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Bridging the Gap Between Prosumer Rights and Market Access: Monitoring Citizen Participation in Europe's Sustainable Electricity Markets

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Abstract

The energy transition depends on citizens producing, storing, and sharing renewable electricity, yet EU rights for active consumers become market access only through national rules. This study proposes the Prosumer Market Access Maturity (PMAM) framework, a tool for monitoring how far regulation enables their contribution to sustainable energy systems, and applies it to six EU-DREAM jurisdictions: Denmark, Flanders, Italy, Greece, Portugal, and Ireland. Each is scored on eight capability-specific dimensions, from L0 (absent) to L4 (market-integrated), using evidence available by 31 August 2026. For every score, legal status and operational evidence are recorded separately. All six jurisdictions fall in the advanced band, and none reach the frontier band. Ireland ranks last, or joint last, whichever dimension is omitted, and under all level-value mappings tested, whereas the order of Denmark, Flanders, and Portugal depends on how far strengths may compensate for weaknesses. Explicit peer-to-peer settlement and network-tariff treatment of shared energy are the least mature capabilities, while aggregated balancing access is more developed than community-specific routes suggest. Validated interval data, transparent network charging, and routes for small resources to reach aggregation and balancing would let distributed renewables and flexibility support decarbonization, fair cost allocation, and citizen participation.

Keywords: prosumers; energy sharing; peer-to-peer energy trading; renewable energy communities; balancing markets; electricity market design; regulatory maturity; sustainable energy transition; sustainability policy monitoring; energy democracy

Academic Editor: Byungik Chang

Received: 1 November 2026
Revised: 21 November 2026
Accepted: 24 November 2026
Published: 29 November 2026

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1. Introduction

Electricity policy in Europe now treats citizens and small businesses as market actors rather than passive end-users. Under Directive (EU) 2018/2001 (RED II) [1], renewable self-consumers may generate, consume, store, and sell renewable electricity. Directive (EU) 2019/944 (the Electricity Market Directive) adds active customers and citizen energy communities [2]. Directive (EU) 2023/2413 (RED III) strengthened this framework [3]. The 2024 reform of electricity market design took it a step further. It created a standalone right to energy sharing through private agreements or through an energy-sharing organizer. It also required shared electricity to be netted over an interval no longer than the imbalance

settlement period, and it obliged system operators to validate and communicate metering data [4]. Distributed participation is therefore no longer only a matter of technology adoption. It has become a question of market architecture.

Implementation of these rules differs considerably between EU Member States. A legal right to export does not, on its own, provide a transparent route to payment. A recognized energy community may still lack workable registration, allocation, and billing. An operational sharing scheme may not let the shared portfolio reach wholesale, flexibility, or balancing markets. These differences matter because distributed resources create value for the system only when metering, aggregation, settlement, and imbalance responsibility tie local action to system operation [5–8].

Several studies have already examined how prosumer and energy-community rights are implemented. Cross-country studies cover collective prosumer regulation in nine European countries and regions [9], the legal design of renewable and citizen energy communities [10–12], national implementation in Spain, Italy, and Greece [13], and the technical, regulatory, and social conditions in selected Member States [14–16]. The European Energy Communities Facility has compiled national policy fiches for all EU Member States, and the European Court of Auditors has examined the implementation gap at the Union level [17,18]. Less attention has been paid to an auditable capability scale. Such a scale would record, for each dimension, whether a jurisdiction has merely an enabling rule, a route in operation, or a route integrated with the wider system, and it would keep wholesale access and balancing responsibility apart.

This article addresses the narrower gap, and its contribution has four parts. PMAM is first specified as eight dimension-specific scales. Each cell receives one ordinal level, together with a two-part code that records the legal status of the capability and whether its operation is verified. Wholesale and aggregation access are then distinguished from balancing and balance responsibility, two related capabilities that are not equivalent, and both are assessed against the same system-level standard. The framework is then applied to the six jurisdictions of the EU-DREAM project (Effective Uptake of Digital Services to Repower European Consumers and Communities as Active Participants in Energy Transition and Markets), with a common evidence hierarchy and a single regulatory cutoff. Finally, the totals are interpreted through maturity bands and checked with tests for dimension omission, weights, level values, aggregation rules, band thresholds, and coding errors. PMAM is designed as a transparent diagnostic tool for regulators and project developers and makes no claim to measure implementation outcomes or social welfare directly. By linking legal rights to their operational use, this study contributes to measuring and monitoring sustainability policy, showing whether institutional conditions are in place for citizens to take part in a low-carbon, fair, and cost-effective electricity system.

The literature and the contributions of this study are discussed in Section 2, and the framework and coding procedure are discussed in Section 3. Section 4 reports the jurisdictional evidence and the robustness analysis, and Section 5 discusses regulatory implications and limitations. Section 6 concludes, and Appendix A provides the full cell-level evidence record.

2. Literature Review and Analytical Positioning

2.1. Prosumers and Energy Communities as Market Actors

Research on prosumers has moved from behind-the-meter optimization toward participation in organized markets. Parag and Sovacool describe this as a transition to prosumer markets at the peer-to-peer, prosumer-to-grid, and community levels, each with its own market-design choices [19]. Gržanić et al. trace a progression from bill reduction and self-consumption to local trading, aggregation, ancillary services, and direct or indirect market participation [5]. For Lowitzsch et al., renewable energy communities are

governance structures that can coordinate assets and participants, distinguished from ordinary commercial aggregators by ownership and decision rights [20]. According to several reviews, the social arrangements, technical configurations, and business models of community energy vary widely, from collective ownership of generation to integrated community systems that offer flexibility to the grid [21–23]. In regulation, active-customer, renewable-energy-community, and citizen-energy-community rights overlap, but their permissible activities, control criteria, and geographical conditions are not the same [10–12].

Justice is the focus of a second group of studies, because the way the rules are transposed determines who can participate and who benefits. Hoicka et al. argue that national implementation must settle questions of ownership, proximity, autonomy, and access to finance if renewable energy communities are to support a just transition [11]. According to Sokołowski, legal recognition needs registers, proportionate procedures, and tailored support [10]. A statutory definition is therefore a weak indicator of accessibility or operational maturity.

2.2. Comparative Regulatory and Implementation Research

Campos et al. compare nine European countries and regions, including Flanders, Italy, and Portugal, and find that administrative procedures, spatial restrictions, support design, and market access all shape collective prosumer development [9]. De Almeida et al. examine how the law treats P2P trading and energy communities and point to open questions on licensing, consumer protection, and the role of intermediaries [12]. In their review of how Member States transposed the provisions on collective self-consumption and energy communities, Frieden et al. find the basic provisions largely in place. Integration into the energy system and the market, however, is only partly addressed, and registration and data access are often complicated [24]. Losada-Puente et al. combine desk research with stakeholder evidence from Spain, Italy, and Greece and report formal progress alongside persistent financing, grid, and administrative barriers [13]. As these studies suggest, legal text alone does not reveal how a framework works in practice.

Similar findings appear in more recent work. For Taromboli et al., who compare regulatory, technical, and social arrangements in several EU Member States, incentives and national design choices change participants' economics substantially [14]. In a structured review that concludes with anchor-prosumer pathways for Romania, Glămeanu et al. identify metering, settlement, cybersecurity, and allocation rules as preconditions for scaling up [15]. Timofeeva et al. run one reference community through four national frameworks and find that legislation redistributes economic benefits even when the physical community does not change [16]. At the institutional level, the European Energy Communities Facility publishes structured national fiches for the EU [18]. The European Court of Auditors concludes that the potential of energy communities remains under-realized [17]. Broad comparison is therefore already available. The contribution of PMAM is methodological and diagnostic rather than a claim to be the first comparative study. Practitioner and regulatory mappings overlap parts of this scope. LCP Delta and smartEn track explicit demand-side flexibility and aggregator access by country [25], ACER and CEER monitor retail-market and active-consumer provisions [26], and REScoop.eu tracks the transposition of energy-community rules [27]. These mappings report access conditions or transposition status, but they do not apply a common ordinal scale with a cell-level evidence trail.

2.3. Peer-to-Peer Electricity Trading

In peer-to-peer (P2P) electricity trading, consumers and prosumers exchange electricity among themselves and can influence the terms, including whom they trade with. Sousa et al. review P2P and community-based markets from a consumer-centered perspective and discuss how participant preferences and coordination relate to established electricity markets [28]. Tushar et al. separate fully decentralized, community-based, and composite architectures, and distinguish the virtual layer, in which transactions are negotiated, from the physical network that carries the electricity [29]. Morstyn et al. show how P2P platforms can group prosumers into federated power plants that sell services to system operators, which connects local trading with wholesale and balancing participation [30]. It follows that an energy community and a P2P market are different things. Community governance concerns how participants organize, whereas the trading architecture concerns how their exchanges are coordinated.

Pricing and allocation rules decide whether participants have a reason to trade and how the gains are shared. Game-theoretic methods, double auctions, and constrained optimization each rest on different assumptions about cooperation and information exchange [29], and storage adds an intertemporal choice whose value depends on the tariffs and settlement rules assumed [31].

Pilots show why a platform must be judged together with its institutional setting. In the Brooklyn Microgrid, the technical and market components of a blockchain-based local market were well advanced, but regulation remained the binding constraint [32]. For a regulatory assessment, the question is whether a transaction can be recognized and settled under the market arrangements that apply to the participants, and a working digital platform does not answer that question by itself.

Shan et al. move from single pilots to a comparison of existing P2P trading platforms, organized around five themes: setup, market, information, price, and regulation [33]. They call for platform features that bring technical operation, market mechanisms, and regulatory conditions together. Their work and ours are complementary. Platform comparisons identify the functions that trading needs, whereas PMAM asks whether the regulatory framework allows those functions to operate. Because information requirements and regulatory conditions are linked in this way, PMAM assesses explicit P2P status (D4) together with metering and data enablement (D8). The existence of a trading platform is not treated as sufficient evidence of market access.

Physical delivery is a separate question from commercial matching. Voltage and capacity limits, losses, and the allocation of network charges mean that a local match proves neither lower network costs nor unconstrained delivery, and scaling P2P sharing into established markets remains difficult [29,34]. Simulations and pilots can inform the design of PMAM, but the higher levels require documentary evidence of operational market arrangements.

Other implementation studies deal with non-technical barriers. Sun et al. group P2P barriers under political, economic, social, technological, legal, and environmental headings and show that deployment depends on how these conditions interact and on suitable participation incentives [35]. Jogunola et al. examine opportunities, security, and implementation barriers [8], and de Almeida et al. analyze the legal relationship between P2P trading and energy communities [12]. Read together, these studies call for an assessment that separates the permission to trade from the procedures and responsibilities needed to complete a trade. PMAM therefore looks at explicit P2P status (D4) alongside network-tariff treatment (D5), wholesale and aggregation access (D6), balancing arrangements (D7), and metering and data enablement (D8).

