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Distributed ledger technology and digital transformation of the EU building sector

RESEARCH

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ABSTRACT

Buildings account for approximately 40% of final energy use and 36% of energy related greenhouse gas emissions in the European Union, yet deep renovation rates remain critically below the trajectory required for climate neutrality by 2050. The recast Energy Performance of Buildings Directive (EPBD, 2024/1275/EU) and the revised Energy Efficiency Directive (EED, 2023/1791/EU) establish a comprehensive digital governance framework, encompassing Building Renovation Passports (BRPs), Digital Building Logbooks (DBLs), Smart Readiness Indicators (SRI), and Building Automation and Control Systems (BACS), that creates new conditions for technology enabled decarbonisation pathways. This paper examines how Distributed Ledger Technology (DLT) can be integrated into EPBD building decarbonisation strategies without undermining data protection, accountability, or distributional fairness. Drawing on a qualitative policy and technology assessment, combined with empirical evidence from business cases, the paper analyses DLT applications in ESCO contracts, energy communities, IoT (Internet of Things) efficiency services, and flexibility aggregation. The findings demonstrate that DLT's constraints are governance and regulatory in character rather than technical. A policy roadmap aligned with EPBD milestones is proposed, structured around four design principles: optionality, interoperability, privacy, and inclusion requirements. The paper concludes that DLT can deliver specific, bounded value as a backend data integrity and coordination layer, but only where the primary digital building infrastructure is already functioning and where the regulatory conditions for the intended application have been met at national level.

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1 INTRODUCTION

The European Climate Law and associated Fit for 55 legislation commit the European Union (EU) to climate neutrality by 2050 and at least a 55% reduction in net greenhouse gas emissions by 2030, positioning buildings as a priority sector because of their large share in final energy demand and emissions (European Commission 2020; European Commission 2021; Müench et al. 2022). Buildings account for around 40% of final energy use and 36% of energy related greenhouse gas (GHG) emissions. Roughly three quarters of the stock is considered energy inefficient by current standards (European Commission 2020). Deep energy renovations that reduce energy demand by at least 60% are estimated to occur in only 0.2% of the stock per year, with an overall weighted renovation rate of about 1% annually, producing an implementation gap relative to climate neutrality pathways (European Commission 2020; Müench et al. 2022). The Renovation Wave strategy therefore calls for at least doubling annual renovation rates by 2030 while increasing the share of deep renovations and prioritising worst performing buildings, energy poor households and public buildings (European Commission 2020).

The recast EPBD (European Union 2024) operationalises this trajectory through a combination of nearly zero energy buildings (nZEBs) before 2030, zero emission buildings (ZEBs) thereafter, and an expanded instrument mix that includes building renovation passports (BRP), minimum energy performance standards (MEPS), national building renovation plans, energy performance certificates (EPCs), Smart Readiness Indicators (SRI), Building Automation and Control Systems (BACS) and digital building logbooks (DBL) (European Commission 2024a). In parallel, the revised Energy Efficiency Directive (EED) (European Union 2023) strengthens the energy efficiency first principle and significantly raises the 2030 efficiency target and annual savings obligations, reinforcing the need for reliable measurement, reporting and verification (MRV) of savings across end-use sectors (European Union 2023).

Within this emerging digital governance regime, Distributed Ledger Technology (DLT)[1] has been proposed as a key enabler of decentralised, programmable and auditable interactions among building assets, users, service providers and energy system actors. EU funded projects, industry pilots and systematic reviews document applications ranging from Peer-to-Peer (P2P) electricity trading and local flexibility markets to Monitoring Reporting Verification (MRV) for building energy performance and carbon credits, and trusted building logbooks and digital twins (Andoni et al. 2019; Woo et al. 2021; Li and Kassem 2021; InEExS 2024). At the same time, the JRC twin transition assessment (Muench et al. 2022) and critical work on digital energy platforms warn that digital tools are not neutral: if poorly governed, they can reproduce inequalities, concentrate power and create new vulnerabilities (Müench et al. 2022; Kloppenburg and Boekelo 2019).

This paper adopts a qualitative policy and technology assessment to explore how DLT can be integrated into EPBD building decarbonisation pathways without undermining data protection, accountability or distributional fairness. It focuses on the EU and wider European Economic Area (EEA) context, with emphasis on non-residential buildings and portfolios, while drawing selectively on residential prosumer and community energy cases where they illuminate the interface between the buildings and the energy system. Empirically, it is based in five business cases that deploy smart services and DLT architectures for photovoltaic (PV) self-consumption and pay-for-performance contracts, energy cooperative tokenisation, IoT (Internet of Things) enabled legacy gas boiler efficiency services, and decentralised energy efficiency power plants (DEEPP). The contribution of this paper lies in synthesising EU policy, academic and institutional insights with these business case findings into a policy roadmap for just and governable DLT integration in building sector decarbonisation.

