—and divert hazardous materials from landfills, its core logic created structural barriers for the BaaS market.

Under this Directive, a battery removed from a vehicle was automatically classified as hazardous waste, forcing valuable assets to comply with prohibitive hazardous-goods transport rules (e.g., UN 38.3). Furthermore, the Directive established traditional EPR frameworks that tied cradle-to-grave liability strictly to the Original Equipment Manufacturer (OEM). This rigid legal structure induced "*liability paralysis*". As a result, OEMs often lock Battery Management Systems (BMS) with

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proprietary software to limit their liability for systems they no longer physically control, which hampers the emergence of independent second-life operators.

Phase 2: The Transition Point and Incremental Circularity (2015–2023)

The data shows a distinct step-up to **1.17 in 2016**, perfectly coinciding with the regulatory momentum that led to the launch of the **European Battery Alliance (EBA)** in 2017. The EBA catalysed a critical paradigm shift, *reframing EV batteries from disposable consumer goods into strategic geopolitical assets* essential to building an innovative, sustainable, and globally competitive European value chain.

However, after this initial step-up, the period from 2018 to 2023 is characterised by slow, incremental gains (shifting only from **1.21** to **1.26**). This slow growth reflects the reality of policymaking: while the EBA and subsequent high-level agendas, such as the 2020 Circular Economy Action Plan (CEAP), successfully established the theoretical "10R" framework — prioritising repurposing over destructive recycling— these were strategic roadmaps rather than binding statutory laws. They signalled intent but lacked the immediate legislative mechanisms required to unblock the deep operational bottlenecks on the ground.

Phase 3: Legislative Shock and Digital-Geopolitical Consolidation (2023–2025)

The "staircase" effect culminates in a sharp, vertical jump to a highly mature score of **2.02** in 2024–2025. This monumental leap is driven by the direct, harmonised application of the **EU Battery Regulation 2023/1542** across all 27 Member States. This discrete legislative shock dismantled the legal frictions of the previous 15 years through three transformative mechanisms:

- *Overcoming the "Waste" Stigma*: The Regulation overhauls the legal definition of battery status, introducing distinct legal pathways for "*preparing for repurpose*". This officially decouples functional second-life assets from hazardous waste classifications, providing the legal certainty required for operators to secure commercial insurance and project financing.

- *Liability Decoupling and EPR Restructuring*: Under Article 56, the Regulation fundamentally redistributes EPR obligations, formally transferring liability from the original OEM to the economic operator who prepares the battery for its second life. This liability decoupling eliminates the primary legal justification for OEM proprietary lock-in, officially sanctioning the growth of a third-party refurbishing sector.

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- *Absolute Data Liquidity*: To eradicate the severe information asymmetry that previously penalised second-life battery valuation, the EU mandated the Digital Battery Passport (DBP)—compulsory by 2027. Serving as a verifiable digital twin, the DBP dynamically tracks a battery's SoH and State of Certified Energy (SOCE), establishing a "source of truth" that drastically reduces the risk profile of secondary investments.

3.2 Analysis of Policy Gaps

The OECD Handbook explicitly states that composite indicators must be transparent and decomposable into their constituent parts to reveal the main drivers of a country's performance. Here, we will present the results of the DTF analysis, which isolates the EU Supranational Score from the Member State scores, enabling a two-tier gap decomposition.

First, it identifies the ***Supranational Gap***, i.e., instances in which both the Member States and the EU Supranational Score fall below the Optimal Frontier of 3, signalling to the EC that the supranational directive lacks the necessary stringency or depth to foster the second-life BaaS market.

Second, it identifies the ***Transposition Gap***, i.e., instances in which a Member State's score falls below the EU Supranational Score, indicating a policy maturity deficit to adequately transpose or enforce existing EU mandates, and recommends calibrated policy interventions for national leaders.

3.2.1 Diagnosing the Supranational Gap (EU-Level Policy Lag)

The EU currently maintains an aggregated BPMS of **2.02 out of 3.0** for the year 2025. While this demonstrates a mature regulatory architecture driven by the EU Battery Regulation (2023/1542), a significant "Supranational Gap" remains between current institutional reality and the theoretical EU Optimal Frontier of 3.0.

To explicitly determine the source of this maturity deficit and provide actionable insights to the EC, we calculate the *Potential Gap Closure (PGC)*. This metric estimates the exact percentage of the total supranational policy gap that would be eliminated if a single KPI were upgraded to the optimal frontier of 3. The result is shown in Figure 4.

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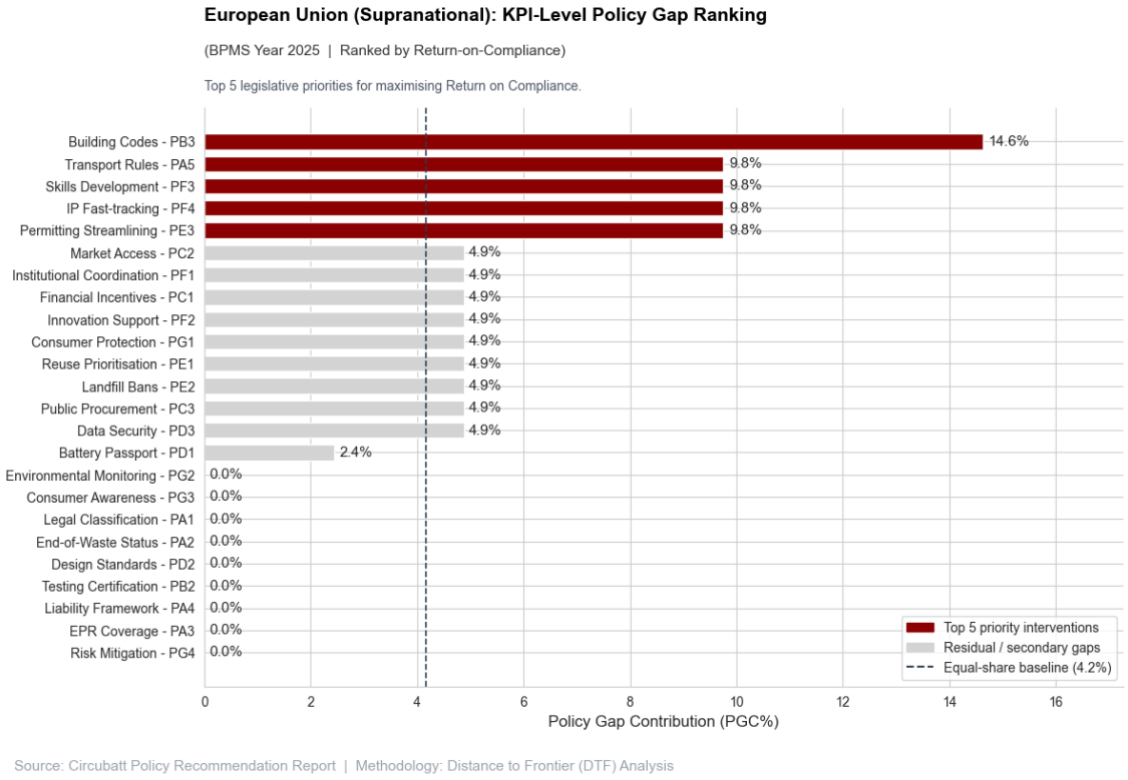


Figure 4 The Supranational Gap (EU-Level Regulatory Bottlenecks)

- **Evaluating Disproportionate Legislative Lag: The "Equal-Share Baseline"**

Because our methodology evaluates exactly 24 active KPIs, we can establish an **equal-share baseline of 4.16%**. This baseline represents the theoretical average for policy gaps, i.e., if the EU's regulatory shortcomings were perfectly and evenly distributed across all legislative areas, each KPI would account for exactly 4.16% of the total gap.

Indeed, comparing actual PGCs against this 4.16% baseline provides two highly insightful, data-driven revelations for policymakers:

(1) Identifying Disproportionate Legislative Lag: If a KPI's PGC hovers around 4.16%, its contribution to the policy maturity deficit is purely average. However, PB3 (Modernised Safety & Building Codes) currently has a PGC of 14.6%. As this is more than three times the equal-share baseline, it mathematically demonstrates to the EC that the regulatory gap is intensely concentrated in this specific area of PB3.

(2) Justifying top-priority bottlenecks: The top 5 bottlenecks all generate PGCs of 9.8% to 14.6%, greatly exceeding the 4.16% baseline. This demonstrates to the EC that resources should not be wasted on broad, minor adjustments

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across all 24 indicators. Instead, interventions must be calibrated to target high-yield bottlenecks to maximise "Return on Compliance".

- **The High-Yield Roadmap: Deep Dive into Top 5 Supranational Bottlenecks**

Figure 3 reveals that the EU's policy gap is intensely concentrated. Currently, just the top five priority bottlenecks alone account for an overwhelming **53.7%** of the total supranational policy gap. By targeting these specific high-yield areas, the EC can effectively close over half of the continent's overarching policy gap with minimal administrative complexity:

PB3: Modernised Safety & Building Codes (PGC: 14.6% | 2025 score: 0/3)

This is the single largest bottleneck hindering the European BaaS market. While Article 12 of the EU Battery Regulation (2023/1542) strictly mandates comprehensive product-level safety testing for stationary BESS (including thermal shock, fire, and gas emission testing), the actual facility deployment rules remain severely fragmented. Without a harmonised EU directive for BESS installations, Member States are resorting to piecemeal local fixes. For instance, Austria published the MVBÖ-004-2023-01 fire guidelines, Denmark relies on DEMA guidelines, and France is drafting a bespoke national BESS ordinance (Ministry of Ecological Transition, 2024). To reach the optimal frontier and prevent deep internal market fragmentation, the EC should issue a harmonised, supranational building and fire code directive specifically tailored for second-life BESS installations.

PA5: Logistics & Transport Rules (PGC: 9.8% | 2025 score: 1/3)

Under the legacy linear waste paradigm, transporting retired LIBs was subject to stringent hazardous goods rules (such as UN 38.3 and the *EU Agreement concerning the International Carriage of Dangerous Goods by Road* - ADR framework), creating prohibitively expensive and legally complex for operators moving thousands of units. While Annex XIV of the new EU Battery Regulation (2023/1542) takes a positive step by requiring SoH testing and documentation to legally distinguish a functional "used" battery shipment from a "waste" shipment, this does not fully resolve the logistical bottleneck. The EU currently lacks a streamlined, dedicated transport regulation that directly interfaces with the forthcoming DBP. A targeted amendment to broader hazardous transport frameworks (such as ADR) is required to utilise certified DBP health data to automatically exempt functional second-life assets from hazardous waste overheads.

PE3: Permitting Streamlining (PGC: 9.8% | 2025 score: 1/3)

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Despite the ambitious targets set by the 2020 CEAP, operators still face highly complex, case-by-case environmental permitting procedures that are not sufficiently differentiated from general hazardous waste permits. The EC can close this gap by heavily leveraging the proposed 2026 Circular Economy Act, which aims to establish a frictionless Single Market for secondary raw materials by introducing a fully Digital Waste Shipment System (DIWASS) and streamlining fragmented waste rules. Upgrading this indicator to a score of 3 requires implementing standardised, EU-wide "permit-by-rule" systems or simplified notification requirements exclusively for battery repurposing facilities.

PF3: Skills Development & PF4: IP Fast-Tracking (PGC: 9.8% each | 2025 score: 1/3)

While the EU has aggressively mobilised its industrial policy—protecting cell manufacturing through the €1.5 billion Battery Booster Strategy and providing massive R&D funding via Horizon Europe—it is severely lagging in the administrative and human capital required to support a circular infrastructure. The transition from linear waste management to the highly technical "10R" circular framework (Repair, Refurbish, Repurpose) requires specialised labour and the rapid commercialisation of new diagnostic technologies. To optimise these indicators, the EC should establish a comprehensive, supranational skills strategy for high-voltage battery triage and retraining, alongside highly efficient IP fast-track procedures for circular technologies.