2.4. Network Charges, Settlement, and Balancing

Network tariffs determine how much local exchanges contribute to the cost of shared infrastructure. Maldet et al. find that regulatory barriers and grid tariffs strongly influence how local electricity markets are designed [6]. Tariffs also have distributional effects. Schittekatte et al. show that netting combined with volumetric tariffs allows prosumers to shift part of the sunk grid cost onto other network users [36]. Part of the private viability of energy communities may come from such cost shifts rather than from real system savings [37]. Read alongside the P2P studies, this is a reason to score the legal status of trading and its tariff treatment separately. Network charges, levies, and administrative costs (D5) can make a bilateral exchange uneconomic even where it is lawful (D4). Whether the agreed volume is then reflected in each participant's bill is a metering and settlement question (D8), and the three dimensions are therefore interpreted jointly.

Balancing needs its own treatment. Using stochastic simulation for a UK community case, Alonso Pedrero and Crespo del Granado find that community portfolios alter the retailer's balancing position when the retailer lacks operational oversight over these [7]. Regulation (EU) 2019/943 assigns balance responsibility to market participants, and the aggregation provisions of Directive (EU) 2019/944 are meant to give smaller resources a route into the market [2,38]. The Electricity Balancing Guideline (Regulation (EU) 2017/2195) harmonizes the imbalance settlement period at 15 min and establishes the framework for standard balancing products and their prequalification [39]. A supplier or aggregator that markets a prosumer's output in the wholesale market is under no obligation, by that fact alone, to allocate imbalances transparently or to offer access to balancing products. Burger et al. point out that part of what aggregators earn is created by market rules rather than by aggregation itself [40]. Poplavskaya and de Vries, looking at three European balancing markets, still find product definitions, minimum bid sizes, symmetric bids, and prequalification standing in the way of distributed resources [41]. That is why D6 (wholesale and aggregation access) and D7 (balancing and balance responsibility) are separate dimensions in PMAM, a split on which much of the framework rests.

2.5. Gaps in the Existing Research and Article Contributions

Table 1 compares PMAM with earlier studies. In most of these studies, a single method dominates: legal comparison, stakeholder evidence, or techno-economic modeling. Table 1 is a purposive selection of the comparative regulatory, implementation, and market-design studies closest to the scope of PMAM, drawn from the literature reviewed in Sections 2.1–2.4 and not the result of a systematic search. Within this selection, none of the studies combine capability-specific ordinal anchors, a source trail for every cell, separate treatment of wholesale and balancing readiness, and a sensitivity analysis that treats the index as a diagnostic tool. Maturity models are a well-established way to represent staged capability development, as long as the level anchors are explicit, and the development path is documented [42]. Composite indicators that aggregate such levels are sensitive to normalization, weighting, and aggregation choices, which therefore must be tested explicitly (Section 3.5). PMAM fills this limited gap for the six EU-DREAM jurisdictions. It is not a substitute for legal analysis, stakeholder research, or outcome evaluation. Its role is to provide a reproducible map that points those deeper methods to the weakest interfaces.

Table 1. The representative literature and the specific gap addressed by PMAM.

Study	Scope	Primary Focus	Method	Balancing Treatment
Lowitzsch et al. [20]	EU	REC governance and ownership	Legal-conceptual	No
Campos et al. [9]	9 European jurisdictions	Collective prosumer regulation	Comparative legal review	No
Frieden et al. [24]	EU Member States	Transposition of collective self-consumption and energy communities	Comparative policy review	No
Sokołowski [10]	EU and national law	REC and CEC design	Doctrinal legal analysis	No
Hoicka et al. [11]	EU transposition	Justice and implementation	Policy analysis	No
de Almeida et al. [12]	EU	P2P and energy-community law	Literature and legal review	No
Maldet et al. [6]	Austria, Ireland, Norway	Local markets and grid tariffs	Comparative design review	No
Alonso Pedrero et al. [7]	UK community case	Retailer imbalance exposure	Stochastic simulation	Balancing only
Poplavskaya and de Vries [41]	Three European balancing markets	Access of distributed resources to balancing	Comparative market-design analysis	Balancing only
Jogunola et al. [8]	Multi-country	P2P opportunities and barriers	Review and policy comparison	Partial
Losada-Puente et al. [13]	Spain, Italy, Greece	Progress and barriers	Desk research and interviews	No
Taromboli et al. [14]	Selected EU states	Regulation, technology, and social factors	Review and quantitative comparison	No
Glămeanu et al. [15]	EU, Romania pathway	Legal and implementation barriers	Structured review	No
Timofeeva et al. [16]	Germany, Austria, Spain, Italy	Regulatory economic effects	Reference-community model	No
EECF [18]	EU-27 and Ukraine (fiches for the six jurisdictions used here)	National policy frameworks	Institutional country fiches	No
Sousa et al. [28], Tushar et al. [29,34]	International literature	P2P architectures, physical constraints, and deployment	Market-design and technical reviews	Partial
Lüth et al. [31], Mengelkamp et al. [32]	London, Brooklyn	Storage value and microgrid market implementation	Optimization, case study	No
Sun et al. [35]	International literature	Interacting barriers to P2P deployment	PESTLE barrier analysis	No
Shan et al. [33]	Existing P2P platforms	Integration of platform features and regulation	Comparative case study	No
This study	6 EU-DREAM jurisdictions	8 market-access capabilities	Auditable maturity coding and sensitivity	Wholesale and balancing separated

3. Materials and Methods

3.1. Scope, Unit of Analysis, and Regulatory Cutoff

The unit of analysis is the regulatory framework that governs prosumer market access in a given jurisdiction. The six cases (Denmark, Flanders in Belgium, Italy, Greece,

Portugal, and Ireland) all take part in the EU-DREAM project. The term "jurisdictions" is used on purpose. The Flemish region holds material competences for distribution, retail-market regulation, and energy sharing, while federal Belgian rules remain relevant to transmission and balancing. The sample follows from the project and is not statistically representative.

The cutoff date of 31 August 2026 was chosen with reference to Article 15a of Directive (EU) 2019/944. Directive (EU) 2024/1711 inserted this article with a transposition deadline of 17 July 2026 [4], so the cutoff falls in the first weeks after it. However, a law transposing Article 15a is not taken as proof that energy sharing is already in operation. The date was chosen so that every jurisdiction was assessed against the same legal deadline, while leaving six weeks for acts adopted close to it to be published. Documents published after the cutoff were used only where they describe the state of affairs at the cutoff, for example, an operator stating that a platform was still under development. Measures adopted or entering into force after 31 August 2026 were not credited.

3.2. Evidence Sources and Coding Procedure

Three tiers of evidence were used. Tier 1 is binding law (EU and national legislation, ministerial decisions, regulator rules, official tariffs, and market codes). Tier 2 is operational documentation from regulators, distribution or transmission system operators, settlement bodies, and government agencies. Tier 3, comprising EECF country fiches and peer-reviewed studies, served to cross-check interpretations and identify barriers. L3 and L4 were awarded only on Tier 1 or Tier 2 operational evidence. A statutory right without implementing or settlement evidence was capped at L2. Sources in national languages were consulted in the original, with translation tools where needed. Where sources conflicted, binding and operator documents took precedence over secondary sources, and more recent documents over older ones. Where no operational document could be found, the cell was capped at L2. The dataset deposited in a public repository (Data Availability Statement) lists, for every cell, sources with URLs, pinpoint references where applicable, and the date of the evidence.

The coding of each cell followed four steps. The applicable legal entitlement was identified first, then the implementation, metering, and settlement rules, and then the actor responsible for allocation, billing, aggregation, or imbalance responsibility. The cell was finally assigned the highest level for which all stated conditions were evidenced, with the lower level chosen in borderline cases. All 48 cells were coded by the first author and recoded independently by a second author against the level anchors (Section 3.3), without access to the first coding but working from the principal sources listed for each cell. The two codings agreed with $\kappa w = 0.899$ (linearly weighted Cohen's kappa), and the four disagreements were resolved through discussions with the third author. Raw agreement was 91.7% (44 of 48 cells). The anchors for D4–D7 were then clarified (Section 3.3). The first author recoded all 48 cells against the revised anchors, and the second author coded all 48 cells again, without access to the first coding and collecting the evidence independently, recording both the level and the two-part code defined below. In this second round, raw agreement was 45 of 48 cells (93.8%) and $\kappa w = 0.922$ (bootstrap 95% confidence interval: 0.811–1.000). The three disagreements, all between L2 and L3 (Denmark D3, Greece D1, and Greece D7), were again resolved through discussions with the third author. In all three, the level of the first coding was retained. Agreement by dimension, the confusion matrix, and the agreement on the two-part code are reported in Appendix B. Appendix A lists the score, rationale, and main sources of every cell.

Because a single ordinal level can combine legal and operational evidence, every cell also carries a two-part code. The first part records legal status: R when implementing rules are in force, P when a principle or right exists without implementing rules, and N when

no specific legal basis was found. The second part records operational verification: V when Tier 1 or Tier 2 documents show the process in use, PV when such evidence covers only part of the capability or is indirect, and NV when no operational evidence was found. Both parts refer to the capability as defined for the dimension, so arrangements that serve only as functional analogues, such as supplier export contracts where explicit P2P status is assessed, do not count as operational verification. Of the 48 cells, 37 are coded R, 5 are coded P, and 6 are coded N, while 32 are coded V, 6 are coded PV, and 10 are coded NV. Both parts are reported in separate columns in Table A1, and the level and code are read together. For example, Italy's D5 is coded L2 with legal status R and operation V, which means that a partial treatment of shared energy is in force and operating, while Ireland's D5 is coded L1 with legal status N and operation NV.

3.3. PMAM Dimensions

PMAM has eight dimensions. D1 to D4 run from the individual right to export (D1), via community frameworks (D2) and collective sharing (D3), to explicit P2P trading (D4). D5 is network charging, on which the economics of those arrangements largely depend. D6 refers to access to energy and flexibility markets, and D7 to balance responsibility and participation in balancing. D8, the metering and data layer, determines whether these arrangements can be settled at the resolution needed for system integration. Definitions are given in Table 2, and the level anchors are provided in Table 3.

Table 2. The eight PMAM dimensions, the capability each score refers to, and the main EU legal basis.

Dim.	Regulatory Capability	What the Score Measures
D1	Surplus remuneration and settlement	Whether exported electricity has a defined and operational payment and settlement route Principal EU legal basis: RED II Art. 21, Electricity Market Directive Art. 15 [1,2]
D2	Energy-community framework	Whether REC/CEC forms, governance, permitted activities, and procedures are established Principal EU legal basis: RED II Art. 22, Electricity Market Directive Art. 16 [1,2]
D3	Collective self-consumption and energy sharing	Whether virtual allocation, metering, and billing operate across participating customers Principal EU legal basis: RED II Art. 21(4), Electricity Market Directive Art. 15a as inserted in 2024 [1,4]
D4	Explicit P2P legal status	Whether customer-to-customer sales are expressly permitted and operationally settled Principal EU legal basis: RED II Art. 21(2)(a), including P2P arrangements, RED III [1,3]
D5	Grid-tariff treatment	Whether charges for shared or locally traded energy are transparent, cost-reflective, and non-punitive Principal EU legal basis: Electricity Market Directive Arts. 15–16, Regulation 2019/943 Art. 18 [2,38]
D6	Wholesale and aggregation access	Whether prosumers or communities can reach energy and flexibility markets directly or through aggregation Principal EU legal basis: Electricity Market Directive Arts. 16–17, Regulation 2019/943 market-access principles [2,38]

D7	Balancing and balance responsibility	Whether imbalance responsibility can be allocated or delegated, and whether balancing participation is workable Principal EU legal basis: Regulation 2019/943 Arts. 5–6, Regulation (EU) 2017/2195 (EB GL), Electricity Market Directive aggregation provisions [2,38,39]
D8	Digital and metering enablement	Whether interval data, allocation, and interoperable information exchange support settlement Principal EU legal basis: Electricity Market Directive Arts. 19–24, Art. 15a(6), Implementing Regulation (EU) 2023/1162, EU digitalisation action plan [2,4,43,44]

Table 3. Dimension-specific maturity anchors. A level is awarded only when the stated conditions are evidenced.