1.1 PEER-TO-PEER ENERGY TRADING AND COMMUNITY SELF-CONSUMPTION

P2P electricity trading and local energy markets are among the most prominent DLT use cases in the energy sector, enabling prosumers to trade surplus renewable electricity directly with

1 In a centralised system, a single authority (e.g. a national database operator) stores and controls the authoritative copy of the data. In a decentralised system, control is split across several independent authorities, each holding and governing its own subset of the data. A distributed ledger goes further, with every participating node holding an identical, continuously synchronised copy of the entire record, with no single node designated as the master copy, and updates are agreed collectively through a consensus mechanism (see also Section 3.3).

neighbours or within communities (Andoni et al. 2019; EU Blockchain Observatory and Forum 2020). IRENA describes platforms where distributed generation and smart meters are linked to digital marketplaces, often using blockchain for transaction recording and automated settlement to support higher shares of variable renewables and to create new revenue streams (IRENA 2020).

The Brooklyn Microgrid project is a well-known example in which rooftop PV households transact with nearby consumers via a platform embedded in a microgrid architecture with defined roles for the DSO and market operator (Mengelkamp et al. 2018). The Renewable Energy Directive (RED III) (European Union 2023b) and the Electricity Directive define Renewable Energy Communities and Citizen Energy Communities, granting them rights to own, develop and share energy, yet Member State transposition remains uneven, limiting the scaling of such models (European Union 2018; European Union 2019; European Union 2024). From an EPBD perspective, participation in such community self-consumption and P2P schemes could be reflected in renovation passports and DBLs as part of a building's operational context (e.g. demand-response capabilities, revenues from flexibility services, or alignment with local renewables integration goals) provided data are integrated via standardised indicators and interfaces (European Commission 2024a; D2EPC 2023).

1.2 ENERGY TOKENISATION AND FLEXIBILITY SERVICES

Tokenisation[2] of energy commodities, flexibility services and environmental attributes is a central DLT application category, with tokens representing units of electricity, heat, gas, flexibility capacity or certificates (Andoni et al. 2019). Recent reviews note that token-based systems can enable fine grained allocation, settlement and trading of services across sectors and carriers, potentially supporting multiple carrier configurations where buildings interact simultaneously with electricity, district heating/cooling and possibly hydrogen networks (EU Blockchain Observatory and Forum 2020; ENTSO-E 2024). While the use of DLT is primarily for secure, auditable recording of events and allocation of benefits rather than speculative energy tokens, the same logic could support more advanced tokenisation of savings, flexibility commitments or environmental attributes, especially when combined with Energy Efficiency (EE) obligations or results-based financing under the EED (European Union 2023; Woo et al. 2021). The evolving EU electricity market design reform highlights the importance of long term contracts such as Power Purchase Agreements (PPAs) and Contracts for Difference (CfDs) to reduce price volatility and support investment in low carbon assets, but does not yet explicitly consider tokenised micro-contracts at building scale (European Union 2024). In this context, tokens could in principle represent granular slices of PPAs, flexibility options or efficiency obligations, but their value depends on robust MRV and clear legal status, areas where significant regulatory and standardisation gaps are identified (EU Blockchain Observatory and Forum 2020).

1.3 BLOCKCHAIN-ENABLED MRV FOR BUILDINGS

A dedicated review by Egunjobi et al. (2024) of blockchain for building energy MRV finds that DLT can support secure, transparent and tamper-resistant recording of energy consumption, emission factors and retrofit interventions, addressing key barriers to participation in carbon credit and performance based schemes. Woo et al. (2021) showed that by combining granular metering data, standardised baselines (establishing these is not a trivial task, typically requiring one of the deemed, metered, scaled or surveyed savings methodologies set out in Annex V of the EED) and smart contracts, systems of this kind could reduce transaction costs, improve trust in reported savings and facilitate integration of building level projects into carbon markets and results-based financing. In the EU, the extension of the Emissions Trading System to buildings and transport (ETS2) and the strengthened role of EE obligation schemes under the EED increase the importance of reliable, auditable MRV for building level efficiency measures (European Union 2023; European Commission 2021). DBL type designs, which store only hashes[3] and minimal metadata on a permissioned ledger while keeping detailed data off chain, illustrate how DLT can

2 Tokenisation is the process of representing a real-world asset, right or unit of value (e.g. a quantity of electricity, a verified energy saving, or an environmental attribute) as a digital token on a ledger, so that it can be recorded, transferred and settled electronically.