By treating these precise metrics not merely as a list of policy gaps but as a calibrated roadmap for Impact Optimisation, the EC can implement the most efficient and impactful amendments to its circular economy framework.

3.2.2 Diagnosing the Transposition Gap (National Policy Lag)

While the BPMS provides a macro-level diagnostic of Europe's circularity status, it often masks specific regulatory bottlenecks at the national level. By isolating the EU Supranational Score from individual Member State scores, the DTF analysis enables a precise deconstruction of the Transposition Gap. This gap highlights instances where a Member State's regulatory framework falls below the EU Supranational baseline, indicating a maturity deficit to adequately transpose or enforce existing European mandates.

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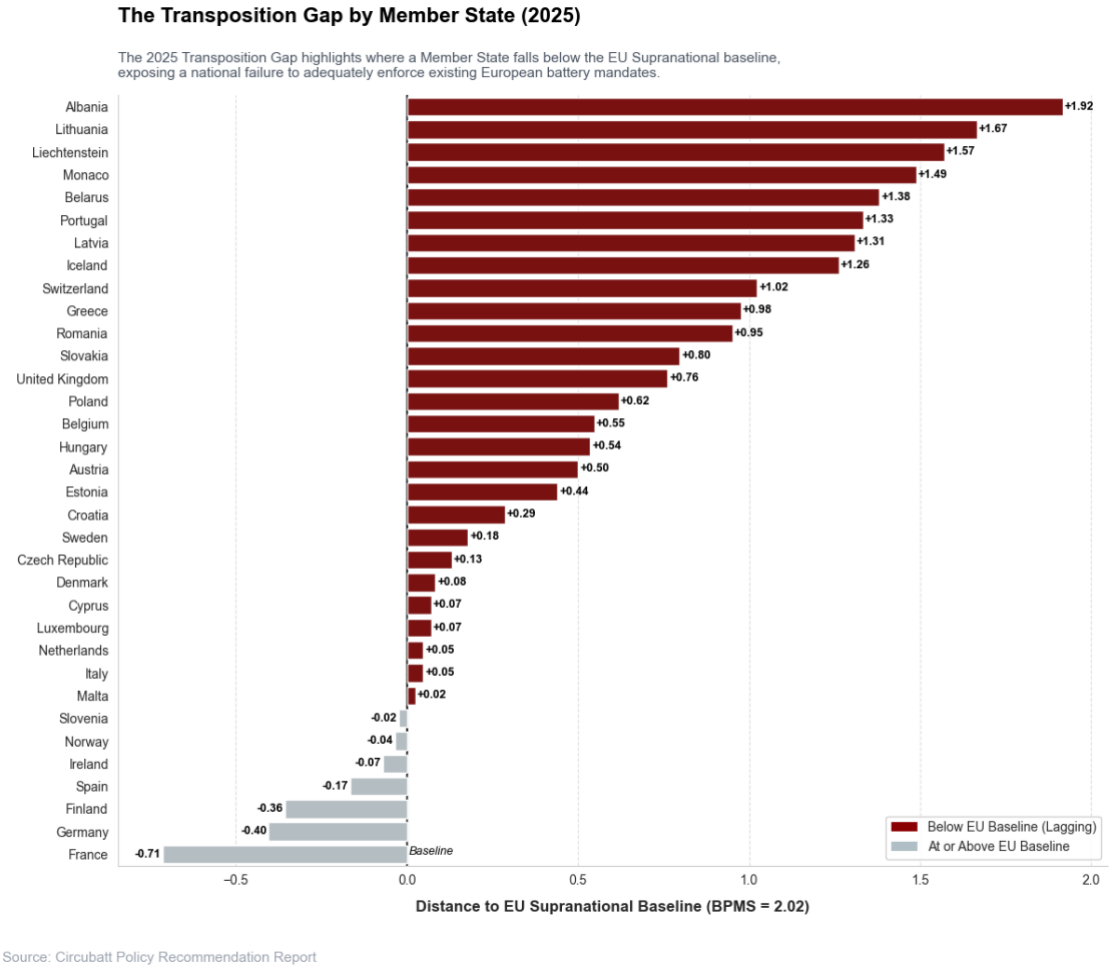


Figure 5 The Transpositional Gap (Member State-level Regulatory Bottlenecks)

Figure 5 visualises the scale of these transposition gaps across 34 assessed countries against the EU Supranational Score. The full summary of the BPMS score, along with the policy deficit profile for each country, is available in Appendix A.4.

As can easily be seen, 7 frontrunners (Germany, France, Norway, Austria, Slovenia, Spain, and Finland) have successfully exceeded the supranational baseline and operate closer to the optimal theoretical frontier of 3.0. Conversely, the chart identifies a massive bloc of 27 laggard Member States whose aggregate policy scores fall below the EU baseline. This severe transposition gap proves that the majority of European economies are failing to operationalise the fundamental circular mandates.

These 27 underperforming nations form the core dataset for the cross-border K-Means clustering analysis deployed in Section 3.2.3 to identify systemic patterns of policy gaps.

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3.3 Clustering Analysis for Cross-border Benchmarking

To translate localised regulatory bottlenecks into actionable EU-wide policy, a clustering algorithm is used to identify systemic, cross-border patterns of policy gaps among underperforming Member States. Critically, the 7 frontrunner economies are deliberately excluded from this modelling because they are largely aligned with the EU Optimal Frontier. Including their minimal gap scores would distort the statistical variance and obscure structural similarities among struggling nations. Restricting the analysis to the 27 lagging nations isolates their specific policy-deficit profiles, allowing the model to accurately group countries with identical legislative gaps. This isolation helps determine whether a transposition gap is a national anomaly or a systemic gridlock affecting multiple Member States, providing the precise geographical targeting needed for supranational interventions.

- **Clustering results**

The K-Means clustering of the 27 laggard Member States yields the optimal number of clusters, **k = 2**, as statistically validated by two evaluation metrics, i.e., the Silhouette Score and the *WCSS* "Elbow" Dynamics (Figure 6).

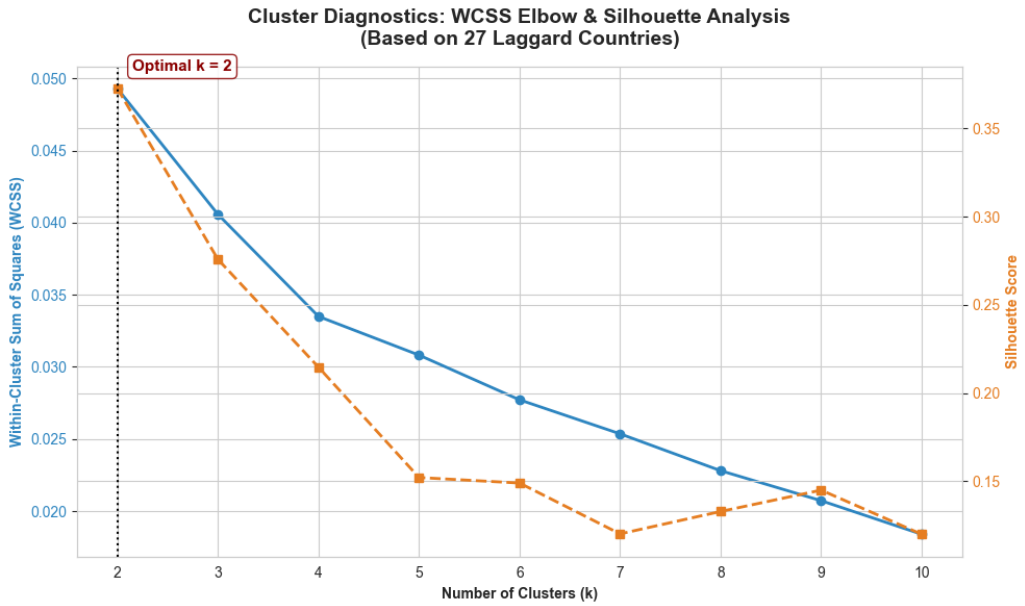


Figure 6 Cluster Diagnostics

The Silhouette Coefficient measures how similar a data point is to its own cluster compared to other clusters, serving as the primary metric for cluster quality in both cohesion (how tightly grouped the points in a cluster are) and separation (how far apart different clusters are). At **k = 2**, the model achieves its highest Silhouette score, **0.3726**. Any further partitioning results in a severe degradation of cluster

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separation. Moving to k = 3 causes the Silhouette score to plummet to 0.2757 (a ~26% drop), and it continues to deteriorate as ***k*** increases. This mathematical drop-off proves that enforcing 3 or more clusters forces the algorithm to artificially split countries that share highly similar policy-deficit profiles.

While the *WCSS* naturally decreases as ***k*** increases (as centroids get closer to individual data points), the goal is to identify the "elbow" point at which the marginal reduction in variance no longer justifies the added complexity of adding another cluster. The WCSS at k = 2 (**0.0493**) represents a highly compacted state for the dataset. Moving from k = 2 to k = 3 only yields a marginal variance reduction (Δ = **0.0087**). This minor reduction in WCSS is not statistically sufficient to justify the substantial loss of cluster distinctness (as seen in the plunging Silhouette score).

From a practical policy perspective, partitioning a relatively small sample size (n=27) into more than two clusters would result in severe over-fragmentation. A higher ***k*** value would create isolated "micro-clusters" of just 3 to 5 countries. By optimising at **k = 2**, the algorithm successfully bifurcates the dataset into two substantial, strategically actionable macro-groups (e.g., "Moderate Laggards" vs. "Severe Laggards"), allowing the European Commission to target broad, supranational interventions rather than hyper-localised fixes.

For cross-border benchmarking, we visualise the two clusters in Figure 7 below. The heatmap visually deconstructs the pan-European regulatory landscape, revealing a critical insight for policymakers: ***a generic, one-size-fits-all European directive would fail***. The divergent visual patterns statistically prove that the two clusters require fundamentally different, highly targeted supranational intervention strategies to successfully reach the optimal policy frontier.

As in Figure 7, the member states in **Cluster 1 (Poland–Malta)** are moderate laggards, featured by administrative and economic bottlenecks that hinder BaaS adoption during the execution and scaling phases. Although they possess the legal scaffolding (low policy deficits in the PA and PB indices), they lack the trained workforce to safely handle advanced, high-voltage repurposed batteries and the state-backed market demand required to scale the sector (high policy deficits in **PF3** - Skills Development and **PC3** - Public Procurement Programs).

On the contrary, the countries in **Cluster 2 (Albania - the UK)** are severe laggards suffering from a deep structural deficit and a fundamental lack of market trust, as depicted by intense, dark red concentrations in **PD3** (Data Interoperability and Security), **PB2** (Battery Testing & Certification), and **PG1** (Warranty and Consumer Protection). Without secure data exchange networks to resolve information asymmetry, standardised safety testing, and performance warranties, neither

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businesses nor consumers will invest in second-life battery technologies. The market is entirely paralysed by risk.