Dim.	L0 Absent	L1 Nascent	L2 Defined	L3 Operational	L4 Market-Integrated
D1	No lawful export/payment route	Right to export only	Payment rules defined or pilot	Routine payment and settlement	Multiple market-referenced, time-granular routes
D2	No REC/CEC basis	Definition or partial recognition	Governance and procedures defined	Registration and activities operational	Broad non-discriminatory market access
D3	No collective route	General sharing right only	Allocation and metering rules defined	Virtual sharing routinely settled	Standalone Article 15a route with organizer and data interfaces
D4	Prohibited or no basis	Functional analogues only (supplier, bilateral, or community allocation)	Explicit legal recognition of P2P sale, without operational settlement	Explicit P2P sale operational but constrained	Standardized multi-party P2P settlement and protections
D5	Discriminatory or undefined	Ordinary tariffs only	Partial or mixed treatment	Transparent, cost-based treatment of the shared/local component	Cost-reflective locational/use-based treatment
D6	No market route	Incumbent-supplier route only	Licensed intermediary route defined	Operational PPA, aggregator, or market route	Non-discriminatory direct or aggregated wholesale/flex access
D7	No responsibility route	General responsibility only	Delegation to supplier, aggregator, or BRP defined	Operational aggregated/community balancing settlement	Competitive direct or aggregated balancing access
D8	Data route absent	Rollout or data plan only	Interval-data rules developing	Validated interval data supports allocation/settlement	Interoperable data at settlement resolution for authorized parties

Three conventions apply to Table 3. First, across dimensions, L3 requires that the route is in routine use for the relevant customers, as shown by Tier 1 or Tier 2 operational evidence, whereas L4 additionally requires that it is standardized, open to all eligible parties on non-discriminatory terms, and integrated with wholesale, balancing, or data processes at settlement resolution. The L4 anchors are benchmarks taken from EU provisions (the Article 15a route for D3, and the settlement and cost-reflectivity requirements of Directive (EU) 2019/944 for D4 and D5). For D1–D5, they are not yet observed in any of the six jurisdictions, so the attainable scale on those dimensions is, at present, effectively L0–L3. Second, D6 and D7 are scored on the routes that small-scale prosumer and community resources can actually use, whether they are community-specific or system-wide (aggregated portfolios and independent aggregation), and the same standard is applied in all six jurisdictions. L4 on D7 requires that aggregated portfolios, including small or demand

units, are eligible for the standard balancing products, and that a route independent of the supplier's BRP exists. Scores refer to low-voltage household and small-business customers. Where a route is available only to larger or medium-voltage customers, this is stated in Appendix A. For Flanders, D6 and D7 are Belgian-level scores, because balancing and transmission-level market access are federal competences, and for Ireland, they refer to the all-island Single Electricity Market. Third, D5 is coded L1 when shared or locally exchanged energy pays the ordinary network tariffs without specific treatment, and L2 only when partial specific treatment is in force. D8 measures interval data at settlement resolution. It is a precondition for L4 on D3 (sharing netted per imbalance settlement period) but not for L3, since virtual sharing can be settled on coarser metering intervals.

3.4. EU-Law Grounding

The dimensions are grounded in EU law, but what they measure is national implementation. Table 2 links each capability to its main legal basis. Article 15a deserves particular attention. It provides for shared electricity to be deducted over an interval no longer than the imbalance settlement period and protects consumer rights. It also allows an energy-sharing organizer and gives system operators the task of validating data [4]. Community law and market operation are thus connected in Article 15a. D8 also draws on Commission Implementing Regulation (EU) 2023/1162, with its interoperability requirements and procedures for access to metering and consumption data [44].

3.5. Index Construction and Robustness Checks

The index is the unweighted sum of the eight ordinal scores and ranges from 0 to 32. Equal weights were chosen because the eight capabilities are links in one chain, from the right to export to settlement, and no defensible external basis for different weights was found. The sum treats the distance between adjacent levels as equal, an interval assumption that ordinal data do not guarantee [45,46]. The index is therefore used diagnostically; this assumption is tested with alternative level values and non-compensatory rules; and the capability profile, not the total, is the primary result. Totals are assigned to four bands of equal width on the theoretical scale, foundational (0–8), developing (9–16), advanced (17–24), and frontier (25–32), which correspond to an average level of up to L1, L2, L3, and above L3. Because no L4 is observed on D1–D5 (see the note in Table 3), the frontier band can, in practice, be reached only with L4 on most system-integration dimensions, and it should be read as a benchmark rather than an observed class.

Robustness was examined with five groups of tests. (i) Each of the eight dimensions is removed in turn. (ii) The score matrix is weighted with 200,000 non-negative vectors from a symmetric Dirichlet distribution with unit concentration parameters (uniform on the weight simplex), from which the rank-acceptability matrix (the probability of each jurisdiction occupying each rank) and all pairwise ordering probabilities are computed. (iii) The equal-interval assumption is replaced by a convex level mapping (0, 1, 2, 4, 8), which rewards higher levels, and a concave mapping (the square root of the level), which rewards breadth. (iv) Three non-compensatory rules are applied: the number of cells at L3 or above, the minimum level, and a leximin ordering that compares profiles from their weakest dimension upwards. Weak (Pareto) dominance between profiles is also reported. (v) Coding errors are simulated in 100,000 draws per scenario. All rates are per direction: a cell moves one level up with probability p_up and one level down with probability p_down, so that a cell away from the ends of the scale changes level with total probability p_up + p_down. Results are truncated to L0–L4. The scenarios fall into two groups. The empirically anchored scenarios are calibrated on the revised double coding (Section 3.2), in which 3 of 48 cells (6.25%) were coded differently, all at the L2/L3 boundary: 2 of the 9 cells coded L2 by the first coder were coded L3 by the second, and 1 of the 29 cells coded

L3 was coded L2 (Table A6). Scenario H1 applies the observed total rate to all cells (3.125% in each direction). Scenarios H2–H4 confine changes to the L2/L3 boundary, where all disagreements occurred and where partial or indirect operational evidence has to be classified: H2 uses the directional rates of the confusion matrix (22.2% upward from L2, 3.4% downward from L3), H3 uses the pooled rate of 3 of 38 L2 and L3 cells (7.9%) in both directions, and H4 uses the upper limit of its 95% Clopper–Pearson interval (21.4%). The remaining scenarios are stress tests: 10% in each direction (20% in total, A), 20% in each direction (40% in total, C), an upward bias (10% up, 5% down) reflecting the rule that borderline cells were coded at the lower level (D), dimension-specific rates (15% in each direction for D4–D7, whose anchors were most contested, and 5% elsewhere, E), and correlated errors (F and G). In F and G, a common one-level shock with a probability of 10%, split equally between up and down, hits all cells of a jurisdiction (evidence or language gaps) or all jurisdictions on one dimension (misreading of an anchor), combined with independent noise of 5% in each direction. Every scenario is run unrestricted and evidence-constrained. In the evidence-constrained run, an upward move must be a plausible alternative coding of the evidence available at the cutoff. A cell can move up to L3 only if Tier 1 or Tier 2 operational evidence was found (operation code V or PV). It can move up to L4 only on D6–D8 and only from a cell coded R and V, because the L4 anchors on D1–D5 are benchmarks not met in any jurisdiction (note to Table 3). Moves into L1 and L2 are not restricted, because these levels require no operational evidence and the legal-status code is the least reproducible element of the coding (Appendix B). Upward moves excluded by these rules would represent changes in implementation after the cutoff, not coding uncertainty, and are not counted as such. Alternative band thresholds (shifted by ±1 and ±2 points), a conjunctive rule that assigns the band of the lowest level, and bands computed after rescaling each dimension to its observed maximum are also examined. All random draws use NumPy's default generator with seed 42. Because of truncation, L4 cells can only move down, and three of Denmark's cells are at L4.

4. Results

4.1. Regulatory Profiles

Denmark has implemented a community framework, a central data hub (DataHub), and market arrangements built around BRPs, with clearly assigned responsibilities. Its gaps concern P2P settlement, for which no distinct decentralized model exists, and network charging, since local exchanges remain subject to ordinary grid tariffs (D5 = L1) [47–51]. Collective self-consumption, moreover, operates only behind a single main meter with one shared supplier, and sharing over the public grid was not yet operational at the cutoff, because Energinet's sharing platform was still being developed (D3 = L2) [52,53].

In Flanders, energy sharing and explicit energy selling are both settled on quarter-hourly data within the data process of the Flemish DSO, Fluvius. Most sharing and retail rules are Flemish, whereas transmission-level rights and balancing are federal. Wholesale access through licensed market parties is operational, and 80 energy communities were registered by September 2025 [18,54–57]. Shared energy, however, receives no specific network-tariff treatment (D5 = L1). No balancing pathway specific to communities was found, but the Belgian TSO Elia admits aggregated low-voltage resources: about 17,000 low-voltage delivery points take part in FCR, aFRR has been open to low-voltage units since 2024, and a balancing service provider can operate independently of the customer's supplier and BRP through transfer-of-energy, opt-out, or pass-through arrangements [58,59]. Because low-voltage participation is so far limited to FCR, with no aFRR volume yet and mFRR access planned for 2026, Flanders is coded L3 on D7 rather than L4.

Italy's arrangements for REC incentives and virtual sharing are among the most elaborate in the sample. Legislative Decree 199/2021, ARERA's integrated regulation, and the

national incentive decree together put the calculation and remuneration of shared energy on an operational footing. P2P trading has no explicit legal status and is represented only by functional analogues (contracts, market sales, and community allocation), so D4 is coded L1. Under the TIAD, shared energy receives a partial restitution of network-tariff components in addition to the incentive, which places D5 at L2. Aggregated mixed units (UVAM), which may combine small generation, storage, and demand, have provided dispatching services to the TSO since the 2018 pilot, so D7 is coded L3 [60–64].