3 A hash is the output of a mathematical function that converts a piece of data into a unique, fixed-length digital fingerprint.

provide tamper-evident provenance without exposing sensitive consumption data, and can be aligned with General Data Protection Regulation (GDPR) and Data Governance Act requirements when embedded in robust governance frameworks (Li and Kassem 2021; European Union 2022). When combined with dynamic EPCs (i.e. certificates that update automatically from live building and sensor data, in contrast to today's EPCs, which in most EU countries are static documents that might be periodically re-issued and stored in a centralised national database) and DBLs, such MRV architectures could make it easier to link realised performance improvements to BRPs, MEPS compliance and eligibility for financial instruments, thereby addressing some of the enforcement and financing gaps identified in Renovation Wave and EPRS analyses (European Commission 2020; European Parliament Research Service 2024).

2 METHODOLOGY

This paper adopts a qualitative policy and technology assessment methodology, combining systematic analysis of EU legislative and policy documents with a narrative, thematically organised review of peer reviewed and grey literature, and empirical evidence drawn from five business cases developed within the InEExS project (EU project ID 101077033).[4]

The literature review covers academic and grey literature on DLT in the energy and building sectors published between 2018 and 2025. Sources included peer reviewed journals, systematic reviews, thematic reports from EU bodies, and project deliverables. Searches combined the core terms "distributed ledger technology", "blockchain" and "smart contract" with Boolean and/or operators with terms relating to building and energy sectors (e.g. "EPBD", "building renovation passport", "digital building logbook", "MRV", "energy community") and a thesaurus of related synonyms ("DLT", "distributed ledger", "tokenisation"), where used across academic databases (Scopus, ScienceDirect and Google Scholar). Inclusion criteria required that sources address DLT applications in energy or construction contexts, provide policy analysis of the EU digital building governance framework, or offer empirical evidence on distributed ledger deployments in building decarbonisation settings. The synthesis was conducted thematically, linking regulatory, technical and socioeconomic dimensions of DLT adoption across these sources.

The policy analysis draws on primary EU legislative sources, specifically the EPBD recast (Directive 2024/1275/EU), the Energy Efficiency Directive (EED, 2023/1791/EU), and the Renewable Energy Directive III (RED III, 2023/2413/EU), alongside European Commission communications, guidance documents, and European Parliament Research Service assessments. These are used to map the regulatory and institutional context into which DLT integration is examined.

The empirical component draws on five business cases developed within the InEExS project, spanning residential and commercial buildings across Germany (BC1), Spain (BC2), Greece (BC3), and Sweden (BC4), with a fifth conceptual case (BC5) designed to examine the conditions for aggregated energy savings at portfolio scale. These cases were selected on three criteria: they represent diverse DLT application types relevant to building decarbonisation; they span distinct EU national regulatory contexts; and, where deployed, they were implemented within the scope of directly relevant EU legislative frameworks. BC5 is included as a conceptual reference case that illustrates regulatory barriers at the frontier of what current EU law permits for aggregated savings models, complementing the four deployed cases.

Barrier identification within the business case analysis was conducted through a structured qualitative engagement process comprising two rounds of workshops and interviews undertaken within the InEExS project. The engagement examined which barriers impede smart service and DLT integration, which actors are most affected, and how policy can accelerate adoption (InEExS 2024). Findings were analysed thematically alongside the literature synthesis, with barriers organised into three clusters: (i) regulatory fragmentation and market design failures; (ii) data governance, privacy and interoperability; and (iii) sociotechnical and distributional constraints.

This analytical structure is subsequently used to evaluate the conditions under which DLT integration can be considered appropriate and governable within building decarbonisation pathways, and to inform the phased policy roadmap set out in Section 6.

4 Project website: https://ieecp.org/projects/ineexs/.

3 POLICY LANDSCAPE

3.1 BUILDING SECTOR DECARBONISATION

The EPBD recast anchors a trajectory towards a fully decarbonised building stock by 2050, with nZEB standards up to 2030 and ZEB requirements for new and, progressively, existing buildings thereafter (European Commission 2024a). Guidance on EPBD Article 12 and Annex VIII clarifies that BRPs must provide building roadmaps for deep renovation in a maximum number of steps, aiming to achieve nZEB or ZEB standards, or at least 60% primary energy reduction in technically or economically constrained cases (European Commission 2024a). Member States are required to introduce renovation passport schemes by 29 May 2026, covering the entire building stock with flexibility to differentiate by building type, tenure and ownership structure (European Commission 2024a).

The Renovation Wave communication diagnoses persistent underinvestment and regulatory disincentives as key reasons for low renovation rates and proposes a mix of regulatory tightening, targeted support for vulnerable groups, and mobilisation of public and private finance (European Commission 2020). The updated EED consolidates this approach by raising the 2030 EU wide energy efficiency target, more than doubling the annual savings obligation by 2028, and embedding the energy efficiency first principle into planning and investment decisions (European Union 2023). An EPRS assessment stresses that, despite this reinforced framework, implementation gaps in the National Energy and Climate Plans (NECPs) and slow progress in buildings and heating remain major risks for meeting 2030 objectives, highlighting the importance of robust MRV and effective national policies (European Parliament Research Service 2024).