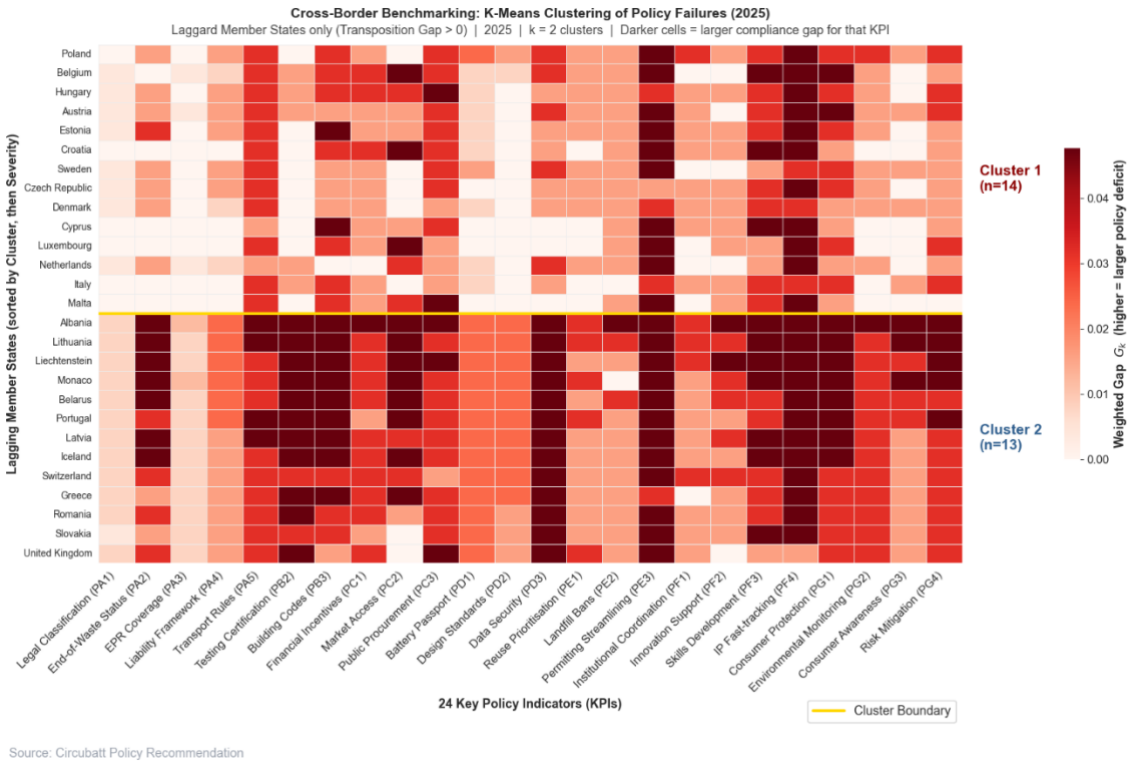


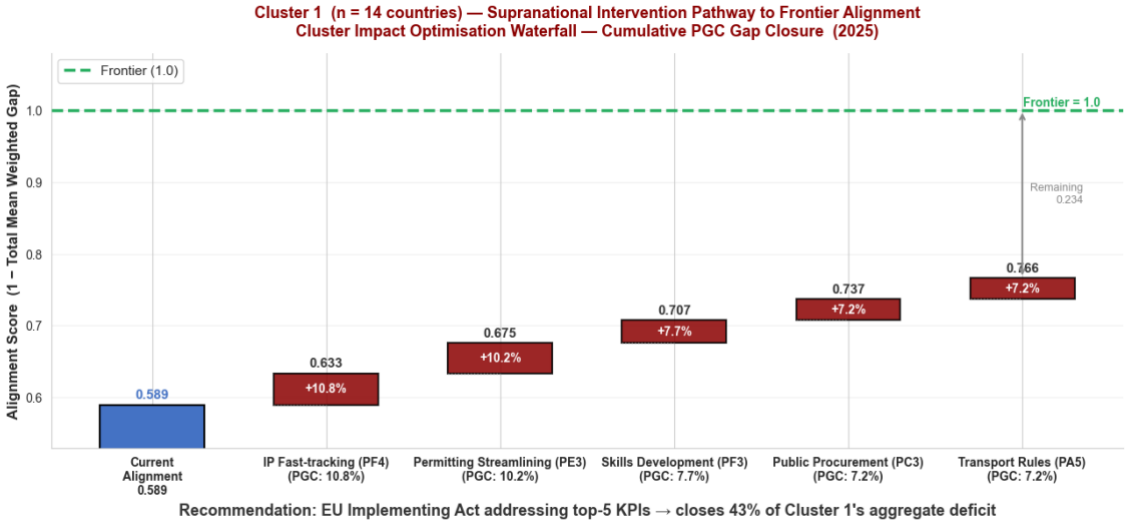
Figure 7 Cross-Border Benchmarking: K-Means Clustering of Policy Gaps

- **Strategic Prioritising Supranational Interventions**

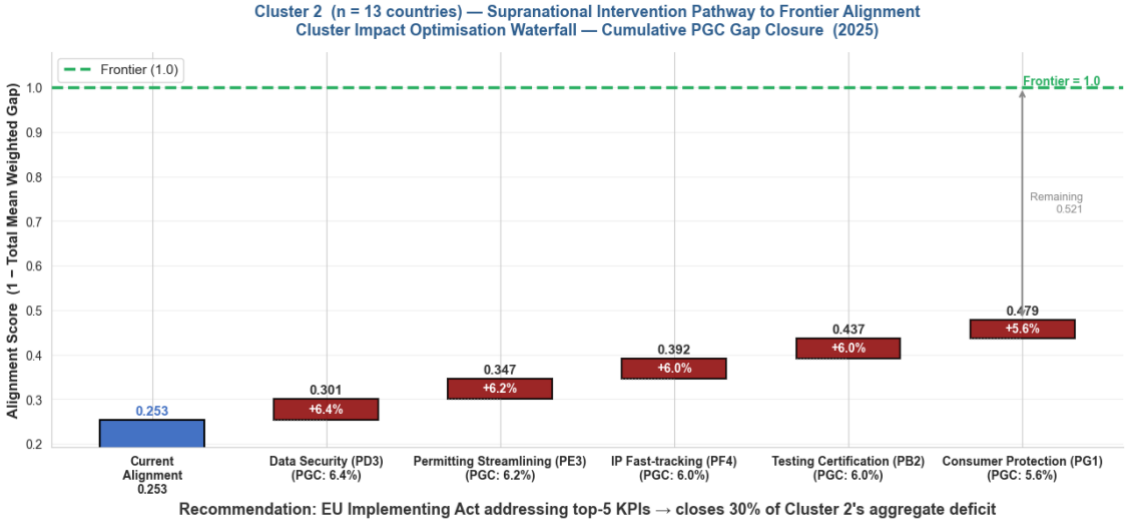
While the heatmap clearly illustrates that these two clusters require fundamentally different intervention strategies, visual diagnosis alone is insufficient to allocate EU resources or draft targeted legislative instruments. To deliver an actionable, data-driven roadmap to the EC, these visual observations must be mathematically validated and ranked.

By calculating the PGC at the cluster level, the analysis transitions from merely diagnosing shared regulatory gaps to mathematically prioritising legislative solutions. The PGC estimates the exact percentage of a cluster's aggregate policy deficit that would be eliminated if a single regulation were upgraded to the optimal theoretical frontier of 3, as illustrated in Figure 8. Analysing the highest-yielding bottlenecks reveals exactly where the European Commission should direct its legislative capital to achieve the highest "Return on Compliance".

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Source: Circubatt Policy Recommendation



Source: Circubatt Policy Recommendation

Figure 8 Supranational Intervention Pathway for Cluster 1 and Cluster 2

Cluster 1

For the Member States in Cluster 1, the regulatory deficit is highly concentrated. Enacting just five targeted legislative upgrades would eliminate a massive 43.1% of the cluster's policy gap. The data indicate that this cluster requires urgent economic and administrative unblocking.

PF4: IP Fast-tracking (10.77% PGC) & PE3: Permitting Streamlining (10.21% PGC)

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These two administrative frictions are the most severe bottlenecks, together accounting for over 20% of the cluster's deficit. Complex environmental permitting protocols and slow innovation pipelines currently paralyse market deployment. For example, Cyprus and Belgium still rely on complex, regionalised environmental departments (such as the Flemish VLAREMA decree) for case-by-case End-of-Waste status, highlighting severe operational friction. Conversely, independent national fixes demonstrate the value of streamlining: the Czech Republic recently reduced the 6-month Battery Energy Storage System (BESS) approval process to a 2-month "filing system" for systems under 10 MW, while Poland officially removed building permit requirements for small BESS installations up to 30 kWh.

PF3: Skills Development (7.73% PGC)

Scaling the circular economy is constrained by a lack of comprehensive national skills strategies. Frontrunners within the cluster have recognised this: the Netherlands addressed its skills deficit by awarding €158 million from its National Growth Fund to the Battery Competence Cluster (BCC-NL), while Hungary's National Battery Industry Strategy 2030 and Sweden's Fossil Free Sweden roadmap have launched strategic dialogues specifically targeting workforce retraining.

PC3: Public Procurement (7.18% PGC) & PA5: Transport Rules (7.18% PGC)

Establishing an economic "demand-floor" and reducing logistics costs are critical to making second-life batteries competitive. Currently, Denmark, Austria, and Luxembourg lead the cluster by directly mandating or subsidising the use of circular criteria in public procurement—such as Denmark's mandatory Total Cost of Ownership (TCO) assessments and Austria's "naBe" guidelines (National Action Plan for Sustainable Public Procurement). This contrasts sharply with the cluster's laggards, who lack binding green procurement mandates and still subject all used batteries to prohibitive hazardous-goods transport rules.

Cluster 2

The Member States in Cluster 2 exhibit a more dispersed deficit profile, with the top five interventions required to close 30.25% of the collective gap. While they share administrative hurdles with Cluster 1 (PF4, PE3), their deficit is deeply rooted in the absence of structural market safeguards, creating a systemic "*trust deficit*".

PD3: Data Interoperability and Security (6.38% PGC)

There is a critical, unmet need for secure, open data-exchange networks with tamper-proof technologies. Lithuania provides stark evidence of this security gap, having to legally ban foreign threat entities from remotely accessing BESS control

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systems (over 100 kW) to protect its grid infrastructure. Meanwhile, Monaco illustrates a highly fragmented approach to operational tracking by strictly enforcing manual data transparency via paper-based Waste Tracking Slips.

PB2: Testing & Certification (6.05% PGC) & PG1: Consumer Protection (5.56% PGC)

Without mandatory testing against accredited standards and bespoke performance warranties, end-users face significant adoption risks. The United Kingdom, serving as a representative anchor for this cluster, exemplifies this gap. The UK currently relies on its 2015 Consumer Rights Act, which provides only baseline retail protections and lacks the bespoke performance and SoH warranties necessary to assess the degradation of second-life assets. Furthermore, rather than enforcing bespoke safety standards tailored exclusively for repurposed batteries, severe laggards rely entirely on transposing generalised European CE marking rules.

PE3: Permitting Streamlining (6.21% PGC) & PF4: IP Fast-tracking (6.05% PGC)

Crucially, PE3 and PF4 also rank among the top 5 highest-yielding bottlenecks in Cluster 2. The cross-border overlap of bottlenecks in PF4 and PE3 provides a paradigm case for targeted EU harmonisation. When multiple Member States struggle with the same policy indicators, it provides undeniable proof that administrative gridlock is a systemic, pan-European crisis rather than an isolated national anomaly. Because countries are independently drafting localised fixes, relying on uncoordinated national corrections will inevitably result in conflicting rules that severely fragment the EU internal market. Therefore, this overlap indicates that an **EU-level Implementing Act** explicitly targeting harmonised, fast-tracked permitting and IP procedures is required to achieve maximum immediate market acceleration across the entire European BaaS ecosystem.