Greece replaced net metering with net billing and virtual net billing, for which detailed rules were issued in 2024. HEDNO accepts and connects net-billing units, but the crediting of exported energy was often delayed because the required DAPEEP and HEDNO data arrived late or not at all, and a revised framework was adopted only after the cutoff, so D1 is coded L2 [65,66]. Energy-community activity is extensive, but the evidence shows that commercial generation has far outweighed self-generation. Market access works through licensed aggregators. One of them is the last-resort aggregator run by DAPEEP under Law 4414/2016, which the commercially oriented community stations use [67]. Demand-response aggregators can register as balancing service providers with the TSO (IPTO), and aggregated loads have provided mFRR since 2023, so D7 is coded L3 [68,69]. Explicit P2P settlement has not yet been demonstrated, and shared energy pays the ordinary network charges (D5 = L1). The low-voltage smart-meter rollout was under way but incomplete at the cutoff [70,71], so for most low-voltage customers, virtual net billing is not settled on validated 15 min interval data. This affects D8 but not D3, because the D3 anchor requires routine settlement of virtual sharing, which takes place on the existing meters, not settlement at interval resolution. D4 and D8 therefore remain at the defined level [18,72–74].

Portugal combines collective self-consumption, 15 min allocation coefficients, and favorable treatment of some tariff components. It has no net metering, but the lack of one remuneration model should not be confused with the lack of the capability itself. DGEG states that surplus electricity may be sold to the grid, and Decree-Law 15/2022 provides market, aggregator, and bilateral routes. D1 is therefore coded L3 [75–78]. Explicit P2P trading is recognized in law, but no evidence was found that it works as a routine decentralized market. Consumption units may provide mFRR under the system-management rules approved by ERSE in 2023, but participation through aggregation of small units was not documented, so D7 remains at L2 [79].

Ireland pays for exported electricity under the Clean Export Guarantee, and the regulator publicly recognizes active consumers and energy-community activities. Institutional sources suggest, however, that REC recognition is still closely tied to support schemes, and a complete operational framework for community sharing and P2P settlement is still being developed. Ireland takes part with Northern Ireland in the all-island Single Electricity Market (SEM), so wholesale and balancing rules are set at the all-island level, while retail, tariff, and community rules are national. Demand side units, which aggregate individual demand sites, are registered in the wholesale market and are scheduled and dispatched in the balancing market [80,81]. More than four in five households have smart meters, and exports are paid on metered data [82]. Accordingly, Ireland is coded L3 on D1 and D6–D8 but L1–L2 on the collective, P2P, and tariff dimensions [18,83–86].

4.2. PMAM Scores and Maturity Bands

The scores are reported in Table 4 and Figure 1. Denmark has the highest total (23/32), followed by Flanders and Portugal (22/32), Italy (21/32), Greece (19/32), and Ireland (17/32). All six fall in the advanced band and none reach the frontier band; therefore, at the band level, the comparison discriminates little, and the differences lie in the profiles.

Flanders and Portugal tie with different strengths: Flanders is one level higher on explicit P2P status (D4) and balancing access (D7), whereas Portugal is two levels higher on tariff treatment (D5). Ireland's total equals the lower bound of the advanced band. The tie and the near-ties are informative in themselves and should not be turned into a spurious exact ranking.

Table 4. Scores by jurisdiction and dimension, with maturity bands.

Jurisdiction	D1	D2	D3	D4	D5	D6	D7	D8	Total	Band
Denmark	L3	L3	L2	L2	L1	L4	L4	L4	23/32	Advanced
Flanders	L3	L3	L3	L3	L1	L3	L3	L3	22/32	Advanced
Italy	L3	L3	L3	L1	L2	L3	L3	L3	21/32	Advanced
Greece	L2	L3	L3	L2	L1	L3	L3	L2	19/32	Advanced
Portugal	L3	L3	L3	L2	L3	L3	L2	L3	22/32	Advanced
Ireland	L3	L2	L1	L1	L1	L3	L3	L3	17/32	Advanced
Modal level	L3	L3	L3	L2	L1	L3	L3	L3	21/32	Advanced

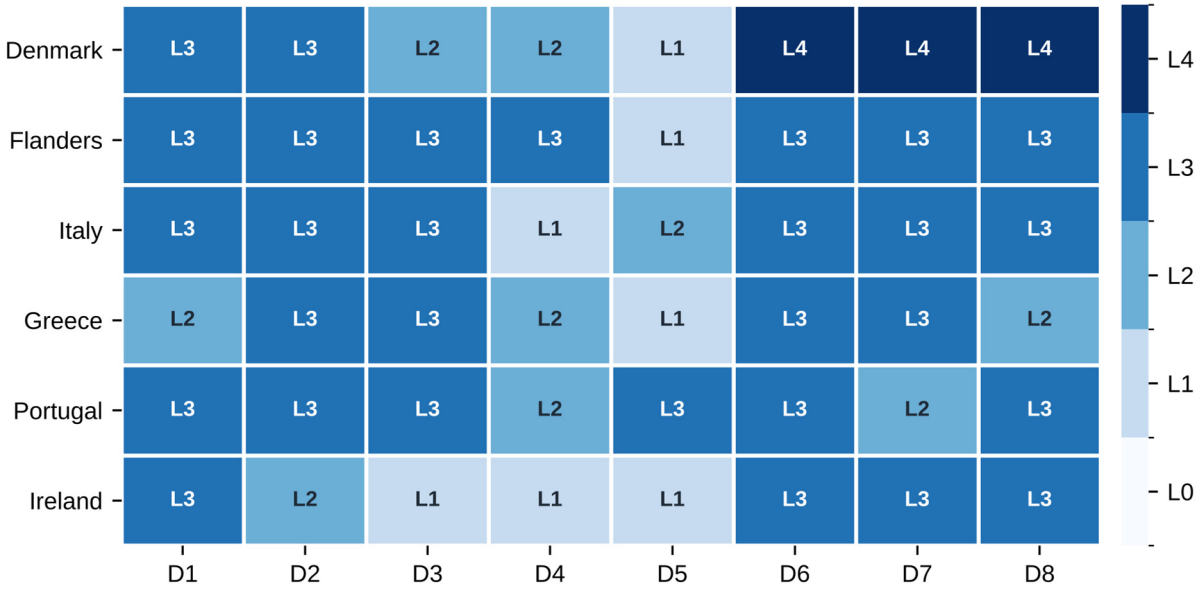


Figure 1. PMAM maturity heatmap. Levels: L0—absent; L1—nascent; L2—defined; L3—operational; L4—market-integrated. Shading indicates the documented capability level of each cell. Outcomes are not measured.

The highest scores are found in D1–D3, as export remuneration, community recognition, and some form of collective allocation operate in most jurisdictions. D4 and D5 score lowest. Operational explicit P2P selling is found only in Flanders, and specific tariff treatment of shared energy is in force only in Portugal (L3) and partially in Italy (L2). D6 and D7 score higher than a focus on community-specific routes would suggest. In five jurisdictions, aggregated portfolios that can include small or demand units take part in balancing, but these are system-wide TSO arrangements that were not designed for communities. Portugal is the exception, with D7 one level below D6. These cross-dimension comparisons should be read with care. Each anchor defines what "operational" means for its own capability, so the same level on D1 and on D4 does not denote the same quantity. What the comparison shows is that the operational stage defined for P2P settlement and tariff treatment has been reached in fewer jurisdictions than the operational stage defined for export, community registration, and sharing.

4.3. Sensitivity Analysis

The robustness analysis tests whether the conclusions depend on the choice of dimensions, the weights, the value given to each level, the aggregation rule, the band thresholds, or the coding of individual cells. A monotonic rescaling of the equal-weight sum cannot change the order, so it is not used as a test. Systematic omission, random weights, alternative level values, non-compensatory aggregation rules, alternative band thresholds, and perturbation of the coding are used in its place. The results under omission of single dimensions and under random weights are given in Table 5.

Table 5. PMAM results under omission of single dimensions and under random non-negative weights.

Jurisdiction	Equal-Weight Total	Leave-One-Out Total Range	Leave-One-Out Position	Probability of Ranking First
Denmark	23	19–22	1st in 7 cases (sole 1st in 5), 2nd when D7 is omitted	53.5%
Flanders	22	19–21	1st to 4th	18.1%
Portugal	22	19–20	1st to 3rd	27.7%
Italy	21	18–20	2nd to 4th	0.8%
Greece	19	16–18	5th in all cases (tied with Ireland once)	0.0%
Ireland	17	14–16	6th in all cases (tied 5th once)	0.0%

Across the eight leave-one-out runs, Denmark is sole first in five, shares first place with Flanders and Portugal when D6 or D8 is omitted, and falls to second behind Portugal when D7 is omitted. Greece is fifth in every run, and Ireland is sixth, the two tying only when D3 is omitted. With random weights, Denmark ranks first in 53.5% of draws, Portugal in 27.7%, Flanders in 18.1%, and Italy in 0.8% (Appendix B gives the full rank-acceptability matrix and all pairwise probabilities). Pairwise, Denmark is ahead of Flanders in 68.7% of draws and ahead of Portugal in 63.8%, Flanders is ahead of Portugal in 55.6%, Portugal is ahead of Italy in 75.0%, Italy is ahead of Greece in 87.5%, and Greece is ahead of Ireland in 77.9%. Ireland ranks last in 76.6% of draws, Greece in 21.6%, and Portugal in 1.8%. Only four orderings hold under every weighting, because they rest on weak dominance: Denmark, Flanders, and Italy over Ireland, and Flanders over Greece. The results support reading the scores in bands and profiles, not as a stable, precise ordering.

Table 6 shows that the bottom of the ranking does not depend on how levels are valued or aggregated. Ireland is last under both alternative mappings and under the leximin rule, and it ties for last place with Greece on the number of L3+ cells. Greece is fifth under both mappings. The top depends on compensation between dimensions. Denmark leads under the linear and convex mappings because of its three L4 cells, but it falls to fourth under the leximin rule and has fewer L3+ cells than Flanders, Portugal, and Italy, because its sharing and tariff cells are at L2 and L1. Portugal, the only jurisdiction without a cell below L2, leads under the leximin and minimum-level rules, and Flanders has the most cells at L3 or above.

Table 6. Rankings under alternative level values and non-compensatory aggregation rules (rank in parentheses, with tied jurisdictions sharing the better rank).

Jurisdiction	Linear Sum	Convex 0–1–2–4–8	Concave √Level	Cells at L3+	Minimum Level	Leximin Rank	Weakly Dominates
Denmark	23 (1)	37 (1)	13.29 (1)	5	L1	4	Ireland
Flanders	22 (2)	29 (2)	13.12 (3)	7	L1	2	Greece, Ireland
Portugal	22 (2)	28 (3)	13.22 (2)	6	L2	1	–
Italy	21 (4)	27 (4)	12.81 (4)	6	L1	3	Ireland
Greece	19 (5)	23 (5)	12.17 (5)	4	L1	5	–
Ireland	17 (6)	21 (6)	11.34 (6)	4	L1	6	–

Band membership is sensitive to the thresholds only at the margins. Shifting the equal-width thresholds by one or two points leaves Flanders, Portugal, Italy, and Greece in the advanced band. A downward shift of two points moves Denmark into the frontier band, and an upward shift of one point moves Ireland into the developing band. The conjunctive rule, which assigns the band of the weakest dimension, places every jurisdiction except Portugal in the developing band, because each has at least one dimension at L1. Rescaling each dimension to its observed maximum moves Denmark, Flanders, Portugal, and Italy into the top quartile. The band labels are therefore a coarse summary, and the profile in Table 4 is the primary result.