Within this architecture, renovation passports, DBLs, MEPS and national renovation plans are intended to translate EU level targets into building level pathways and decision contexts (Geissler and Sticher 2024). Yet empirical evidence from InEExS shows that outdated or fragmented building regulations, lack of MEPS or weak enforcement, and misaligned national support schemes continue to slow energy efficient retrofits and the integration of smart technologies across the five business cases, particularly in multi-owner buildings and complex portfolios (InEExS 2024). This underscores the need to consider DLT not as a standalone innovation but as one element in a broader regulatory and financial ecosystem for renovation.

3.2 DIGITALISATION OF BUILDINGS UNDER THE EPBD

The EPBD explicitly couples decarbonisation with a digitalisation agenda that leverages automation, data and smart services as enablers of efficiency, flexibility and user comfort (Verbeke et al. 2018; European Commission 2024a). At EU level, this agenda has materialised in instruments such as the SRI, reinforced BACS requirements, national energy performance databases, DBLs and a harmonised framework for renovation passports (Verbeke et al. 2018; European Commission 2024a). The SRI rates a building's capability to adapt its operation to occupant needs and external signals (Verbeke et al. 2018).

EPBD guidance (Art. 22) requires Member States to establish national energy performance databases collecting data from EPCs, renovation passports, SRI assessments and inspections, enabling stock-level analysis and enforcement (European Commission 2024a). DBLs are defined as common repositories for building related information, including EPCs, BRPs, SRI results and lifecycle GHG indicators, accessible to owners and authorities over the building lifecycle (European Commission 2024a; European Commission 2024b). Technical work under ALDREN and D2EPC proposes data models and architectures in which BRPs, Building Information Modelling (BIM) digital twins, information management layers and DBLs are integrated to generate dynamic EPCs and renovation roadmaps (D2EPC 2023).

The Digitalisation of the Energy System Action Plan further frames these developments within a broader EU strategy for interoperable smart metering, an EU energy data space, and a digital twin of the electricity grid, emphasising standardised data models, application programming interface (APIs) and secure data sharing across actors (European Commission 2022). Together with the Data Governance Act and provisions on smart metering and energy data access in the EED, this implies that any DLT-enabled building data architecture must operate within evolving

EU level frameworks for data sharing, governance and cybersecurity (European Union 2022; European Union 2023).

InEExS business cases are situated within EU policies presented in Figure 1, which outlines the objectives, mandated outputs, and the cross cutting rules that the DLT layer must operate within. These in turn rely on smart meters, Internet of Things (IoT) controllers, home energy management systems and cooperative platforms to deliver services. They repeatedly encounter data access, interoperability and privacy barriers that reflect the incomplete implementation of these EU level digital building instruments (InEExS 2024).

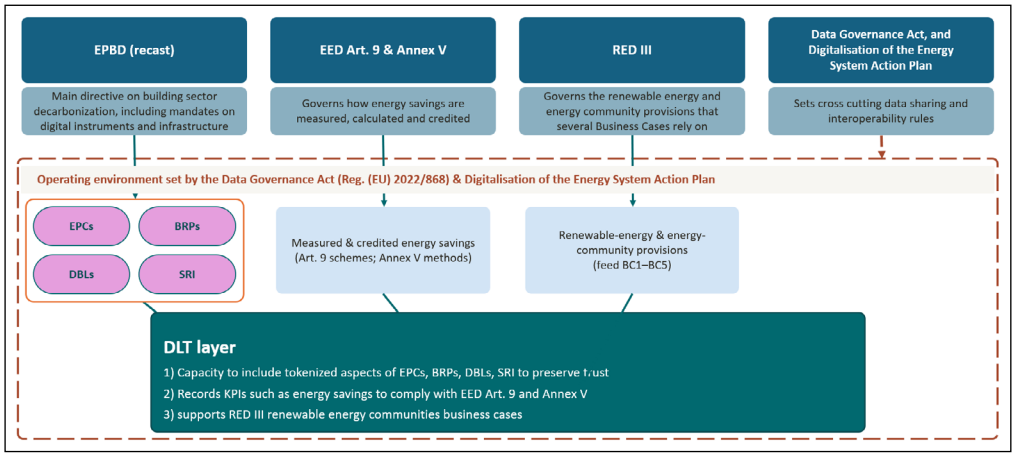


Figure 1 Regulatory requirements that any DLT layer must operate within.