4. Policy Recommendation

Grounded in a 20-year longitudinal trajectory that secures baseline BPMS data, our analyses mathematically demonstrate that a generic, one-size-fits-all European directive will fail to scale the second-life BaaS sector. By capturing the path-dependent nature of legislative momentum, the historical panel also proves that the transition toward a circular ecosystem relies on cumulative policy sequencing. Consequently, the laggard Member States identified in the Transposition Gap diagnostic are at fundamentally different stages of policy evolution and face distinct regulatory deficits, while simultaneous supranational gaps reveal structural weaknesses in overarching EU directives.

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As empirical evidence shows that new policies constantly layer over existing historical frameworks rather than emerging on a blank slate, policymakers should abandon sweeping overhauls. To de-risk industrial investments and facilitate market entry for circular battery actors, the EC should instead deploy highly calibrated, cluster-specific interventions targeted at the highest-yielding bottlenecks.

To maximise regulatory efficiency, the following legislative roadmap allocates finite political capital exclusively toward these precise interventions, structured as a macro-to-micro geographic funnel:

- ***The Supranational Baseline***: It begins by addressing the "Universal Frontier Deficits" affecting all 34 assessed economies—establishing the indispensable pan-European foundation for skills, safety, and transport.

- ***Systemic Gridlock***: From this universal foundation, the roadmap narrows to resolve the systemic administrative and permitting overlap plaguing the 27 laggard Member States.

- ***Targeted Archetypes***: Finally, it zooms in on the highly bespoke interventions required for Cluster 1 (market scaling) and Cluster 2 (data safeguards).

This sequential approach ensures that interventions are strictly allocated toward the highest-yielding bottlenecks and structurally separated by their exact governance level and target actor, aiming to maximise the "**Return on Compliance**" and accelerate the continent's transition to a BaaS circular economy.

A Note on Jurisdictional Scope and Applicable Geographies

Before detailing the specific policy interventions, it is crucial to clarify the jurisdictional realities across the targeted laggard economies. While these recommendations are primarily designed for EU Member States directly bound by European Commission mandates, the identified clusters also encompass non-EU nations that require distinct implementation mechanisms. Specifically, EFTA/EEA members (such as Iceland, Liechtenstein, and Norway) must formally incorporate and transpose these European regulations and directives into their national legal frameworks. Furthermore, external sovereign states outside the EEA (including the United Kingdom, Albania, and Monaco) operate as alignment monitors; for these nations, adopting the recommended EU standards is achieved through domestic legislative mirroring, driven by the economic imperative of maintaining technical parity and cross-border access to the Single Market.

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Recommendation 1: Establishing the Supranational Baseline (Pan-European Enablers)

Applicable Geographies

All 34 studied economies and the EU Supranational level

Recommendation

To resolve universal physical and human deficits, the EC should establish a unified foundation of second-life fire safety codes, data-driven cross-border transport logistics, and high-voltage workforce training.

Rationale

The DTF analysis reveals that specific physical and logistical bottlenecks are systemic across Europe, stifling the circular battery market before it even reaches the commercialisation phase.

- The single largest bottleneck hindering the European BaaS market is Modernised Safety & Building Codes (PB3), accounting for a massive 14.6% of the supranational gap. While **Article 12 of the EU Battery Regulation (2023/1542)** mandates product-level safety testing, facility deployment rules remain severely fragmented. Member States are resorting to piecemeal local ordinances—such as Austria's MVBÖ-004-2023-01 guidelines, Denmark's DEMA fire guidelines, and France's bespoke BESS draft ordinance—that paralyse cross-border indoor BESS deployments.
- Concurrently, the physical movement of these assets triggers the application of prohibitively expensive hazardous-goods rules (PA5), while a severe, continent-wide human-capital deficit (PF3) leaves these markets without the technical workforce required to safely perform high-voltage triage. These three enablers represent the non-negotiable physical baseline required for the internal market to function.

Actionable Interventions

Action 1.1: Mandate Harmonised Technical Standards for BESS (Targeting PB3)

- *Target Actors*: The Directorate General for Energy (DG ENER) & CEN/CENELEC.
- *The Mechanism*: Recognising that local building codes and zoning laws remain a protected national competence under the subsidiarity principle, the

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Commission should provide a unifying alternative to fragmented local ordinances by standardising the underlying physical technology. The Commission should issue an urgent standardisation request to CEN/CENELEC to finalise a comprehensive, harmonised technical standard (EN) specifically governing the safe indoor and co-located installation of second-life BESS. Concurrently, the Commission should leverage the **Energy Performance of Buildings Directive (EPBD)** to strongly incentivise National Building Control Authorities to adopt this harmonised standard into their domestic fire codes.

Action 1.2: Digitise and Exempt Cross-Border Transport (Targeting PA5)

- *Target Actors*: The Directorate-General for Mobility and Transport (DG MOVE) and the UNECE (Working Party 15).

- *The Mechanism*: Recent updates to *the European Agreement concerning the International Carriage of Dangerous Goods by Road* (**ADR 2025**) and draft 2027 amendments show a continued reliance on the legacy UN 38.3 physical testing paradigm, refusing to automatically exempt functional second-life batteries from strict overheads. To bypass this, DG MOVE could execute a dual-timeline strategy. Globally, it could consider petitioning the UNECE to formally amend the ADR to legally recognise digital tracking. Regionally and immediately, DG MOVE should coordinate a pan-European **ADR Multilateral Agreement (MA)**. This MA will act as a legal sandbox, utilising certified SoH data from the forthcoming 2027 DBP to act as proof of safety, automatically exempting functional second-life assets from restrictive Dangerous Goods (Class 9) transport classifications and destructive testing mandates across participating states.

Action 1.3: Scale the EBA Academy via the Pact for Skills (Targeting PF3)

- *Target Actors*: The Directorate-General for Employment, Social Affairs and Inclusion (DG EMPL) and National Ministries of Education/Labour.

- *The Mechanism:* Given that the EC cannot legally mandate domestic educational curricula, it could use targeted financial leverage to close the human capital deficit. DG EMPL, operating through the EU Pact for Skills, should heavily subsidise and strictly condition funding on the integration of the EBA Academy's high-voltage triage and circular-economy curricula into national vocational frameworks. Concurrently, National Ministries of Labour should draw down **European Social Fund Plus (ESF+)** and **Just Transition Fund (JTF)** allocations to localise and deploy these harmonised standards. By formally designating circular battery diagnostics and high-voltage repurposing as

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National Shortage Occupations, Member States can rapidly unlock financing for targeted vocational retraining. To ensure execution, a prime example to emulate is Slovenia's successful deployment of Just Transition Funds for its Training and Carbon-Free Technologies Centre, or the Netherlands' decisive €158 million grant to establish its Battery Competence Cluster.

Recommendation 2: Resolving the Battery EoW-Permitting Gridlock

Applicable Geographies

The 27 Laggard economies in both Cluster 1 and Cluster 2.

Recommendation

The EC should establish a harmonised, two-pronged approach to battery repurposing that simultaneously tackles material End-of-Waste status (PA2) and Facility Permitting (PE3).

Rationale

A functional BaaS circular economy requires two simultaneous legal clearances: the physical repurposing facility (***The Infrastructure***) must be authorised to operate (PE3), and the battery itself (***The Material***) must be legally reclassified from hazardous waste to a viable product (PA2). If the Commission only accelerates factory permitting (PE3), it solves the infrastructure hurdle but leaves the material trapped in complex waste-transit bureaucracies—resulting in state-of-the-art facilities sitting idle. Therefore, successfully resolving the Permitting Streamlining deficit, which yields a critical 9.8% PGC, strictly requires treating PE3 and PA2 as a systemic ***compound*** bottleneck. Expanding the legal pathway for the facility is futile unless the material flowing into it is simultaneously liberated.

Target Actors

The Directorate-General for the Environment (DG ENV) and National Environmental Agencies

Suggested Actionable Steps

It is noteworthy that Member States are more likely to fiercely protect their sovereignty over local zoning and industrial permitting under the principle of subsidiarity. The Commission cannot simply impose a top-down "permit-by-rule" system. Instead, the EU should leverage existing strategic frameworks to legally bypass this jurisdictional trap.

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To clear these compound administrative deployment bottlenecks, the EC should consider a two-pronged strategy:

- *Harmonising End-of-Waste Product Status (Targeting PA2):*

To clear the first administrative hurdle, DG ENV could consider enacting an Implementing Act under Article 73(4) of the Batteries Regulation (EU) 2023/1542. This act should establish harmonised EoW criteria linked to SoH diagnostics from the DBP, clarifying the legal transition of the battery itself from "waste" to "product".

- *Accelerated Facility Permitting via the NZIA (Targeting PE3):*

To resolve the facility-permitting bottleneck without violating the subsidiarity principle, the Commission should anchor deployment in the Net-Zero Industry Act (NZIA). Rather than creating new rules under a future Circular Economy Act, the Commission should formally classify battery repurposing sites as "Net-Zero Strategic Projects", thereby compelling Member States to apply the NZIA's accelerated, streamlined permitting timelines without violating national sovereignty over local environmental site assessments.

Recommendation 3: Accelerating Circular Commercialisation

Applicable Geographies

All 34 studied economies and the EU Supranational level

Recommendation

To secure European industrial sovereignty, the EC should urgently explore collaborative diplomatic avenues to establish an accelerated Intellectual Property (IP) protocol specifically tailored for circular battery technologies and diagnostic algorithms.

Rationale

The PGC analysis highlights IP Fast-tracking (PF4) as a major yield bottleneck, accounting for 9.8% of the EU supranational gap. Crucially, this bottleneck is pervasive across maturity levels, accounting for 10.77% of the policy gap for Cluster 1 (moderate laggards) and 6.05% for Cluster 2 (severe laggards). This cross-border overlap provides undeniable evidence that administrative gridlock regarding IP is a systemic, pan-European crisis rather than an isolated national anomaly.

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Sluggish patent processing times disproportionately harm circular BaaS start-ups, whose business models rely heavily on proprietary diagnostic software, SoH algorithms, and rapid hardware adaptation. When core intellectual property is trapped in administrative limbo, it chills venture capital investment and stalls commercialisation, allowing heavily subsidised global competitors to outpace the European internal market.

Target Actors

The Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW), the European Patent Office (EPO), and National Intellectual Property Offices.

Suggested Actionable Steps

- *Evaluate Avenues for Circular IP Fast-Tracking at the EPO (Targeting PF4)*

Recognising that the Commission does not set independent EPO processing timelines, DG GROW should explore alternative diplomatic mechanisms to expedite BaaS patents. The Commission should initiate a formal dialogue with the EPO to assess the feasibility of a dedicated "Circular Tech Fast-Track" under the newly operational Unitary Patent system. This initiative would prioritise applications for battery repurposing, diagnostic algorithms, and critical mineral recovery, significantly reducing time-to-market.

- *Anchor IP Priority to the NZIA and the 2026 Industrial Accelerator Act*

Next, to provide immediate political leverage for this fast-track, the Commission could anchor IP processing speed to both existing and upcoming industrial security frameworks. Under the NZIA, battery circularity is recognised as a critical pillar of resilience. The Commission could formally advise that technologies granted "Net-Zero Strategic Project" status under the NZIA automatically receive priority administrative and IP filing support from National Competent Authorities. Concurrently, to elevate this priority to the supranational level, the Commission should leverage the forthcoming **2026 Industrial Accelerator Act**—which explicitly introduces "Made in Europe" conditionality and mandatory intellectual property licensing obligations—to formally treat circular IP processing speed as a matter of urgent industrial sovereignty in its dialogues with the EPO.

<u>Recommendation 4: Cluster 1 Interventions (Market Scaling & Execution)</u>

Applicable Geographies

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The 14 "Moderate Laggard" economies in Cluster 1.