Perturbing the coding confirms the bottom of the ranking. The position at the top depends on the error model (Table 7). Under the empirically anchored scenarios, Ireland is last (including ties) in at least 97.8% of draws, and the five upper jurisdictions stay in the advanced band in at least 95.5% of draws. Ireland's advanced classification is the least secure result: it holds in 73.8–89.5% of draws under H1–H3 and in 46.9% at the upper bound H4, because Ireland's total equals the lower threshold. Denmark is the sole highest scorer in 56.8% of draws when the observed rate applies to all cells (H1), and in 75.2–81.9% when changes are confined to the L2/L3 boundary (H2–H4). Its higher figure in H2–H4 reflects the calibration rather than additional evidence, because its three L4 cells are not perturbed, and its two L2 cells can only gain. Under the stress tests, the lead is not secure. With 10% in each direction (A), Denmark is the sole leader in 34.8% of draws, and some jurisdictions reach the frontier band in 9.1%, rising to 24.3% at 20% (C) and 27.1% under a jurisdiction-wide shock (F). Restricting upward moves to those consistent with the evidence rules removes almost all frontier entries: the probability falls to 0.8% in A, 2.5% in C, and at most 0.1% in the empirically anchored scenarios. Only the jurisdiction-wide shock maintains a material probability (17.4%), because all L3 cells of a jurisdiction on D6–D8 can then move to L4 together. Excluding new L4 cells reduces it to 4.6%, all of which is for Denmark, whose D3 and D5 cells can then rise together. The restriction also strengthens Denmark's position, because its L4 cells can only move down in either run, whereas Flanders and Portugal lose upward movement on D1–D5 and on cells without operational evidence. In scenario A, Denmark is then sole first in 42.0% of draws and ahead of Flanders and Portugal in 59.1% and 62.3% of draws, while Flanders and Portugal remain indistinguishable (Flanders is ahead in 38.5% of draws and the two tie in 27.8%). Coding uncertainty thus leaves the order among the three less open than the stress tests suggest, but the dependence of that order on compensation between dimensions (Table 6) is unaffected. Changes in implementation after the cutoff are a separate question and are not modeled as coding errors. Denmark is two points from the frontier band, Flanders and Portugal are three points away, Italy is four points away, Greece is six points away, and Ireland is eight points away.

Table 7. Coding-perturbation scenarios (100,000 draws each, % of draws). Each result cell gives the unrestricted/evidence-constrained value. Rates are per direction. Total change is the probability that a cell away from the ends of the scale changes level.

Scenario	Up/Down per Direction (%)	Total Change (%)	Denmark Sole First	Ireland Last (Incl. Ties)	Lowest Band Retention (All Except Ireland)	Ireland Stays Advanced	Any Jurisdiction Frontier
Empirically anchored							
H1. Observed rate, all cells	3.125/3.125	6.25	56.8/67.2	99.1/99.2	99.2/99.8	81.8/81.3	1.0/0.1
H2. L2/L3 boundary, directional	22.2 from L2/3.4 from L3	22.2 (L2), 3.4 (L3)	75.2/81.6	99.9/99.9	95.5/100.0	89.5/89.5	4.5/0.0
H3. L2/L3 boundary, pooled	7.9/7.9 (L2, L3 only)	7.9	81.9/84.4	99.7/99.7	99.5/99.8	73.8/73.8	0.5/0.0
H4. L2/L3 boundary, 95% upper bound	21.4/21.4 (L2, L3 only)	21.4	79.8/80.8	98.2/97.8	97.2/98.0	46.9/46.9	2.8/0.0
Stress tests							
A. Symmetric	10/10	20	34.8/42.0	91.8/91.7	95.5/97.2	66.7/64.4	9.1/0.8
C. Symmetric, high	20/20	40	25.7/31.3	81.3/79.5	91.3/88.8	61.2/57.3	24.3/2.5
D. Upward bias	10/5	15	36.0/46.6	95.0/95.0	93.9/99.3	82.1/80.7	11.9/1.1
E. Dimension-specific	15/15 (D4–D7), 5/5 (others)	30 (D4–D7), 10 (others)	33.1/37.6	91.9/91.4	96.5/97.4	66.4/65.3	8.1/0.9
F. Jurisdiction-wide shock + noise	Shock 5/5, noise 5/5	18.5	37.8/44.6	73.6/73.7	88.8/90.1	69.6/72.2	27.1/17.4
G. Dimension-wide shock + noise	Shock 5/5, noise 5/5	18.5	42.1/51.4	97.7/97.0	95.6/97.2	67.2/65.0	7.3/0.7

4.4. Positioning Rights Against Market Integration

In Figure 2, rights and sharing capabilities are plotted against market and system integration. The horizontal axis is the average maturity of D1–D4 (surplus remuneration, energy-community frameworks, energy sharing, and explicit P2P trading). The vertical axis shows the mean of D5–D7, which cover network-tariff treatment, wholesale and aggregation access, and balancing. The D8 level is printed next to each name instead of being shown by marker size. This keeps the ordinal level explicit and avoids giving some observations more visual weight than others.

Denmark is highest on market and system integration, owing to mature wholesale, aggregation, balancing, and data-exchange arrangements, and it is the only jurisdiction at L4 for D8. Horizontally, it is at 2.50, together with Italy and Greece, because grid-wide energy sharing (Denmark), explicit P2P status (Italy), and net-billing settlement (Greece) are less developed. Flanders lies furthest to the right, since P2P energy selling there is both explicitly recognized and operational, while the lack of specific tariff treatment of shared energy keeps it at 2.33 on the vertical axis, level with Greece and Ireland. Flanders, Italy, Portugal, and Ireland are at L3 for D8, which means that validated interval data support allocation or settlement, although data are not yet interoperable at market-settlement resolution.

Portugal (2.75, 2.67) and Italy (2.50, 2.67) reach the same integration level with different profiles: Portugal through its tariff treatment of shared energy (D5 = L3), and Italy through balancing access for aggregated mixed units (D7 = L3). Greece is at the same horizontal position as Italy, but it is lower because shared energy pays the ordinary network charges, and it is the only jurisdiction at L2 for D8, because validated low-voltage interval data were not yet available for most customers at the cutoff. Ireland lies furthest to the left

but at the same integration level as Greece and Flanders, since its system-level wholesale and balancing routes (D6 and D7 = L3) offset the lack of specific tariff treatment. Its smart-meter data support export payments, but no multi-party sharing process exists yet.

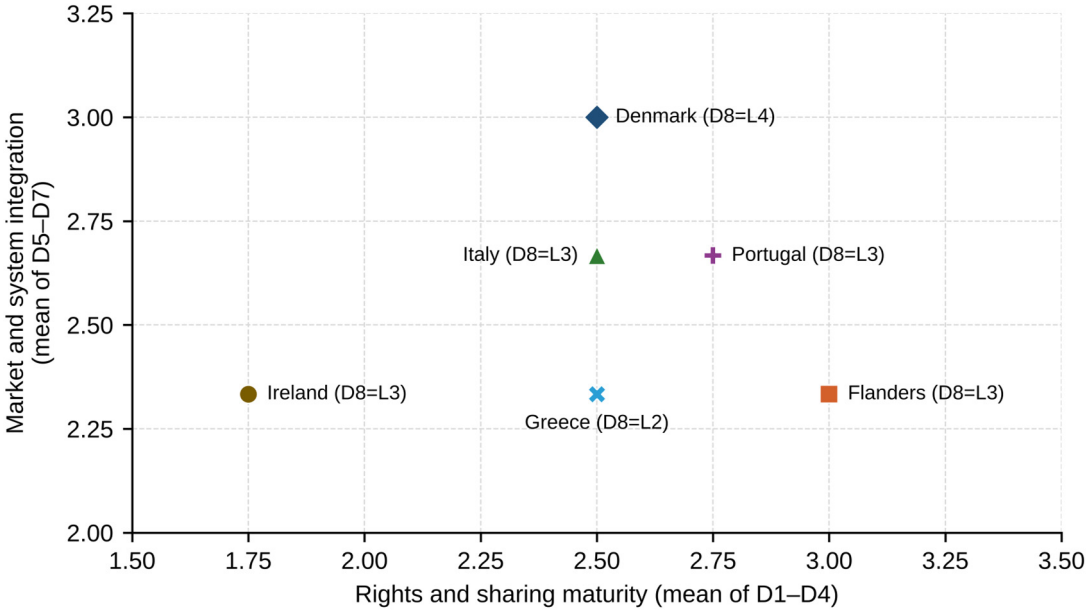


Figure 2. Rights and sharing maturity (mean of D1–D4) versus market and system integration (mean of D5–D7). Labels report the D8 level of each jurisdiction. Axes are truncated to the range of the observed values.

Figure 2 thus suggests that rights and integration do not develop together. In Flanders, Greece, and Portugal, rights and sharing capabilities are ahead of market and system integration, mainly because the network-tariff treatment of shared energy lags behind. Denmark, Italy, and Ireland show the reverse pattern, with system-wide market and balancing routes more developed than collective sharing or P2P settlement. Because the two axes average different anchors, this is a comparison of where each jurisdiction has reached the operational stage, not of the size of a gap. The regulatory task is to link these rights to validated interval data, transparent tariffs, effective aggregation, and workable balancing pathways.

5. Discussion

5.1. Institutional Determinants of Cross-Dimensional Maturity Differences

A plausible institutional explanation for the pattern in Section 4.2, which this study does not test, is the number of bodies that each capability involves. D1–D3 depend largely on processes that one body already runs: exports are paid by a supplier or support agency, communities are entered in a register, and shared volumes are allocated by the DSO within the existing metering and billing chain. D4 and D5, in contrast, involve several actors and regulatory cycles. Explicit P2P settlement (D4) requires a supplier-centered retail model to recognize transactions between customers who may have different suppliers. For cost-based tariff treatment (D5), network-cost evidence and a revision of tariff methodologies are needed, and such revisions usually follow multi-year regulatory periods. Balancing pathways (D7) depend on TSO product design, prequalification, and imbalance-settlement rules, which are set at national or Union level by bodies other than those administering community schemes [39]. Where TSOs have opened their products to aggregated portfolios, small resources reach balancing through system-wide routes even

when no community-specific route exists. The Flemish case illustrates this, with energy sharing regulated by the region and balancing access open to aggregated low-voltage resources, which are set at the Belgian level. D6 and D8 are intermediate, since existing supplier, aggregator, and metering infrastructure can be reused, although L4 again requires multi-party data exchange at settlement resolution.

5.2. Operational Integration as the Central Gap

Prosumer and community activity is broadly recognized in all six jurisdictions, but recognition does not constrain implementation to the same degree everywhere. The D1–D3 scores show that individual export, community formation, and virtual allocation have been made operational under quite different institutional models. Difficulties increase at D4 and D5, which concern settlement among several customers and allocation of network costs, and at the interface between sharing arrangements and balance responsibility. Progress there depends on coordination between suppliers, DSOs, TSOs, aggregators, and settlement bodies, which a new legal definition cannot provide on its own.