3.3 DLT AND BLOCKCHAIN IN THE ENERGY AND BUILDING SECTORS

DLT comprises consensus architectures for storing and updating shared records across multiple nodes without a single trusted intermediary. Every participating node holds an identical, continuously synchronised copy of the register, and updates are only added once agreed through a consensus mechanism, which is what gives the register its immutability, typically offering auditability and programmable logic via smart contracts (Andoni et al. 2019). Systematic reviews distinguish permissionless from permissioned ledgers and note that energy sector applications overwhelmingly favour permissioned architectures due to performance, governance and data protection considerations (Andoni et al. 2019; EU Blockchain Observatory and Forum 2020).

Across more than a decade of experimentation, two broad clusters of use cases have emerged, the a) transaction oriented applications such as P2P trading, local flexibility markets, Electric Vehicle (EV) charging and settlement; and b) certificate based applications such as guarantees of origin, energy attribute certificates and carbon credits (Andoni et al. 2019; Egunjobi et al. 2024). In construction and buildings more narrowly, a systematic review identifies eight DLT application themes encompassing information management, payments, procurement, supply chain management, regulatory compliance, construction management, dispute resolution and technological systems, concluding that DLT remains a supplementary technology that enhances coordination but faces substantial sociotechnical and organisational barriers to adoption at scale (Li and Kassem 2021). A review focused on building energy MRV finds that DLT can underpin tamper-resistant records of energy use, emission factors and retrofit interventions, potentially lowering transaction costs and enabling more credible building scale participation in carbon markets, while highlighting unresolved issues around data quality and integration with existing registries and accreditation systems (Woo et al. 2021).

In the EU context, the EU Blockchain Observatory's thematic report on energy documents a landscape of European pilots spanning P2P trading, flexibility services, renewable generation certificates, digital identities for assets and grid support services, often combined with IoT and smart metering (EU Blockchain Observatory and Forum 2020). ENTSO-E's technopedia entry on DLT similarly emphasises the technology's potential for secure, transparent coordination of distributed flexibility resources while stressing research needs around large scale simulations, interoperability and integration with market platforms and system operation tools (ENTSO-E 2024).

Emerging work on DLT-enabled DBLs and digital twins for buildings, such as the Trusted DBL architecture and IOTA-based sensor-network security, illustrates how DLT can function as a data integrity layer within EPBD infrastructures rather than as a frontend market platform (Li and Kassem 2021; Priyadarshini et al. 2025). Critical analyses of digital energy platforms from the United Nations Development Programme's work on digital tools and anticorruption underline that the governance of such infrastructures, including who sets rules, who can participate, and who captures value, is as important as their technical properties (Kloppenburg and Boekelo 2019; UNDP 2025). These insights frame the subsequent analysis of where DLT can address real bottlenecks in building decarbonisation and where it risks introducing new ones.

4 DLT BUSINESS CASES FOR BUILDING DECARBONISATION

The five business cases developed within the InEExS project span residential and commercial buildings, electricity and natural gas, and four EU Member States. Together they constitute an empirical basis for examining how DLT and smart energy services interact with the legal frameworks, markets, and technical infrastructures governing the decarbonisation of the building sector (Table 1).

Table 1 Overview of InEExS business cases and DLT functions.

BUSINESS CASE	COUNTRY	APPLICATION FOCUS	DLT FUNCTION	POLICY LINK	KEY BARRIER IDENTIFIED
BC1: Innovative Energy Contracts with Pay-for-Performance Guarantees	Germany	Pay-for-performance PV contracts in housing cooperative	Tamper-evident MRV for billed energy savings (metered consumption), kept distinct from GHG/ emissions accounting	EED (MRV requirements), performance-based contracting	Lack of standardised MRV protocols and dynamic tariff structures
BC2: Improved Self-Consumption of DERs in Energy Cooperatives	Spain	Energy cooperative self-consumption optimisation	Token-based incentives via smart contracts (non-P2P settlement)	RED III (Art. 22), Electricity Directive (Art. 16)	Incomplete legal operationalisation of energy communities and tariff frameworks
BC3: Efficiency and Flexibility Services for Legacy Natural Gas Boilers	Greece	Efficiency services for legacy gas boilers using IoT and Machine Learning (ML)	Verified savings calculation and potential DLT-based MRV integration	EED (EEOS schemes)	Absence of recognised MRV standards and regulatory support for gas efficiency services
BC4: Smart Energy Management for EV Chargers	Sweden	Smart home flexibility (EV chargers) via aggregation	Transparent recording of flexibility provision and compensation	Electricity Regulation (EU) 2019/943, Market Directive (EU) 2019/944 (Art. 17)	Incomplete implementation of aggregator rights and compensation mechanisms
BC5: Decentralised Energy Efficiency Power Plant (DEEPP)	N/A	Decentralised Energy Efficiency Power Plant (DEEPP)	Immutable ledger for savings, contracts and financial flows	EED (innovative financing), EEOS	Lack of legal recognition of aggregated savings as a bankable asset

Across the examined cases, DLT is implemented as a supporting digital layer embedded within broader system architectures that include smart metering, IoT devices, cloud-based energy management systems and platform based coordination mechanisms. Its primary contribution lies in enabling verifiable and tamper-resistant data recording, facilitating the transparent allocation of incentives and flexibility value, and supporting the automation and auditability of contractual arrangements across multiple actors.