Recommendation

Cluster 1 governments need to secure the commercial viability of the circular economy by implementing binding public procurement mandates and targeted financial incentives to establish a baseline of guaranteed demand and drive market uptake.

Rationale

Cluster 1 faces severe economic and execution bottlenecks. Even if legal barriers are removed, second-life batteries face a structural economic disadvantage compared with the rapidly declining manufacturing costs of imported virgin Lithium-Iron-Phosphate (LFP) cells (Reid *et al.*, 2016). Relying on voluntary guidelines that treat repurposed batteries as merely "desirable" is insufficient. Without binding public procurement mandates and targeted financial incentives to establish a guaranteed baseline of demand, it is commercially unviable for independent repurposers to secure the capital needed to industrialise the multi-life trajectory of lithium-ion assets.

Target Actors

- The EC (DG GROW, DG ENV): To fast-track harmonised procurement guidelines under the EU Battery Regulation.
- National Procurement Authorities and Ministries of Finance: To proactively implement binding quotas domestically and deploy targeted financial incentives to drive market uptake.

Suggested Actionable Steps

- *Establish a Guaranteed Demand Baseline (Targeting PC3)*

To overcome the existential price disadvantage that second-life batteries face, the EC could consider fast-tracking the Delegated Acts under **Article 85 of the EU Battery Regulation (2023/1542)**. To prevent market stalling, Member State National Procurement Authorities must not wait for this top-down enforcement. Drawing on the Spanish and Danish models, national governments should proactively set binding sustainability thresholds in public tenders (specifically for micro-grids and smart-city infrastructure). Concurrently, Ministries of Finance could drive market uptake through targeted financial incentives—emulating Austria's €150/kWh grants for Battery Energy Storage Systems (BESS) or Hungary's Home Energy Storage Program, which subsidises up to 80% of residential installation costs.

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Recommendation 5: Cluster 2 Interventions (Structural Safeguards)

Applicable Geographies

The 13 "Severe Laggard" economies in Cluster 2

Recommendation

Cluster 2 governments should immediately prioritise the establishment of structural market safeguards by enforcing secure data interoperability networks and mandating bespoke SoH warranties and safety certifications.

While the EC cannot directly legislate for non-EU Cluster 2 nations (e.g., the UK, Albania), it could leverage market access conditions, Association Agreements, and the Energy Community treaty to compel these nations to adopt the following structural safeguards.

Rationale

The deficit in Cluster 2 (Severe Laggards) is deeply rooted in the absence of structural market safeguards, including data security (PD3), testing standards (PB2) and bespoke consumer protections (PG1), collectively accounting for 18% PGC. These create a severe "trust deficit" that stunts adoption. Without secure data networks to verify degradation, commercial institutions cannot underwrite second-life assets. The severity of this gap is illustrated by the extreme measures and fragmented approaches currently taken by these nations:

- *Lithuania (Data Security):* To protect critical grid infrastructure from foreign interference, the Lithuanian Parliament had to adopt a law banning remote access to Battery Energy Storage Systems (BESS) over 100 kW by entities from countries deemed national security threats, applicable to all new projects by May 2025.

- *Monaco (Data Fragmentation):* At the other end of the spectrum, Monaco relies entirely on highly fragmented, manual transparency. Under Ministerial Decree n° 2021-317, any entity handling waste batteries must use a paper-based Waste Tracking Slip (*Bordereau de Suivi des Déchets*) to track waste codes and destinations, leaving the system vulnerable to data loss and inefficiencies.

- *United Kingdom (Consumer Protection):* Furthermore, anchor nations like the UK rely on inadequate, generalised consumer retail laws—specifically the 2015 Consumer Rights Act. While this Act gives consumers a short-term right to reject a faulty product within 30 days or demand a repair within six

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months, it relies entirely on general contract law. Crucially, it does not mandate the disclosure of SoH metrics, cycle history, or minimum remaining capacity promises. This leaves a massive void instead of enforcing bespoke performance warranties or mandatory secondary-life testing standards (PB2, PG1).

Target Actor

The EC's Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW) and Directorate-General for Communications Networks, Content and Technology (DG CNECT).

National Digital/Cybersecurity Agencies and Environmental/Consumer Protection Authorities within the 13 economies in Cluster 2.

Actionable Steps

- *Break BMS Lock-ins via DBP and Data Act Alignment (Targeting PD3)*

To resolve severe data fragmentation—and mitigate reactionary national security bans—the EC should finalise the secondary delegated acts under Article 77 of the EU Battery Regulation (2023/1542), explicitly coupling them with the open-access mandates of the EU Data Act (2023/2854). This combined legislation must clearly define cybersecurity standards and selective read/write permission protocols before the February 2027 deadline to legally compel OEMs to eliminate proprietary Battery Management System (BMS) lock-ins.

Consequently, National Digital and Environmental Agencies within Cluster 2 (and external alignment monitors) should urgently align their domestic data regulations with this combined EU framework. Rather than building isolated tracking systems, these national governments must strictly enforce these EU interoperability protocols, ensuring that dynamic lifecycle data is machine-readable and transferable across borders without vendor lock-in, creating a single, secure source of truth.

- *Mandate SoH Disclosure to Enable the Warranty Market (Targeting PG1)*

To foster enterprise and consumer trust, National Consumer Protection Authorities within Cluster 2 should introduce bespoke Consumer Protection legislation for secondary-life batteries. These governments must legally mandate the absolute and proactive disclosure of dynamic SoH metrics, cycle history, and initial capacity prior to any B2B or B2C secondary transaction. By legally enforcing this transparency—mirroring the EU's DBP framework—national regulators will

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eliminate the information asymmetry (adverse selection) that currently prevents commercial insurers from underwriting bespoke second-life performance warranties.

- *Establish Distinct Conformity Assessments for second-life applications (Targeting PB2)*

National standardisation bodies and market surveillance authorities within Cluster 2 must reject reliance on generic Low Voltage Directives for second-life applications. Instead, to maintain technical parity with the Single Market, these nations should formally integrate the rigorous, harmonised testing standards for battery repurposing currently being finalised by CEN/CENELEC under the mandate of the EU Battery Regulation. National authorities could consider mandating that entry into the secondary-life market require an accredited Conformity Assessment based on these specific electrochemical protocols. This testing must explicitly verify capacity fade, internal resistance, and mitigation of thermal runaway propagation before an asset can legally earn its CE mark or equivalent national safety mark for its second life.

5. Conclusion and Future Agenda in Year 3

5.1 Report Summary

Deliverable D1.9 provides a highly calibrated, data-driven policy roadmap designed to accelerate the European second-life BaaS ecosystem. By introducing the 25-indicator BPMS and systematically evaluating 34 nations over a 20-year longitudinal panel, the study mathematically demonstrates that a generic, one-size-fits-all EU directive is insufficient to scale the sector. Utilising DTF and K-Means clustering analyses, the study isolates high-yield legislative bottlenecks and diagnoses profound "Supranational" and "Transposition" gaps. Ultimately, it categorises 27 lagging Member States into two distinct clusters that require highly targeted interventions - focusing either on market execution or on structural safeguards - to actively de-risk circular industrial investments.

5.2 Contributions to European Policymakers

- **Strategic Prioritising for high-yield Roadmap with Finite Resources**

The report transitions regulatory strategy away from broad, untargeted legislative overhauls. Calculating PGC metrics equips the EC and national authorities with a prioritised list of bottlenecks. For example, the study reveals that targeting just five supranational enablers—such as modernising safety codes (PB3), digitising

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transport rules (PA5), and IP fast-tracking (PF4)—can close an overwhelming 53.7% of the overarching EU policy deficit. This allows regulators to allocate finite political capital to maximise the "Return on Compliance".

- **Deconstructing the "One-Size-Fits-All" Fallacy**

By mathematically proving the existence of a substantial Transposition Gap across 27 Member States, the study shows that lagging nations require tailored strategies rather than blanket mandates.

For "Moderate Laggards" (Cluster 1), regulators should focus on stimulating economic demand and removing administrative barriers, specifically through binding public procurement programmes (PC3) and skills development (PF3) to overcome early-stage commercialisation hurdles.

For "Severe Laggards" (Cluster 2), the report urges policymakers to urgently enforce structural market safeguards to address a severe market "trust deficit." This includes utilising the EU Data Act to mandate data interoperability (PD3), distinct safety testing protocols (PB2), and proactive SoH disclosures for performance warranties (PG1)

5.3 Contributions to Academic Researchers

- **Methodological Advancements in Index Construction**

The study resolves major vulnerabilities in composite indices—specifically, the issue of double-counting—by employing a rigorous two-stage diagnostic process that combines Pairwise Correlation Matrices with PCA. This robust statistical method enables researchers to objectively eliminate extreme redundancy (e.g., removing PB1 because it shares the same dominant latent component as PB2) and to apply reduced joint weights to partially overlapping indicators. Furthermore, its use of an absolute "EU Optimal Frontier" rather than an empirical baseline solves the "moving goalpost" problem common in comparative regulatory studies.

- **A 20-Year Longitudinal Policy Trajectory**

The report presents a comprehensive multi-country dataset (2006–2025) tracking the evolution of structural, contractual, and interactive policy instruments. It shows, both visually and mathematically, that institutional policy maturity does not follow a smooth, continuous curve. Instead, regulatory frameworks progress along a "staircase-like" trajectory, marked by long periods of stagnation punctuated by transformative legislative shocks, most notably the EU Battery Regulation

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2023/1542, which successfully decoupled functional assets from hazardous waste classifications and mandated digital tracking.

5.4 Future Research Agenda for Deliverable D1.10

A key limitation of Deliverable D1.9 is that the BPMS methodology exclusively evaluates abstract policy design features—such as legal stringency, legislative depth, and regulatory predictability. The current framework successfully diagnoses structural gaps in this design that lead to regulatory bottlenecks and measures the presence and theoretical strictness of enacted interventions. However, it does not assess policy outcomes, the effectiveness of administrative enforcement, or the success of localised implementation.

To bridge this limitation, Deliverable D1.10 (scheduled for Year 3) will transition the research from Phase 1 (diagnostic policy evaluation) to Phase 2 (causal impact assessment). The future research agenda will pivot to ingesting market effectiveness data relevant to second-life EV batteries. By building interpretable predictive models, D1.10 will rigorously assess the causal impact of these documented government interventions, ultimately measuring how the established policy mixes translate into tangible market readiness, operational scaling, and overall maturity for the European second-life BaaS ecosystem.

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Appendix

Appendix A1: Definition and codebook of Key Policy Indicator

Table A. 1 Definition and codebook of Key Policy Indicator

KPI Code	KPI Name	KPI Definition
PA. Regulatory & Legal Framework Index *(Measures enacted regulations, legal definitions, and liability frameworks)*		
PA1	Legal Classification	Measures the extent to which the law distinguishes and defines a distinct legal category for used batteries destined for reuse/ repurposing, as opposed to automatically classifying them as waste.
PA2	End-of-Waste (EoW) Status	Evaluates the clarity and comprehensiveness of the legal pathway for batteries to cease being treated as waste.
PA3	EPR Coverage	Assesses whether Extended Producer Responsibility (EPR) legislation explicitly defines mandatory obligations for BaaS and circular actors, rather than just original OEMs.
PA4	Liability Framework	Measures the clarity of legislation in defining the chain of legal liability across the entire BaaS value chain.
PA5	Logistics & Transport Rules	Evaluates whether transport regulations are streamlined for certified reused batteries or if they are burdened by stringent hazardous waste transport rules.
PB. Safety & Standards Index *(Measures established safety, testing, and performance standards)*		
PB1	Reuse/Repurposing Safety Standards	Assesses the presence of mandatory, binding safety standards tailored exclusively for second-life battery applications.
PB2	Battery Testing & Certification	Measures whether testing prior to market entry uses standardized protocols and requires formal, accredited certification.
PB3	Modernised Safety & Building Codes	Evaluates if national building and fire codes have been formally updated with specific requirements addressing second-life battery systems.
PC. Incentives & Economic Enablement Index *(Measures financial, fiscal, and market support mechanisms)*		
PC1	Financial Incentives	Assesses the availability of subsidies and tax credits, and whether these structures are technology-neutral or offer specific bonuses for second-life batteries over new ones.
PC2	Market Participation & Access	Measures if energy market regulations have been reformed to allow distributed storage to aggregate and gain fair access to relevant revenue streams like ancillary services.
PC3	Public Procurement Programs	Evaluates if green procurement guidelines feature comprehensive, binding mandates requiring the use of second-life batteries or BaaS in public projects.