The relation between D6 and D7 is less straightforward than a focus on communities suggests. Under the common system-level standard, balancing access is at least as developed as wholesale access in five jurisdictions, because TSOs admit aggregated portfolios, often through aggregators independent of the supplier. Portugal is the exception. The remaining gap lies at the prosumer and low-voltage scales. In Belgium, for example, low-voltage units take part in FCR, but aFRR was opened to them only in 2024, and mFRR access is planned for 2026 [59]. Through an intermediary, a prosumer can gain wholesale or PPA access without any change in who carries imbalance risk. Balancing requires five additional conditions: validated data at settlement resolution, a clear contract with a BRP or aggregator, rules for allocating deviations, minimum-bid and prequalification terms that aggregated resources can meet, and consumer protection when a third party controls flexibility. If all of this is treated as "market access", the final and often most difficult operational steps are missed.

These conditions also mark where regulatory access ends and technical operation begins. Prequalification, telemetry, baseline methods, and communication between aggregators, DSOs, and TSOs determine whether an access right can be used in real time [40,41]. Technical studies show what these interfaces require in operation. Gao et al. keep clusters of multi-energy microgrids coordinated across cloud and edge layers under communication latency, packet loss, and noise, using a digital twin to predict system states when data arrive late or not at all and reconfiguring the communication topology [87]. Zheng et al. develop an asynchronous distributed learning algorithm for aggregative games in which agents grouped in clusters face uncertain costs and must estimate the aggregate of all decisions locally, without a central aggregator. The method is applied to power generation [88]. Both studies show that the coordination of distributed resources depends on the data and information available to each participant. Such studies evaluate the performance of control and coordination methods. PMAM records whether rules and processes for these interfaces exist and operate, on the basis of regulatory and operator documents, but it does not assess their technical performance, which requires operational data from the actors concerned.

5.3. Implications of Article 15a

Article 15a, which Member States had to transpose by July 2026, extends energy sharing beyond communities. Any eligible active customer may share renewable energy, either by private agreement or through an organizer, while keeping supplier choice and consumer rights. The deduction of shared energy is tied to the imbalance settlement period, and system operators must validate the data [4]. National frameworks should

therefore be judged by whether they can register arrangements, communicate allocations, apply cost-reflective charges, and manage balance responsibility at scale. Supporting a long-standing collective self-consumption program is not enough. Italy is a case in point. In Italian renewable energy communities, shared energy is calculated hourly under ARERA's integrated regulation on widespread self-consumption (TIAD) [61]. The Italian imbalance settlement period, however, has been 15 min since the transitional phase of the integrated dispatching code (TIDE) began on 1 January 2025 [89]. The statement applies only to the incentive-based configurations for widespread self-consumption regulated by the TIAD (renewable energy communities and groups of jointly acting self-consumers). Their hourly calculation is operational (D3 = L3), but it would not meet the requirement that shared electricity be netted per imbalance settlement period if the same calculation were used for energy sharing under Article 15a. It is not a finding on Italian community energy arrangements in general, nor on how Legislative Decree 3/2026 will be implemented [90].

None of the scores are a legal opinion on full conformity with Article 15a. The cutoff falls soon after the transposition deadline, and implementation documents may be published some time after a law is adopted. What PMAM records is the strongest operational evidence available at the cutoff, so that the remaining gaps in evidence are visible.

Table 8 summarizes the transposition status of Article 15a at the cutoff, together with indicative uptake figures that frame what the scores do not measure. Denmark, Italy, and Portugal had adopted transposing legislation, whereas Belgium, Greece, and Ireland were among the 18 Member States to which the Commission sent letters of formal notice on 25 September 2026 for not notifying complete transposition [91]. In none of the six jurisdictions was a standalone Article 15a route in operation at the cutoff, which is why no D3 cell reaches L4. The D3 scores therefore describe the collective-sharing routes that existed before Article 15a, not compliance with it. In Denmark, Italy, and Portugal, the transposing instruments were already in force at the cutoff. In Portugal, they were in force only three days before the cutoff, but the implementing rules, platforms, and settlement processes that an Article 15a route requires were not yet in operation, so none of these instruments raises a D3 score.

Table 8. Transposition of Article 15a at the cutoff and indicative uptake (latest figures available).

Jurisdiction	Article 15a Transposition at the Cutoff	Indicative Uptake
Denmark	Electricity Supply Act amended (bill L 69, 2024–25), defining energy sharing and empowering Energinet to operate a sharing platform, which was still under development [52,92]	No official statistics on energy communities. State grants for community projects have existed since 2023 [93]
Flanders	Regional energy-sharing framework in force since 2022 (Energy Decree). Belgium received a letter of formal notice on 25 September 2026 [54,91]	80 energy communities (September 2025) and 0.28% of access points for sharing or selling (December 2024) [57]
Italy	Legislative Decree 3/2026 transposing Directive (EU) 2024/1711 [90]	3315 renewable-energy-community configurations in operation (May 2026) [94]
Greece	Complete transposition not notified. Letter of formal notice on 25 September 2026 [91]	1747 active energy communities (October 2025) [95]
Portugal	Decree-Law 130/2026 amending Decree-Law 15/2022, presented as transposing the electricity market design directive and in force since 28 August 2026 [96,97]	1218 energy communities connected to the grid (April 2026) [98]
Ireland	Complete transposition not notified. Letter of formal notice on 25 September 2026 and regulator call for evidence on energy sharing [91,99]	More than 140,000 smart-meter customers paid for exports, but no energy-sharing arrangements [82]

5.4. Policy Priorities by Jurisdiction

For each jurisdiction, the PMAM profile points to the regulatory interfaces at which further action would have the most effect. Table 9 lists the lowest-scoring dimensions, the immediate regulatory task, and the existing asset that reform can build on. The point is not to raise the PMAM score for its own sake but to close the operational gaps that the low-scoring cells expose.

Table 9. Priority regulatory interfaces indicated by the PMAM profiles.

Jurisdiction	Priority Dimensions	Immediate Regulatory Task	Asset to Preserve
Denmark	D3–D5	Put grid-wide energy sharing into operation, standardize contracts for local and P2P trade, and check whether tariffs reflect measurable network use	Preserve mature BRP and DataHub interfaces
Flanders	D5	Set out cost-reflective tariff treatment of shared energy and of energy selling	Extend proven quarter-hourly data processes
Italy	D4 and D5	Go past incentive allocation by linking REC (CER) settlement to clear P2P rules and by extending the tariff treatment of shared energy	Use GSE/ARERA operational infrastructure and UVAM experience
Greece	D1, D4, D5, and D8	Make net-billing settlement routine and add transparent tariffs for shared energy and validated 15 min data for low-voltage customers to the existing rights	Build on 15 min settlement rules, aggregator routes, and balancing participation of aggregated loads
Portugal	D4 and D7	Put the recognized P2P trade into practice and publish the responsibilities of BRPs and aggregators	Retain transparent shared-energy tariff treatment
Ireland	D2–D5	Finish the statutory and settlement arrangements for community sharing and P2P trade, and define tariff treatment of shared energy	Build from the export-payment framework, smart-meter data, and the DSU regime

The tasks in Table 9 differ in who controls them and how quickly they can be completed. Data and metering tasks (D8) and the operation of sharing platforms (D3) lie with DSOs, TSOs, and data-hub operators and can follow the national implementation of Article 15a. Tariff treatment (D5) follows multi-year tariff periods set by national regulators. Balancing access (D7) depends on TSO product design under the balancing guideline and on the forthcoming network code on demand response, and explicit P2P settlement (D4) requires changes to supplier-centered retail models. A plausible sequence is therefore data and sharing processes first, tariff treatment in the next tariff period, and P2P and balancing rules as the EU network codes are adopted.

5.5. Implications for Sustainability and Market Design

Whether distributed investment is economically accessible, socially inclusive, and useful to the power system is largely a matter of regulation. Export remuneration improves the business case of individual projects. Community governance can bring in more participants, and through energy sharing, customers without a suitable roof or capital can use local renewable output. Whether these benefits materialize depends on the detailed rules: network charges may conceal cross-subsidies, allocation rules may lack transparency, and vulnerable customers may be formally eligible yet unable to participate in practice [11,14,17].

From a system perspective, mature data and balancing pathways can make distributed flexibility visible and accountable. A potential mechanism, which this study does not

measure, is that system costs are then reduced and not merely shifted between users, provided that the settlement boundary, baseline, activation, and imbalance allocation are clearly specified. Energy-sharing reform therefore needs to be assessed together with smart-meter data governance, aggregation rules, and balancing-product design. Handled in separate policy silos, these four areas would probably leave the gap found in Section 4 between enabling rights and market integration in place. The network code on demand response, for which ACER submitted a framework guideline in December 2022, offers a chance to align them across Member States [100].

5.6. Applying PMAM in Practice

PMAM is intended as an evidence-based checklist and comparison framework. Low-scoring cells point regulators to missing rules, a jurisdiction's profile helps project developers anticipate contracting and settlement constraints, and individual cells can be updated by researchers when new instruments become operational. The index cannot, however, be used to infer deployment volumes, consumer benefits, overall regulatory quality, or causal policy effects. Answering such questions requires market data, project outcomes, and stakeholder evidence.

5.7. Limitations and Future Research

Five limitations should be noted. First, the jurisdictions were selected through the EU-DREAM project and are not representative of the EU. Large markets such as Germany, Spain, France, and the Netherlands are not included. Second, the scores are ordinal judgements based on documents. The explicit coding rules and the source trail for each cell reduce subjectivity, but borderline cells still require interpretation, which double coding and the perturbation test limit without eliminating. Some arrangements may also have been missed because they are documented only in national languages or were not yet published. Third, the assessment is a snapshot taken on 31 August 2026, shortly after the Article 15a transposition deadline, when several jurisdictions were still adopting implementing acts. Fourth, levels on different dimensions are defined by different anchors, so cross-dimension comparisons show where the operational stage has been reached rather than equal distances, and the L4 anchors on D1–D5 are benchmarks not yet observed in the sample. Finally, PMAM measures regulatory capability. Outcomes such as the number of active sharing arrangements, participant savings, or avoided network costs are outside its scope, and Table 8 reports uptake figures only to frame this limit.

Future work could link PMAM profiles to outcome indicators of this kind and extend the sample to other Member States. The contested cells should be checked with national experts from the EU-DREAM Living Labs, regulators, and DSOs. Repeating the assessment at regular intervals would also make it possible to follow the implementation of Article 15a and of the forthcoming network code on demand response.

6. Conclusions

PMAM offers an auditable comparison of prosumer market access in Denmark, Flanders, Italy, Greece, Portugal, and Ireland. Its contribution is mainly conceptual and methodological. The framework uses eight capability-specific rubrics and records, for every cell, both the legal status of the capability and whether its operation is verified. It treats wholesale access and balancing separately, assesses both against the same system-level standard, and works with a fixed evidence cutoff. The sensitivity analysis covers dimension omission, random weights, alternative level values, non-compensatory aggregation, alternative band thresholds, and independent, biased, and correlated coding errors, calibrated on double coding and restricted to moves consistent with the evidence rules.