5 BARRIERS

The barriers documented in this analysis were identified through the structured empirical process described in Section 2. The barrier identification framework addressed five guiding questions, examining which barriers impede smart service and DLT integration, which actors are most affected, and how policy can accelerate adoption. Findings were analysed thematically and organised into three clusters, as set out in the subsections below (see also Papapostolou et al. 2023 for a PESTLE/SWOT analysis of blockchain barriers).

5.1 REGULATORY FRAGMENTATION AND MARKET DESIGN FAILURES

The most consequential barriers across the examined business cases originate in the incomplete and uneven transposition of the Clean Energy Package, whose ambitions for energy markets centred on consumers remain largely unrealised at the national level. The Electricity market Directive (EU) 2019/944 establishes explicit rights for Citizen Energy Communities (Art. 16) and independent aggregators (Art. 17), yet these provisions have not been operationalised consistently across Member States. The Spanish energy cooperative at the centre of BC2, which sought to implement token-based incentive schemes for collective PV self-consumption, found itself without a stable legal basis, since neither the operational scope of Renewable Energy Communities under Article 22 of Directive 2023/2413/EU (RED III) nor the metering and allocation rules required to underpin the DLT architecture were fully enacted in national law at the time of deployment (InEExS 2024). A 2024 European Parliament Priority Question (P-001533/2024) documented that energy communities across multiple Member States continue to be blocked from accessing dispatch markets because the implementing frameworks demanded by Articles 16 and 22 remain deficient. Andoni et al. (2019) anticipated this impasse, observing that DLT-enabled community platforms need to be integrated with current regulatory practice and that the failure to define flexible tariffs and new contract types constitutes an overarching barrier to energy DLT adoption.

The aggregation and demand response barriers exposed in BC4 and BC5 are structurally related. The Regulation (EU) 2019/943 on the internal market for electricity requires demand response products to be accessible to aggregators, yet national implementing rules frequently impose discriminatory restrictions. A 2024 European Parliament Question (E-001449/2024) documented that Article 17 of the electricity market Directive (EU) 2019/944/EU on independent aggregators had not been fully implemented in Italy, leaving limited possibilities for consumers to conclude aggregation contracts, which is an illustration of the broader transposition deficit across Member States. BC5's DEEPP virtual power plant faced a compounded version of the same problem, since the Energy Savings Agreements and the payments linked to performance that form the basis of its financial structure depend on an aggregator status that has not been yet adequately developed in EU law, nor in any substantial fashion across Member States. ENTSO-E (2024) identifies this failure, noting that without consistent market products and regulatory interfaces for flexibility, DLT platforms risk permanent disconnection from core balancing and congestion management mechanisms, regardless of their technical sophistication.

Building regulations create additional constraints. BC1's pay-for-performance contracts for PV-equipped housing cooperatives in Germany were limited by the absence of standardised dynamic tariff frameworks and remuneration rules for surplus energy production, while BC3's deployment of IoT controllers for legacy gas boilers in Greece encountered a regulatory environment that neither recognised nor financially rewarded the efficiency gains produced (InEExS 2024). Article 9 of Directive 2023/1791/EU (EED recast) requires Member States to establish energy efficiency obligation schemes or alternative measures (Article 10) and monitoring frameworks, but provides limited operational guidance for pay-for-performance services integrated with IoT or DLT systems, leaving ESCOs and building owners without a legally secure contractual basis. This aligns with the subsidiarity built into the EED, where Annex V of Directive (EU) 2023/1791 sets out common methods and principles for calculating the impact of energy efficiency obligation schemes under Articles 8, 9 and 10, but leaves Member States to transpose these into their own national contractual and metering rules, which means that there is no EU wide legal template for the kind of DLT-based MRV that BC3 explores. The broader EU policy shift towards gas phaseout has compounded this by deprioritising support for transitional efficiency improvements to existing gas infrastructure, thus creating, as BC3 demonstrates, a gap between what the technology can deliver and what the regulatory ecosystem will reward. This also points to a broader lock-in risk, since channelling MRV investment into incremental gas efficiency gains can tie capital and institutional attention to fossil fuel infrastructure that delivers a smaller lifetime GHG reduction than redirecting the same investment towards renewables and the electrification of heating.