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PD. Data & Information Transparency Index *(Measures mandates for transparency and digital standards for battery data)*		
PD1	Battery Passport or Tracking Mandate	Assesses the mandate for detailed, dynamic digital records of a battery's performance and material composition.
PD2	Data Access Rules	Measures whether regulations mandate that OEMs provide open, secure access to key Battery Management System (BMS) data for third parties or legal owners.
PD3	Data Interoperability and Security	Evaluates compliance with interoperable, secure open data exchange networks utilizing standard encryption and tamper-proof technologies.
PE. Circular Economy Integration Index *(Measures integration into broader circular economy and waste management policies)*		
PE1	Reuse Prioritisation	Assesses whether there is a mandatory legal hierarchy and binding operational procedures that prioritize reuse over recycling.
PE2	Landfill Bans	Measures the strictness of prohibitions against landfilling untreated waste batteries, up to an absolute zero-landfill requirement.
PE3	Permitting Streamlining	Evaluates the existence of streamlined, dedicated permitting procedures (e.g., permit-by-rule systems) tailored for battery repurposing compared to general waste permits.
PF. Institutional Capacity & Governance Index *(Measures government capacity to enforce, coordinate, and foster innovation)*		
PF1	Dedicated Institutional Coordination/ Governance	Assesses the presence of an integrated, resourceful governance framework and coordination mechanisms for the sector.
PF2	R&D Grants & Innovation Support	Measures government support for innovation through dedicated funding streams, grants, and open-access testing facilities.
PF3	Skills Development Programs	Evaluates the scope of skills development, ranging from basic awareness to comprehensive national strategies with structured vocational programs and large-scale retraining.
PF4	IP Fast-tracking	Assesses the availability and efficiency of fast-track procedures for Intellectual Property related to green technologies.
PG. Consumer & Environmental Protection Index *(Measures safeguards and public information policies)*		
PG1	Warranty and Consumer Protection	Measures the existence of a harmonised protection framework with mandated warranties for both B2C and B2B transactions.
PG2	Environmental Impact Monitoring	Evaluates if there is mandatory, comprehensive lifecycle monitoring and reporting of environmental metrics enforced by independent third-party verification.

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PG3	Consumer Awareness/Labelling	Assesses whether a standardised, enforceable consumer information regime exists, including labelling, warnings, and SoH access.
PG4	Operational Risk Mitigation & Financial Compliance	Measures the mandate for operational controls (like emergency plans), robust financial guarantees, and third-party safety audits to mitigate reuse risks.

Appendix A.2. Redundancy and Double-Counting Assessment

To ensure the statistical integrity of the composite index, a two-stage diagnostic process was employed to identify and mitigate the risk of double-counting. In policy analysis, double-counting occurs when multiple policy indicators measure the same underlying dimension, which implicitly overweights that dimension in the final index.

First, the pairwise correlation matrix was examined to screen for KPI pairs exhibiting strong linear association. As an initial criterion, pairs with an absolute correlation coefficient of at least $r \geq 0.70$ were flagged as potential candidates for redundancy. This threshold-based screening was used only as a preliminary indicator of possible overlap, since high correlation alone does not necessarily imply that two variables measure the same underlying construct. Therefore, these pairs are moved to the second stage for structural verification.

In the second stage, Principal Component Analysis (PCA) is applied to the flagged indicators to assess whether their high correlation translates into a systemic double-counting risk (OECD, 2008). PCA mathematically transforms overlapping, collinear indicators into a set of completely uncorrelated variables (i.e., Principal Components). By analysing how much variance each principal component explains and which original indicators cluster together on these components, we can precisely identify redundancies. This allows us to adjust our methodology—either by grouping overlapping indicators into sub-pillars or by applying fractional weights—ensuring that the final index provides a balanced, statistically sound measure of all intended policy dimensions.

Prior to estimation, KPIs were first Z-score standardised to ensure comparability across different scales. The analysis then generated principal components, each representing a linear combination of the original indicators, ranked by the proportion of total variance explained. The scree plot and cumulative explained variance were used to evaluate how many components were needed to summarise the dataset, while the component loadings were examined to identify which KPIs contributed most strongly to each latent dimension.

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The PCA loading matrix was inspected for the leading components, and highly correlated indicator pairs flagged in the first stage were considered at greater risk of double-counting if both loaded most strongly on the same principal component. In practical terms, a pair was treated as a stronger candidate for redundancy when: (i) both indicators loaded on the same dominant component; (ii) the absolute loadings on that component were substantively meaningful, for example ≥0.40; and (iii) the loadings were of the same sign, indicating that the indicators moved in the same direction on the shared latent dimension. Conversely, pairs with high correlations but dominant loadings on different components were treated as lower-risk cases, as this suggested that their association did not reflect substantial latent overlap.

By combining pairwise correlation thresholds with PCA loading rules, the analysis distinguished between simple statistical associations and deeper structural redundancy, thereby providing a more robust basis for identifying indicators at risk of double-counting. Depending on their double-counting risk, we can adjust their weights in the composite index accordingly.

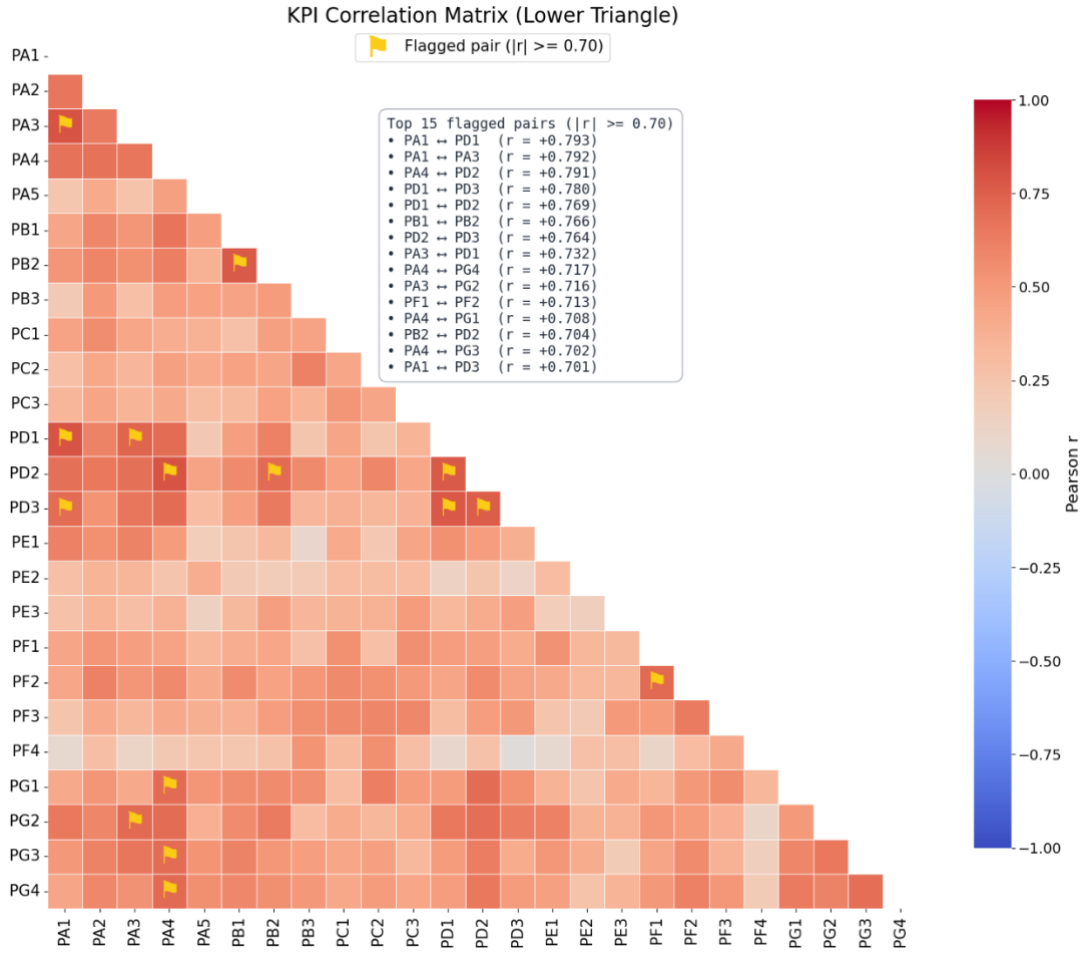


Figure A. 1 Correlation Matrix

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As a result of the first stage, the correlation matrix (Figure A.1) has flagged the top 15 pairs with the highest correlation coefficients. We do not detect any strongly correlated pair ($r \geq 0.8.0$) in our data.

The PCA results in the second stage are illustrated in the scree plot (Figure A.2), which indicates that our KPI set contains both a strong common policy dimension and several additional distinct dimensions. The first principal component explains 48.4% of the total variance, suggesting that a substantial share of the KPIs move together and may be capturing overlapping aspects of the same underlying policy construct. However, eight principal components are required to explain more than 80% of total variance, indicating that the dataset is not purely one-dimensional and still contains meaningful variation across multiple policy dimensions. This pattern suggests a moderate risk of double-counting rather than complete redundancy: some indicators appear to reinforce the same signal, while others contribute unique information.