Progress has been greatest in export remuneration, recognition of energy communities, and collective allocation, and slowest in explicit P2P settlement and network-tariff treatment of shared energy. Balancing access is more developed than community-specific routes suggest, since TSOs in five jurisdictions admit aggregated portfolios that can include small resources. No jurisdiction reaches the frontier band. All six jurisdictions are in the advanced band: Denmark scores 23/32, Flanders and Portugal score 22, Italy scores 21, Greece scores 19, and Ireland scores 17. Ireland comes last under every level mapping tested, and Greece comes fifth, but the order of the leaders depends on how much compensation between dimensions is allowed. The jurisdictions have different strengths, and their order should not be read as a stable league table.

For sustainability, the results show where regulation still limits the contribution of citizens to the energy transition. Environmentally, workable sharing, aggregation, and balancing routes allow distributed renewable generation and flexibility to be used locally and to support system operation as renewable shares rise. Economically, cost-reflective network charges for shared energy decide whether local exchange lowers system costs or shifts them to non-participants. Socially, the rights widen participation only if households and small businesses can actually use them, not only actors able to handle complex contracts and imbalance risk. PMAM turns these conditions into a transparent and repeatable indicator, so regulators and researchers can monitor the implementation of Article 15a and related sustainability policies over time and in other Member States.

For policy, the next gains for prosumers will come mainly from implementing existing rights: registration, contracts, validated interval data, allocation, cost-reflective charges, aggregation, and balance responsibility have to work as one operational chain. Article 15a sets out where national frameworks should be heading, and PMAM offers a way to monitor their progress.

Author Contributions: Conceptualization, G.D. and P.B.; methodology, G.D.; software, P.M.; validation, P.M. and P.B.; formal analysis, G.D. and P.M.; investigation, G.D. and P.M.; data curation, P.M.; writing—original draft preparation, G.D.; writing—review and editing, P.M. and P.B.; visualization, P.M.; supervision, P.B.; project administration, P.B.; funding acquisition, P.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union's Horizon Europe program under grant agreement No. 101160614 (EU-DREAM Project, DOI: 10.3030/101160614). The APC was funded by the EU-DREAM project.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The coded PMAM dataset (the 48 jurisdiction–dimension scores and two-part codes, the two independent codings with the script that computes their agreement, the evidence records of Appendix A with source URLs, pinpoint references, and evidence dates, and archived copies of the web sources) and the Python scripts (Python 3.13, Python Software Foundation, Wilmington, DE, USA, with NumPy 2.5) used for all robustness analyses and figures are deposited on Zenodo (https://doi.org/10.5281/zenodo.24322087) and mirrored on GitHub at https://github.com/PavlosManakidis/PMAM_Framework_Analytics (accessed on 23 November 2026). The script pmam_perturbation_r2.py reproduces Tables 7 and A11, and the repository README documents, for every perturbation scenario, the per-direction and total probabilities, the boundary handling, the evidence caps, and the correlated shocks. No personal data were collected. Section 3.5 specifies the random-weight analysis in full. It can be reproduced from the score matrix with a Dirichlet(1,…,1) distribution, 200,000 draws, and NumPy's default random generator with

seed 42 (numpy.random.default_rng(42)). Each coding-perturbation scenario uses 100,000 draws from the same generator and seed.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ACER	European Union Agency for the Cooperation of Energy Regulators
ARERA	Italian Regulatory Authority for Energy, Networks and Environment
BRP	Balance Responsible Party
CEC	Citizen Energy Community
CER	Comunità Energetica Rinnovabile (Italian REC)
CIEG	costs of general economic interest (Portugal)
CRU	Commission for Regulation of Utilities (Ireland)
DAPEEP	Renewable Energy Sources and Guarantees of Origin Operator (Greece)
DGEG	Directorate-General for Energy and Geology (Portugal)
DSO	Distribution System Operator
EB GL	Electricity Balancing Guideline
EECF	European Energy Communities Facility
ERSE	Energy Services Regulatory Authority (Portugal)
GSE	Gestore dei Servizi Energetici
P2P	Peer-to-Peer
PESTLE	Political, Economic, Social, Technological, Legal, and Environmental
PMAM	Prosumer Market Access Maturity
PPA	Power Purchase Agreement
REC	Renewable Energy Communities
RED	Renewable Energy Directive
TIAD	Testo Integrato Autoconsumo Diffuso (Italian integrated regulation on widespread self-consumption)
TIDE	Testo Integrato del Dispacciamento Elettrico (Italian integrated dispatching code)
TSO	Transmission System Operator

Appendix A. Cell-Level Evidence Record

Table A1 gives the score and a short statement of the evidence for each of the 48 jurisdiction–dimension cells. Here, "operational" means that documents show a payment, allocation, market, or data process in actual use. It says nothing about how widely the process is used or how satisfied participants are. The columns Legal status and Operation give the two-part code defined in Section 3.2, which is explained in the table caption.

Table A1. PMAM score, legal status, operational verification, rationale, and principal evidence for every jurisdiction–dimension pair. Legal status: R, implementing rules in force. P, principle or right without implementing rules. N, no specific legal basis. Operation: V, verified in Tier 1 or Tier 2 sources. PV, partly verified. NV, not verified.

Jurisdiction	Dim.	Level	Legal Status	Operation	Rationale and Principal Sources
Denmark	D1	L3	R	V	Surplus is remunerated through net settlement and the supplier/BRP chain, and settlement is routine. Multiple independent retail routes were not found [47–50].

Denmark	D2	L3	R	PV	The electricity and renewable-energy acts and BEK 1069/2021 implement REC and CEC definitions, rights, obligations, and enabling rules. Danish Energy Agency grants support projects run by established energy communities, but no register or activity statistics were found [18,47–49,93].
Denmark	D3	L2	R	PV	Collective self-consumption operates behind a single main meter with sub-meters and one shared supplier. Sharing over the public grid was not yet operational at the cutoff, as Energinet's sharing platform was still under development [49,50,52,53].
Denmark	D4	L2	P	NV	P2P rights exist, as do bilateral and aggregator-mediated analogues. A standard decentralized settlement market between customers was not found [47–51].
Denmark	D5	L1	N	NV	Local exchanges remain subject to ordinary network tariffs. No general locational relief was found in operation [51].
Denmark	D6	L4	R	V	Mature, non-discriminatory routes to wholesale and flexibility markets run through suppliers, aggregators, and BRPs [47,50].
Denmark	D7	L4	R	V	Energinet prequalifies aggregated portfolios, demand facilities included, for FCR, FCR-N/D, FFR, aFRR, and mFRR. In DK2, the minimum bid for frequency-containment and fast-frequency products is 0.1–0.3 MW, and elsewhere, it is 1 MW. FCR (DK1), FFR, and FCR-D (DK2) can be offered without a BRP contract. In all other cases, imbalance responsibility is delegated through established BRP arrangements [50,101,102].
Denmark	D8	L4	R	V	Under flex or quarter-hour settlement, metering points are settled on 15 min values. Grid companies send metered data to DataHub every day. DataHub validates the data and forwards them to suppliers by 08:00 the next day [50,103].
Flanders	D1	L3	R	V	Injection is metered separately and paid for under supplier contracts based on quarter-hourly data [54–56].
Flanders	D2	L3	R	V	The region has implemented the REC/CEC framework, registration, and permitted activities, and 80 energy communities were registered by September 2025. Federal competence still applies to transmission and balancing [18,54,55,57].
Flanders	D3	L3	R	V	Fluvius runs energy sharing, with defined allocation rules and quarter-hourly settlement [55,56].
Flanders	D4	L3	R	V	Energy selling is expressly allowed and works through the DSO data process. Settlement is still organized around suppliers [55,56].
Flanders	D5	L1	N	NV	Sharing lowers only the energy component of the bill. Network tariffs, levies, and administrative costs apply in full to shared energy, with no specific tariff treatment [55,56].
Flanders	D6	L3	R	V	Prosumers reach energy and flexibility markets through suppliers and aggregators, and both routes are in use [54,55].

Flanders	D7	L3	R	V	Balancing is regulated at the Belgian level. Elia admits aggregated portfolios, including low-voltage units, as balancing service providers. About 17,000 low-voltage delivery points take part in FCR, and aFRR has been open to low-voltage units since 2024. Transfer-of-energy, opt-out, and pass-through arrangements allow a BSP to operate independently of the supplier and its BRP. No community-specific route was identified. Low-voltage participation is so far limited to FCR, with no aFRR volume yet and mFRR access planned for 2026, so L4 is not awarded [58,59].
Flanders	D8	L3	R	V	Sharing and energy selling rely on digital meters and validated quarter-hourly data [56].
Italy	D1	L3	R	V	Exported and shared renewable electricity is paid for through GSE mechanisms that are in operation [60–63].
Italy	D2	L3	R	V	Legislative Decree 199/2021 and its implementing acts have put the CER framework, registration, governance rules, and national incentives into operation [60–63].
Italy	D3	L3	R	V	Virtual sharing works under ARERA rules and GSE procedures, with shared energy calculated hourly [61–63]. This interval is longer than the 15 min Italian imbalance settlement period [89].
Italy	D4	L1	N	NV	No explicit legal status for P2P sales was found. PPAs, market sales, and CER allocation act as functional analogues [60–63].
Italy	D5	L2	R	V	Shared energy earns an incentive and, under the TIAD, a partial restitution of network-tariff components calculated on hourly shared energy. Otherwise, network charges follow the standard tariffs, with no general use-based local tariff [61,62].
Italy	D6	L3	R	V	Producers and communities can sell through GSE, the market, PPAs, or aggregators. Access runs through licensed parties and is in operation [60–63].
Italy	D7	L3	R	V	Aggregated mixed units (UVAM), which may combine small generation, storage, and demand, are enabled to provide dispatching services to the TSO. The regime has operated since the 2018 pilot and is now part of the TIDE. No community-specific pathway was found [60,61,64,89].
Italy	D8	L3	R	V	Hourly metering, virtual allocation, and GSE settlement are in place and working [61–63].
Greece	D1	L2	R	PV	Net billing and related surplus-settlement models were defined by the 2024 ministerial decision, and HEDNO connects net-billing units. Crediting of exported energy was often delayed by missing DAPEEP and HEDNO data, and the revised framework was adopted only after the cutoff [65,66,72].
Greece	D2	L3	R	V	REC, CEC, and older energy-community forms all have a legal basis, and many projects are documented [18,73,74].