5.2 DATA GOVERNANCE, PRIVACY AND INTEROPERABILITY

A second major barrier cluster concerns the mismatch between EU data protection law and the architectural requirements of smart energy services, which presents simultaneously as a legal

compliance challenge and as a systemic design constraint on DLT components that depend on real-time, verifiable data inputs for smart contract execution and MRV. Across all five InEExS business cases, stakeholders (utilities, cooperatives, service providers and application developers) reported uncertainty about which data they could lawfully access, on which legal basis, and how to design architectures compliant with both the GDPR and sector-specific energy data regulations (InEExS 2024). In BC3, transmitting granular heating data from residential IoT devices to a cloud-based energy management system required navigating GDPR obligations, including data minimisation[5] under Article 5(1)(c) and the complex chain of joint controllership among the gas supplier's platform, the technology providers, and the retail company.

The European Parliament Research Service's legal analysis of blockchain and the GDPR (EPRS 2019, Study 634445) establishes that blockchain immutability may be incompatible with GDPR rights to rectification and erasure under Articles 16 and 17, while transparency characteristics may conflict with data minimisation norms. Permissioned, hybrid architectures, that allow storing only cryptographic hashes on chain while retaining detailed records in controlled off chain repositories, they represent a recognised technical mitigation, but do not resolve underlying legal ambiguities about controllership, territorial jurisdiction, and the validity of consent in automated smart contract environments (EPRS 2019). Woo et al. (2021) reinforce this from an MRV perspective, emphasising that verification of savings requires standardised baselines, registry integration, and careful handling of consumption data. These preconditions presuppose resolved data governance arrangements that deployments such as those in InEExS had not yet been able to establish.

The interoperability dimension extends this barrier further. ENTSO-E (2024) identifies divergent token standards and bespoke DLT platforms as active fragmentation risks, calling for alignment with CEN-CENELEC, IEC, and IEEE standards and with existing market platform interfaces. Egunjobi et al. (2024), in a PRISMA-based systematic review of 156 post-2021 studies, confirm that standardisation and IoT interoperability remain the dominant unresolved technical barriers, with studies developing new platforms or consensus mechanisms consistently encountering practical implementation challenges. In the buildings domain, Directive 2024/1275/EU (EPBD recast) requires Building Renovation Passports uploaded to national databases and stored in or accessible through Digital Building Logbooks, meaning that any DLT layer must conform to preexisting data models and governance arrangements rather than create parallel, non-interoperable structures. The Data Governance Act (Regulation 2022/868) and the European Commission's Digitalisation of the Energy System Action Plan (2022) envisage sectoral data spaces and standardised interfaces for energy data sharing, but their concrete implementation within building and energy data ecosystems remained incomplete across all InEExS national contexts at the time of deployment.

5.3 SOCIO-TECHNICAL AND DISTRIBUTIONAL BARRIERS

Regulatory and technical barriers depend on the social and economic conditions in which DLT services are deployed. Kloppenburg and Boekelo (2019) argue that digital energy platforms reshape power relations by influencing who sets rules, who captures value, and who participates, noting that even platforms oriented toward community provisioning can generate dependencies where governance remains concentrated. This structural insight finds direct empirical grounding in the examined business cases, where high upfront capital requirements, limited consumer awareness of demand response programmes, and restricted access to finance were among the most consistently cited barriers for households, SMEs, and energy communities considering engagement with smart services and DLT models (InEExS 2024). These barriers fundamentally determine whether the value propositions of the examined services can reach the actors they are designed to serve.

The EPBD recast (Directive 2024/1275/EU) addresses renovation related justice concerns by strengthening the enabling framework for fair and inclusive building upgrades. It requires Member States to ensure that Building Renovation Passport schemes are implemented in an affordable manner, to provide targeted financial support for vulnerable households as part of their national renovation planning, and to link these measures with accessible advisory

5 Data minimisation is the GDPR principle (Article 5(1)(c)) that organisations should only collect, process and store the minimum amount of personal data necessary to achieve a specific, stated purpose.

structures and one stop shops that guide citizens through the renovation process. Yet DLT architectures for MRV, local energy markets, or Digital Building Logbooks, if deployed without explicit distributional assessment, could reproduce precisely the asymmetries that Kloppenburg and Boekelo (2019) identify, privileging digitally literate, asset-owning prosumers and technology intermediaries while shifting administrative complexity and financial risk onto less resourced actors. The EU Blockchain Observatory and Forum (2020) similarly flags consumer protection gaps and the absence of coherent regulatory treatment of DLT platforms as compounding existing inequalities in energy market access. An analytically rigorous integration of DLT into EPBD implementation must accordingly treat distributional impact and participatory governance as primary design constraints, evaluated alongside the technical and compliance requirements that currently dominate regulatory and project discourse.