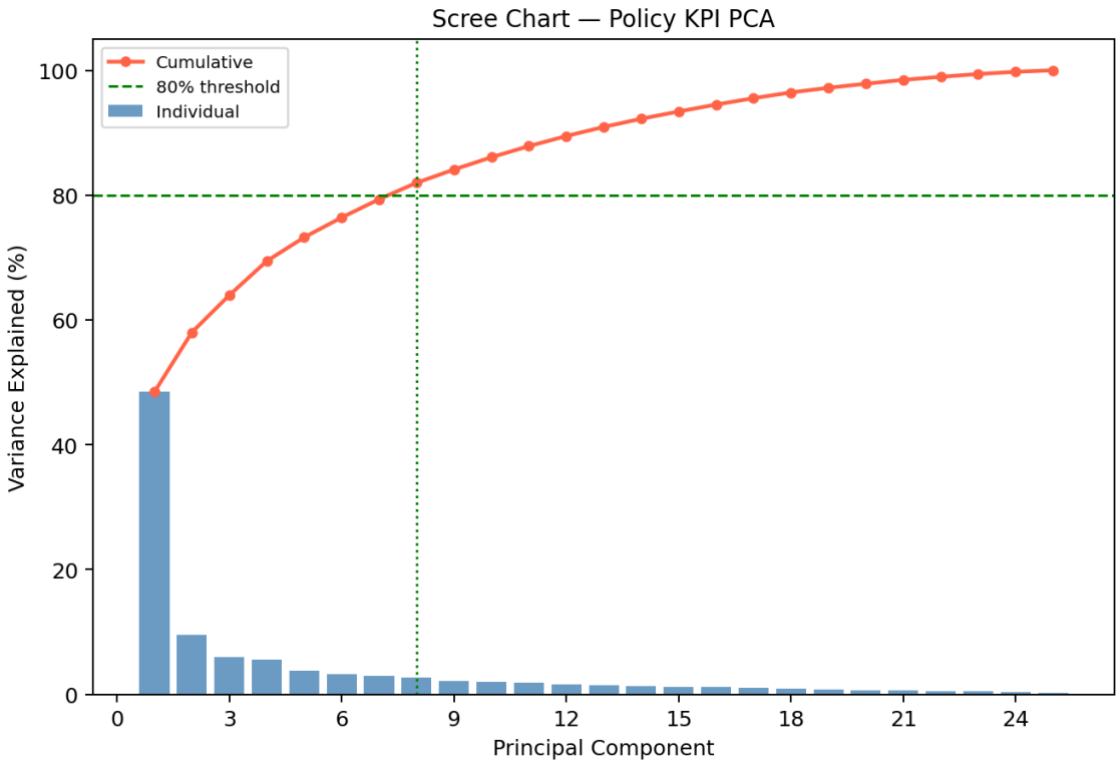


Figure A. 2 PCA Scree Chart

For index construction, this implies that equal weighting across all KPIs may overstate the importance of the dominant dimension captured by the first component. A more robust approach would be to inspect the loading structure, identify indicators with strong common loadings on the first component, and either downweight or consolidate those indicators while retaining variables that load on later components and capture distinct policy features.

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PCA loadings were then examined as a complementary diagnostic to assess whether the top 15 correlated indicator pairs also clustered on the same principal component, indicating broader latent overlap and a possible risk of double-counting. The result is presented in Table A.2.

Table A. 2 PC loading-based assessment of correlated KPI pairs for double-counting risk

Indicator Pair (A-B)	Correlation score	Shared Top Principal Component (PC)?	Loading A	Loading B
Double-counting risk level: HIGH Reason: Highly correlated, share the same top PC with same-sign, loading score ≥ 0.4 Action: Review for consolidation, downweighting, or retaining only one indicator				
PB1 ↔ PB2	0.766	Yes (PC7)	0.458	0.419
Double-counting risk level: MEDIUM Reason: Highly correlated, share the same top PC & same-sign loading score < 0.4 Action: Retain both indicators but reviewing for potential downweighing				
PA1 ↔ PD1	0.793	Yes (PC2)	−0.318	−0.303
PA1 ↔ PA3	0.792	Yes (PC2)	−0.318	−0.260
PA4 ↔ PD2	0.791	Yes (PC1)	0.244	0.250
PA3 ↔ PD1	0.732	Yes (PC2)	−0.260	−0.303
Double-counting risk level: LOW Reason: Highly correlated, but the KPIs belong fundamentally to different dominant PCs. Action: Distinct, independent domains despite high correlation. No action required.				
PD1 ↔ PD3	0.780	No	PC 2	PC 8
PD1 ↔ PD2	0.769	No	PC 2	PC 1
PD2 ↔ PD3	0.764	No	PC 1	PC 8
PA4 ↔ PG4	0.717	No	PC 1	PC 5
PA3 ↔ PG2	0.716	No	PC 2	PC 1
PF1 ↔ PF2	0.713	No	PC 3	PC 6
PA4 ↔ PG1	0.708	No	PC 1	PC 7
PB2 ↔ PD2	0.704	No	PC 7	PC 1
PA4 ↔ PG3	0.702	No	PC 1	PC 4
PA1 ↔ PD3	0.701	No	PC 2	PC 8

As seen in Table A.2, the PCA identified one pair for which the evidence of redundancy is strong: **PB1 (Reuse Safety Standards)** and **PB2 (Testing and Certification).** These two indicators load on the same dominant principal component with strong, synchronised loadings (0.458 and 0.419, respectively),

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indicating that they measure a closely shared underlying regulatory dimension. Retaining both would therefore risk over-representing the "safety enforcement" dimension within the composite indicator. In line with the principle of parsimony and to avoid double-counting, PB1 was removed, while PB2 was retained as the more comprehensive and statistically robust indicator.

Table A.2 also identified a cluster of indicators that showed partial overlap rather than full duplication. This applies to **PA1–PD1, PA1–PA3, PA4–PD2,** and **PA3–PD1**, which load on the same principal component but with comparatively weak common loadings. These results indicate that the indicators share some common variance, but not to an extent that would justify exclusion. Removing them would risk discarding valuable information. Accordingly, these indicators were retained, but their weighting was adjusted to account for partial redundancy. In practical terms, this means applying reduced or fractional weights to the relevant grouped indicators so as to limit the influence of their shared variance on the overall index.

In particular, the partial-overlap cluster of **PA1 (Legal Classification)**, **PA3 (EPR Coverage)**, and **PD1 (Battery Passport)** is assigned a joint weight of **1 standard indicator**. As a critical digital enabler, PD1 receives half of the joint weight (0.5W), while PA1 and PA3, both belonging to the legal dimension, share the remaining weight (0.25W each). Likewise, **PA4 (Liability)** and **PD2 (Data Access)** are assigned fractional weights (e.g., 50% each) to mathematically correct for their statistical overlap on Principal Component 1.

By contrast, the remaining pairs (i.e., **PD1–PD3, PD1–PD2, PD2–PD3, PA4–PG4, PA3–PG2, PF1–PF2, PA4–PG1, PB2–PD2, PA4–PG3**, and **PA1–PD3**) show moderately high pairwise correlations but load most strongly on different principal components, suggesting that their statistical association does not translate into meaningful redundancy at the latent-construct level. On this basis, these indicators were retained in the framework and assigned standard weights.

Overall, the PCA diagnostics indicate that correlation alone would overestimate overlap within the indicator set, and that only a few pairs require further evaluation for potential consolidation or downweighting.

Based on the PCA findings, the 25 original KPIs are mathematically rescaled to a **21-standard-equivalent baseline** to preserve the required "unity sum" property (where all weights sum to exactly 1 or 100%). The standard base weight (W) is established as **4.76%** (=**1/21**). Variations from this standard weight are allocated as follows:

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- **Elimination of Extreme Redundancy (Weight = 0.00%):** Indicator **PB1** (Safety Standards) is eliminated entirely. PCA proved it shares the exact same dominant latent component as **PB2** (Testing & Certification), indicating extreme redundancy. PB2 is retained as the more rigorous metric of policy enforcement.

- **Reduced Joint Weight 1 - "Legal & Circular Nexus" (Weight = 1 Standard Equivalent):** Indicators **PA1** (Legal Classification), **PA3** (EPR Coverage), and **PD1** (Battery Passport) show partial statistical overlap. To manage this moderate double-counting risk, they are grouped and assigned a joint weight of one standard indicator. As a critical digital enabler, PD1 receives an asymmetric split (0.5W or **2.38%**), while PA1 and PA3 share the remainder (0.25W or **1.19%** each).

- **Reduced Joint Weight 2 - "Liability & Access" (Weight = 1 Standard Equivalent):** Indicators **PA4** (Liability Framework) and **PD2** (Data Access Rules) also partially overlap. They are combined into a joint weight of one standard indicator, split equally (0.5W or **2.38%** each).

The remaining KPIs, even those that exhibit moderately high correlation but load onto completely independent principal components, are retained with the standard weight of W (**4.76%**) to prevent the loss of unique policy dimensions. Table A.3 presents the exact weight allocation for each KPI.

Table A. 3 Final BPMS Weight Allocation

Code	Key Policy Indicator (KPI)	Status	Final Weight	Methodological Rationale
PA1	Legal Classification	Reduced	**1.19%**	Partial overlap with PA3 & PD1. Scaled down to 0.25 W to safely manage moderate double-counting risk.
PA2	End-of-Waste (EoW) Status	Standard	**4.76%**	Retained as a distinct, statistically independent policy pillar.
PA3	EPR Coverage	Reduced	**1.19%**	Partial overlap with PA1 & PD1. Scaled down to 0.25W.
PA4	Liability Framework	Reduced	**2.38%**	Partial overlap with PD2. Scaled down to 0.5 W to manage moderate double-counting risk.
PA5	Logistics & Transport Rules	Standard	**4.76%**	Retained as a distinct, statistically independent dimension.
PB1	Reuse/Repurposing Safety Standards	Eliminated	**0.00%**	Extreme redundancy. Shares the exact same dominant

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				component as PB2; eliminated to remove double-counting.
PB2	Battery Testing & Certification	Standard	**4.76%**	Retained as the primary, most rigorous metric for safety enforcement.
PB3	Modernised Safety & Building Codes	Standard	**4.76%**	Retained as a distinct, statistically independent dimension.
PC1	Financial Incentives	Standard	**4.76%**	Retained as a distinct, statistically independent dimension.
PC2	Market Participation & Access	Standard	**4.76%**	Retained as a distinct, statistically independent dimension.
PC3	Public Procurement Programs	Standard	**4.76%**	Retained as a distinct, statistically independent dimension.
PD1	Battery Passport/Tracking Mandate	Reduced	**2.38%**	Shares a joint weight with PA1 & PA3, but receives a larger asymmetrical split ($0.5W$).
PD2	Data Access Rules	Reduced	**2.38%**	Partial overlap with PA4. Scaled down to $0.5W$.
PD3	Data Interoperability and Security	Standard	**4.76%**	Despite high raw correlation, it loads on a different principal component and poses no double-counting risk.
PE1	Reuse Prioritisation	Standard	**4.76%**	Retained as a distinct, statistically independent dimension.
PE2	Landfill Bans	Standard	**4.76%**	Retained as a distinct, statistically independent dimension.
PE3	Permitting Streamlining	Standard	**4.76%**	Retained as a distinct, statistically independent dimension.
PF1	Dedicated Institutional Coordination	Standard	**4.76%**	High correlation with PF2, but measures a statistically distinct dimension.
PF2	R&D Grants & Innovation Support	Standard	**4.76%**	Retained as a distinct, statistically independent dimension.
PF3	Skills Development Programs	Standard	**4.76%**	Retained as a distinct, statistically independent dimension.
PF4	IP Fast-tracking	Standard	**4.76%**	Retained as a distinct, statistically independent dimension.
PG1	Warranty and Consumer Protection	Standard	**4.76%**	Distinct dimension despite correlation with PA4.

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PG2	Environmental Impact Monitoring	Standard	**4.76%**	Distinct dimension despite correlation with PA3.
PG3	Consumer Awareness/Labelling	Standard	**4.76%**	Distinct dimension despite correlation with PA4.
PG4	Operational Risk Mitigation	Standard	**4.76%**	Distinct dimension despite correlation with PA4.

Appendix A.3. Mathematical Formulations

A3.1 Data Normalisation and BPMS Aggregation

Data Normalisation

As the BPMS aggregates individual KPIs, the raw data must be normalised to dimensionless, comparable values before aggregation. Following the OECD Handbook, the **Min-Max normalisation method** is applied to transform each indicator into a common range. Because the dataset is evaluated as a multi-year panel (2006–2025), a time-adjusted normalisation is used. The theoretical minimum (0) and maximum (3) bounds remain fixed across all countries and years to accurately benchmark historical policy progress.