Greece	D3	L3	R	V	Metering and allocation procedures are defined for virtual net billing and collective arrangements, and the operational rules are in force [72–74].
Greece	D4	L2	P	NV	There is a right to sell, and bilateral contracts serve as analogues. An explicit P2P settlement mechanism in operation was not found [73,74].
Greece	D5	L1	N	NV	Normal tariffs, charges, and taxes still apply, and no general tariff relief for local sharing is in operation [72].
Greece	D6	L3	R	V	Renewable stations, including community-owned ones, sell through licensed aggregators or through the last-resort aggregator run by DAPEEP. This route works. Direct access of communities to flexibility markets is not documented [67,72–74].
Greece	D7	L3	R	V	Demand-response aggregators register as balancing service providers through IPTO's Dispatchable Load Registry, and aggregated loads have provided mFRR since 2023. A balancing pathway specific to communities is not defined [68,69].
Greece	D8	L2	R	PV	Fifteen-minute settlement provisions and DSO metering rules exist. The smart-meter rollout was under way but incomplete at the cutoff, with national coverage planned by 2030, so most low-voltage sharing was still settled without validated interval data [70–72].
Portugal	D1	L3	R	V	According to DGEG, unconsumed surplus may be sold to the grid. Decree-Law 15/2022 sets up market, aggregator, and bilateral routes, all of which operate [75,76].
Portugal	D2	L3	R	V	Decree-Law 15/2022 sets out REC and CEC entities, proximity conditions, and system roles. According to the Government, 1218 energy communities were connected to the grid in April 2026 [18,75,98].
Portugal	D3	L3	R	V	Collective self-consumption and energy sharing are run by an internal manager, with the DSO calculating allocations from 15 min coefficients [75,77].
Portugal	D4	L2	P	NV	The law recognizes P2P commercialization. No decentralized settlement market between customers was found in routine use [75,77].
Portugal	D5	L3	R	V	Self-consumed energy carried over the public grid pays dedicated ERSE network-access tariffs, covering only the voltage levels used. The separate reduction of CIEG components relieves policy costs and is not a network-cost criterion [75,77].
Portugal	D6	L3	R	V	Surplus can be sold through aggregators, markets, or bilateral contracts, with licensed parties operating the route [75–77].
Portugal	D7	L2	R	PV	Consumption units may provide mFRR under the system-management rules approved by ERSE in 2023. Participation through aggregation of small units and a transparent imbalance allocation for communities were not documented [75–77,79].
Portugal	D8	L3	R	V	Fifteen-minute allocation coefficients, DSO calculations, and electronic procedures make settlement operational [75–77].

Ireland	D1	L3	R	V	Under the Clean Export Guarantee, exported electricity must be paid for, and suppliers execute these payments [83–85].
Ireland	D2	L2	P	PV	There are rules for REC recognition and support schemes, and CRU recognizes community activities. The statutory REC/CEC route is still incomplete [18,84–86].
Ireland	D3	L1	P	NV	Energy sharing is recognized as a community activity. By the cutoff, however, no routine process for multi-party allocation and settlement had been documented [84,86].
Ireland	D4	L1	N	NV	No explicit P2P status was found, and supplier export contracts are the only functional analogue [84,86].
Ireland	D5	L1	N	NV	This review identified no special network-charge treatment for shared or locally traded electricity [83,84].
Ireland	D6	L3	R	V	Demand-side units aggregate individual demand sites and are registered in the single electricity market. Suppliers and the renewable support scheme provide further routes to the market [80,81,83–86].
Ireland	D7	L3	R	V	Demand-side units are scheduled and dispatched in the balancing market. A route for communities to delegate imbalance responsibility was not found [80,81,84,86].
Ireland	D8	L3	R	V	More than two million smart meters (over four in five households) are installed, and the exports of over 140,000 smart-meter customers are paid on metered data. Data processes for multi-party sharing are still being developed [82–85].

Appendix B. Additional Robustness and Agreement Results

Tables A2–A5 complement Section 4.3. Tables A2 and A3 use 200,000 weight vectors drawn from a symmetric Dirichlet distribution with unit concentration parameters. Tables A4 and A5 use scenario A of Section 4.3, in which each of the 48 cells moves up one level independently, with a probability of 0.10, and one level down with a probability of 0.10, truncated to L0–L4, in 100,000 draws. All draws use the default generator of NumPy 2.5 with seed 42. Ranks are competition ranks: tied jurisdictions share the better rank, so each row in Tables A2 and A4 sums to 100%, while a column can sum to more than 100%. The pairwise probabilities in Tables A3 and A5 count only strict orderings. When two jurisdictions can tie, the two entries for the pair therefore sum to less than 100%, the remainder being the share of draws in which they tie. For example, Flanders and Portugal tie in 22.6% of the draws in Table A5. Table A11 gives the rank-acceptability matrices under the empirically anchored scenarios H1 and H2 in Section 3.5, with evidence-constrained upward moves. Tables A6–A10 report the full results of the second round of double coding. Coder 1 is the first author, and Coder 2 is the second author (Section 3.2). Where the two disagreed, the level of Coder 1 was retained after discussion with the third author. Across the 48 cells, exact agreement on the levels was 93.8% (45 of 48 cells), with a linearly weighted kappa $\kappa_W = 0.922$ (bootstrap 95% confidence interval 0.811–1.000, 10,000 resamples of cells) and a quadratically weighted kappa of 0.953. All three disagreements lie between L2 and L3 (Table A6), and neither coder assigned L0 to any cell. Agreement was complete on D2, D4, D5, D6, and D8, and 83.3% (5 of 6 cells) on D1, D3, and D7 (Table A7). By jurisdiction, it was complete in four jurisdictions, with 87.5% for Denmark and 75.0% for Greece (Table A8). For the two-part code, exact agreement was 85.4% (41 of 48 cells) for

legal status (Cohen's kappa of 0.485) and 85.4% (41 of 48 cells) for operation (Cohen's kappa of 0.709). All seven legal-status disagreements concern cells in D2 to D5 for Greece, Portugal, and Ireland that the first coder coded P or N and the second coder coded R (Table A9). They reflect the boundary between a recognized right and its implementing rules, which is the least reproducible part of the code. All seven operation disagreements involve the intermediate category PV (Table A10). The cell-level codings of both coders are included in the data deposit described in the Data Availability Statement.

Table A2. Rank-acceptability matrix under 200,000 random Dirichlet weights (% of draws in which each jurisdiction occupies each rank).

Jurisdiction	1st	2nd	3rd	4th	5th	6th
Denmark	53.5	18.6	15.5	8.7	3.6	0.0
Flanders	18.1	39.4	20.5	22.0	0.0	0.0
Portugal	27.7	21.6	27.9	15.1	5.9	1.8
Italy	0.8	20.2	32.5	36.0	10.6	0.0
Greece	0.0	0.1	3.6	16.6	58.0	21.6
Ireland	0.0	0.0	0.0	1.5	21.9	76.6

Table A3. Pairwise ordering probabilities under random weights (% of draws in which the row jurisdiction scores strictly higher than the column jurisdiction, with ties counted in neither direction).

Row > Column	Denmark	Flanders	Portugal	Italy	Greece	Ireland
Denmark	–	68.7	63.8	81.3	95.8	100.0
Flanders	31.3	–	55.6	66.7	100.0	100.0
Portugal	36.2	44.4	–	75.0	91.8	97.3
Italy	18.7	33.3	25.0	–	87.5	100.0
Greece	4.2	0.0	8.2	12.5	–	77.9
Ireland	0.0	0.0	2.7	0.0	22.1	–

Table A4. Rank-acceptability matrix under coding perturbation, scenario A (each cell moved one level up or down with a probability of 0.10 in each direction, 100,000 draws, % of draws).

Jurisdiction	1st	2nd	3rd	4th	5th	6th
Denmark	61.6	24.5	10.1	3.4	0.3	0.0
Flanders	34.1	30.2	22.8	11.4	1.5	0.1
Portugal	34.0	30.2	22.9	11.3	1.5	0.0
Italy	11.9	18.5	26.3	36.5	6.4	0.3
Greece	0.6	2.1	5.6	18.1	66.1	7.5
Ireland	0.0	0.1	0.3	1.9	18.5	79.3

Table A5. Pairwise ordering probabilities under coding perturbation, scenario A (% of draws in which the row jurisdiction scores strictly higher than the column jurisdiction, with ties counted in neither direction).

Row > Column	Denmark	Flanders	Portugal	Italy	Greece	Ireland
Denmark	–	55.4	55.4	76.9	97.0	99.9
Flanders	23.1	–	38.7	61.4	92.2	99.4
Portugal	23.0	38.7	–	61.4	92.1	99.4
Italy	9.4	19.5	19.5	–	80.5	97.5
Greece	0.8	2.5	2.5	7.8	–	80.4
Ireland	0.0	0.1	0.1	0.6	7.8	–

Table A6. Confusion matrix of the levels assigned in the two independent codings (48 cells). Rows give the level assigned by Coder 1 (first author), and columns show the level assigned by Coder 2 (second author). Diagonal entries are agreements. Row totals are 7 (L1), 9 (L2), 29 (L3), and 3 (L4). Column totals are 7 (L1), 8 (L2), 30 (L3), and 3 (L4). Neither coder assigned L0.

	L0	L1	L2	L3	L4
L0	0	0	0	0	0
L1	0	7	0	0	0
L2	0	0	7	2	0
L3	0	0	1	28	0
L4	0	0	0	0	3

Table A7. Inter-coder agreement on the levels by dimension (6 cells per dimension).

Dimension	Agreement Percentage (%)
D1	83.3%
D2	100%
D3	83.3%
D4	100%
D5	100%
D6	100%
D7	83.3%
D8	100%

Table A8. Inter-coder agreement on the levels by jurisdiction (8 cells per jurisdiction).

Jurisdiction	Agreement Percentage (%)
Denmark	87.5%
Flanders	100%
Italy	100%
Greece	75.0%
Portugal	100%
Ireland	100%

Table A9. Confusion matrix for legal status (R/P/N). Rows give the code assigned by Coder 1, and columns show the code assigned by Coder 2. Exact agreement is 85.4% (41 of 48 cells), with Cohen's kappa of 0.485.

	R	P	N
R	37	0	0
P	4	1	0
N	3	0	3

Table A10. Confusion matrix for operation (V/PV/NV). Rows give the code assigned by Coder 1, and columns show the code assigned by Coder 2. Exact agreement is 85.4% (41 of 48 cells), with Cohen's kappa of 0.709.

	V	PV	NV
V	30	2	0
PV	2	4	0
NV	0	3	7

https://doi.org/10.3390/su182312192

Table A11. Rank-acceptability matrix under the empirically anchored scenarios H1 and H2 with evidence-constrained upward moves (100,000 draws each, % of draws, ties sharing the better rank). The last column gives the share of draws in which the jurisdiction stays in its band.

Jurisdiction	Scenario	1st	2nd	3rd	4th	5th	6th	Stays in Band
Denmark	H1	94.1	4.2	1.4	0.3	0.0	0.0	99.9
Flanders	H1	22.8	56.2	17.4	3.5	0.0	0.0	100.0
Portugal	H1	20.6	56.5	19.3	3.5	0.0	0.0	100.0
Italy	H1	2.8	11.1	24.9	60.8	0.5	0.0	100.0
Greece	H1	0.0	0.1	0.3	4.5	94.3	0.8	99.8
Ireland	H1	0.0	0.0	0.0	0.1	5.7	94.2	81.3
Denmark	H2	98.9	1.0	0.1	0.0	0.0	0.0	100.0
Flanders	H2	3.4	63.9	27.8	4.8	0.1	0.0	100.0
Portugal	H2	17.7	69.7	9.5	3.0	0.1	0.0	100.0
Italy	H2	0.8	16.6	23.9	57.7	1.1	0.0	100.0
Greece	H2	0.0	0.1	1.2	8.8	89.8	0.1	100.0
Ireland	H2	0.0	0.0	0.0	0.0	1.9	98.1	89.5

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