For a given country c, individual KPI q, and year t, the normalised KPI score $I_{q,c}^{t}$ is calculated as in Eq (1):

$$I_{q,c}^{t} = \frac{x_{q,c}^{t} - \min(x_q)}{\max(x_q) - \min(x_q)} = \frac{x_{q,c}^{t}}{3} \quad (1)$$

Time-Adjusted Linear Aggregation for BPMS calculation

Following data normalisation and the assignment of PCA-adjusted weights, the aggregated BaaS Policy Maturity Score (BPMS) is computed using the linear additive aggregation method. In accordance with the OECD Handbook, weights are kept unchanged across the 2006–2025 time series to ensure that temporal shifts in the final score purely reflect actual legislative changes rather than methodological fluctuations.

The final time-adjusted BPMS mathematical expression for country c in year t is the summation of the weighted, normalised individual indicators as in Eq (2):

$$BPMS_{c}^{t} = \sum_{q=1}^{24} w_q \left(\frac{x_{q,c}^{t}}{3}\right) \quad (2)$$

Subject to the unity sum mathematical constraints in Eq (3):

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$$\sum_{q=1}^{24} w_q = 1 \text{ and } 0 \leq w_q \leq 1 \quad (3)$$

(Note: The summation iterates over the 24 active indicators as PB1 is eliminated).

A3.2 Distance to Frontier (DTF) and Potential Gap Closure (PGC)

To quantify how many legislative "steps" the country is missing to reach the optimal frontier, we calculate the KPI-level Weighted Gap ($G_{q,c}^t$) as in Eq (4). The raw distance between a country's actual score ($x_{q,c}^t$) and the theoretical maximum score (i.e., *the EU Optimal Frontier*) (x_q^*) must first be normalised to a dimensionless scale, and then adjusted by its PCA-adjusted weight (w_q) to prevent double-counting:

$$G_{q,c}^t = w_q \left(\frac{x_q^* - x_{q,c}^t}{x_q^* - x_q^{min}} \right) = w_q \left(\frac{3 - x_{q,c}^t}{3} \right) \quad (4)$$

Next, we calculate the Potential Gap Closure (PGC), which estimates the percentage of a country's total policy gap (or policy maturity deficit/policy deficit) that would be eliminated if a single regulation were upgraded to the EU Optimal Frontier. To calculate this metric, the specific weighted gap for an individual indicator ($G_{q,c}^t$) is divided by the sum of all weighted gaps across the entire composite index as in Eq (5):

$$PGC_{q,c}^t = \left(\frac{G_{q,c}^t}{\sum_{q=1}^{24} G_{q,c}^t} \right) \times 100 \quad (5)$$

This metric is essential for impact optimisation, as it allows you to rank the $PGC_{q,c}^t$ values in descending order to isolate the top-priority bottlenecks that offer the highest **return on compliance**, i.e., they will close the largest percentage of the country's overall regulatory gap with the least administrative complexity.

A3.3 K-Means Clustering Algorithms

To mathematically group the underperforming Member States, the algorithm assesses similarity among countries based on their specific regulatory bottlenecks. Let the policy maturity deficit profile for a country c at time t be represented by the vector of its 24 KPI-level Weighted Gaps, $G_c^t = \left(G_{1,c}^t, G_{2,c}^t, \dots, G_{24,c}^t\right)$. The algorithm determines the similarity between countries by measuring the distance between their deficit profiles. The OECD Handbook highlights the *Squared Euclidean distance* as an appropriate measure to place progressively greater weight on objects that are further apart. The distance between a country c and a cluster centroid v across all 24 KPIs is calculated as in Eq (6):

$$D(c, v) = \sum_{q=1}^{24} (G_{q,c}^t - \mu_{q,v}^t)^2 \quad (6)$$

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Where $\mu_{q,v}^{t}$ represents the mean (centroid) of the weighted gap for KPI q among all countries currently assigned to cluster v.

The Objective Function: The algorithm partitions the lagging Member States into a predefined number of V distinct clusters (S_1, S_1, …, S_V). To ensure the optimal number of clusters (V) is selected without researcher bias, the Elbow Method and Silhouette Analysis are applied to identify the point at which additional clusters no longer significantly improve the model's explanatory power. In particular, it begins with random clusters and iteratively reassigns countries to minimise the variance of elements within the clusters. This requires finding the specific cluster assignments that minimise the Within-Cluster Sum of Squares (WCSS) in Eq (7):

$$\underset{S}{\operatorname{argmin}} \sum_{v=1}^{V} \sum_{i \in S_v} \sum_{q=1}^{24} (G_{q,c}^{t} - \mu_{q,v}^{t})^2 \quad (7)$$

Where S_v represents the specific set of countries assigned to Cluster v.

By strictly minimising this variance, the algorithm guarantees that countries grouped into the same "cluster of policy lag" share highly similar magnitudes and patterns of missing legislation.

Appendix A4. Country Profile: Policy Maturity Assessment

Table A. 4 Country BPMS in 2025 (Compared to EU Supranational Baseline: 2.024)

Country	BPMS Score	EU Baseline Status	Cluster	Top 5 Priority KPIs (by PGC%)
France	2.738	Above	Frontrunner	Data Security - PD3 | Transport Rules - PA5 | Consumer Protection - PG1 | IP Fast-tracking - PF4 | Permitting Streamlining - PE3
Germany	2.429	Above	Frontrunner	IP Fast-tracking - PF4 | Public Procurement - PC3 | Permitting Streamlining - PE3 | Transport Rules - PA5 | Consumer Protection - PG1
Finland	2.381	Above	Frontrunner	IP Fast-tracking - PF4 | Transport Rules - PA5 | Building Codes - PB3 | Public Procurement - PC3 | Permitting Streamlining - PE3
Spain	2.19	Above	Frontrunner	Transport Rules - PA5 | Building Codes - PB3 | IP Fast-tracking - PF4 | Permitting Streamlining - PE3 | Risk Mitigation - PG4
Ireland	2.095	Above	Frontrunner	IP Fast-tracking - PF4 | Transport Rules - PA5 | Building Codes - PB3 | Financial Incentives - PC1 | Market Access - PC2

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Norway	2.06	Above	Frontrunner	Consumer Protection - PG1 | IP Fast-tracking - PF4 | Transport Rules - PA5 | Building Codes - PB3 | Permitting Streamlining - PE3
Slovenia	2.048	Above	Frontrunner	IP Fast-tracking - PF4 | Building Codes - PB3 | Public Procurement - PC3 | Skills Development - PF3 | Permitting Streamlining - PE3
Malta	2	Below	Cluster 1	Permitting Streamlining - PE3 | Public Procurement - PC3 | IP Fast-tracking - PF4 | Transport Rules - PA5 | Building Codes - PB3
Italy	1.976	Below	Cluster 1	Risk Mitigation - PG4 | Permitting Streamlining - PE3 | Consumer Protection - PG1 | Transport Rules - PA5 | IP Fast-tracking - PF4
Netherlands	1.976	Below	Cluster 1	IP Fast-tracking - PF4 | Permitting Streamlining - PE3 | Data Security - PD3 | Market Access - PC2 | End-of-Waste Status - PA2
Luxembourg	1.952	Below	Cluster 1	Permitting Streamlining - PE3 | Market Access - PC2 | IP Fast-tracking - PF4 | Risk Mitigation - PG4 | Transport Rules - PA5
Cyprus	1.952	Below	Cluster 1	Permitting Streamlining - PE3 | Building Codes - PB3 | IP Fast-tracking - PF4 | Skills Development - PF3 | Public Procurement - PC3
Denmark	1.94	Below	Cluster 1	Transport Rules - PA5 | IP Fast-tracking - PF4 | Skills Development - PF3 | Permitting Streamlining - PE3 | Data Security - PD3
Czech Republic	1.893	Below	Cluster 1	IP Fast-tracking - PF4 | Consumer Protection - PG1 | Transport Rules - PA5 | Skills Development - PF3 | Public Procurement - PC3
Sweden	1.845	Below	Cluster 1	Permitting Streamlining - PE3 | Data Security - PD3 | Transport Rules - PA5 | Consumer Protection - PG1 | IP Fast-tracking - PF4
Croatia	1.738	Below	Cluster 1	IP Fast-tracking - PF4 | Skills Development - PF3 | Market Access - PC2 | Permitting Streamlining - PE3 | Transport Rules - PA5
Estonia	1.583	Below	Cluster 1	IP Fast-tracking - PF4 | Building Codes - PB3 | Permitting Streamlining - PE3 | Consumer Protection - PG1 | Transport Rules - PA5
Austria	1.524	Below	Cluster 1	Consumer Protection - PG1 | IP Fast-tracking - PF4 | Permitting Streamlining

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				- PE3 | Data Security - PD3 | Public Procurement - PC3
Hungary	1.488	Below	Cluster 1	IP Fast-tracking - PF4 | Public Procurement - PC3 | Risk Mitigation - PG4 | Consumer Protection - PG1 | Transport Rules - PA5
Belgium	1.476	Below	Cluster 1	Consumer Protection - PG1 | IP Fast-tracking - PF4 | Market Access - PC2 | Skills Development - PF3 | Permitting Streamlining - PE3
Poland	1.405	Below	Cluster 1	IP Fast-tracking - PF4 | Permitting Streamlining - PE3 | Data Security - PD3 | Public Procurement - PC3 | Environmental Monitoring - PG2
United Kingdom	1.262	Below	Cluster 2	Data Security - PD3 | Public Procurement - PC3 | Permitting Streamlining - PE3 | Testing Certification - PB2 | Environmental Monitoring - PG2
Slovakia	1.226	Below	Cluster 2	Data Security - PD3 | IP Fast-tracking - PF4 | Skills Development - PF3 | Permitting Streamlining - PE3 | Public Procurement - PC3
Romania	1.071	Below	Cluster 2	Data Security - PD3 | IP Fast-tracking - PF4 | Testing Certification - PB2 | Permitting Streamlining - PE3 | Public Procurement - PC3
Greece	1.048	Below	Cluster 2	Data Security - PD3 | IP Fast-tracking - PF4 | Testing Certification - PB2 | Building Codes - PB3 | Market Access - PC2
Switzerland	1	Below	Cluster 2	Data Security - PD3 | IP Fast-tracking - PF4 | Permitting Streamlining - PE3 | End-of-Waste Status - PA2 | Environmental Monitoring - PG2
Iceland	0.762	Below	Cluster 2	Data Security - PD3 | End-of-Waste Status - PA2 | Consumer Protection - PG1 | IP Fast-tracking - PF4 | Testing Certification - PB2
Latvia	0.714	Below	Cluster 2	Data Security - PD3 | End-of-Waste Status - PA2 | Consumer Protection - PG1 | Transport Rules - PA5 | Testing Certification - PB2
Portugal	0.69	Below	Cluster 2	Data Security - PD3 | Building Codes - PB3 | Consumer Protection - PG1 | IP Fast-tracking - PF4 | Permitting Streamlining - PE3
Belarus	0.643	Below	Cluster 2	Data Security - PD3 | Consumer Protection - PG1 | Testing Certification -

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				PB2 | Building Codes - PB3 | IP Fast-tracking - PF4
Monaco	0.536	Below	Cluster 2	Data Security - PD3 | Market Access - PC2 | Consumer Awareness - PG3 | Consumer Protection - PG1 | IP Fast-tracking - PF4
Liechtenstein	0.452	Below	Cluster 2	Data Security - PD3 | Public Procurement - PC3 | Consumer Protection - PG1 | IP Fast-tracking - PF4 | Skills Development - PF3
Lithuania	0.357	Below	Cluster 2	Data Security - PD3 | Market Access - PC2 | Consumer Awareness - PG3 | Consumer Protection - PG1 | IP Fast-tracking - PF4
Albania	0.107	Below	Cluster 2	Data Security - PD3 | End-of-Waste Status - PA2 | Consumer Awareness - PG3 | Environmental Monitoring - PG2 | Consumer Protection - PG1

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