6 TOWARDS A POLICY ROADMAP FOR DLT INTEGRATION

The barriers analysed in Section 5 reflect the current gap between an emerging DLT application landscape and a regulatory ecosystem that was not designed with programmable, distributed ledger architectures in mind. Should there be political momentum for closing this gap, it requires deliberate, sequenced action across regulatory, technical, financial and governance dimensions. The roadmap proposed here is based on empirical evidence and aligned with the EU legislative trajectory marked by the EPBD recast, EED, and the Clean Energy Package.

6.1 A PHASED APPROACH ALIGNED WITH EPBD MILESTONES

DLT experimentation cannot be treated as independent of the broader EPBD implementation timeline. Member States must introduce Building Renovation Passport schemes across the entire building stock by 29 May 2026, and the Renovation Wave sets a target of doubling annual renovation rates by 2030 (European Commission 2020; European Commission 2024a). The European Climate Law establishes a legally binding path to full decarbonisation by 2050 (European Commission 2021). Systematic reviews confirm that DLT in the energy sector remains at a pre-commercial, pre-standardisation stage, with few EU projects having reached full deployment scale (Andoni et al. 2019; Egunjobi et al. 2024; ENTSO-E 2024).

A reliable roadmap therefore unfolds in three stages. In the near term (2026–2028), priority should be placed on establishing interoperable, machine-readable digital infrastructures for EPCs, BRPs, DBLs, SRI and BACS. Within that digital baseline, tightly scoped DLT pilots, specifically Trusted-DBL logbooks and MRV components linked to Energy Efficiency Obligation Schemes (EEOS), should be initiated in controlled environments (Li and Kassem 2021; Woo et al. 2021; InEExS 2024). In the medium term (2028–2030), as regulatory and technical conditions mature, DLT-enabled demand flexibility services and verified pay-for-performance contracting should be progressively integrated into national EEOS and aggregator frameworks. More complex DLT P2P markets and multicarrier tokenisation schemes should only be considered at scale once baseline digital, regulatory and governance readiness is demonstrably established, to avoid compounding fragmentation and justice concerns (EU Blockchain Observatory and Forum 2020; Kloppenburg and Boekelo 2019). The InEExS evidence from the Business Cases confirms that where regulatory foundations are absent, DLT components designed for market participation remain technically functional but commercially inert (InEExS 2024).

6.2 REGULATORY AND STANDARDISATION PRIORITIES

Regulatory alignment is a prerequisite for moving from isolated DLT pilots to architectures that can credibly support EPBD and energy market objectives. The most consequential gaps, as demonstrated across all five InEExS business cases, are the inconsistent transposition of aggregator rights under Article 17 of the electricity market Directive (EU) 2019/944/EU, the absent or fragmented legal treatment of energy communities under Articles 16 and 22 of Directive (EU) 2018/2001/EU, and the lack of nationally defined Virtual Power Plant (VPP) operational standards (InEExS 2024; Eurelectric 2020). The InEExS regulatory roadmaps offer these findings in concrete priorities, namely the development of standardised Demand Response and renewable grid integration approaches at Member State level; the establishment of clear national legal definitions and operational standards for VPPs including incentives for VPP participation; and the introduction of transparent demand response compensation mechanisms that allow building scale flexibility contributions to be equitably rewarded (InEExS 2024).

On the buildings side, EPBD guidance already requires digital BRPs uploaded to national databases and storable in, or accessible through, DBLs (European Commission 2024a). Future implementing acts on BRPs and DBLs should explicitly address DLT-relevant technical requirements, standardised schemas, open APIs, and auditable change histories, irrespective of whether a DLT backend is ultimately used, a point underscored by D2EPC's analysis of the interoperability preconditions for linking EPCs, digital twins and renovation roadmaps (D2EPC 2023; Li and Kassem 2021). ENTSO-E similarly calls for alignment of any DLT component with existing CEN-CENELEC, IEC and IEEE standards and with established market-platform interfaces for balancing and congestion management, to prevent the bespoke platform proliferation that currently risks reinforcing silos (ENTSO-E 2024). A technology neutral regulatory environment, and one that defines the performance and governance requirements for digital building infrastructures without mandating or precluding specific architectures, would allow DLT to compete on its merits rather than advance or retract based on regulatory ambiguity alone.

6.3 GOVERNANCE AND FUNDING MECHANISMS

Even well designed DLT architectures will struggle without appropriate funding instruments and supervised governance environments. The European Blockchain Sandbox provides a validated model where selected projects engage directly with regulators to clarify legal questions, test compliance approaches and develop safeguards before broader market deployment (EU Blockchain Observatory and Forum 2023). In the building and energy domain, sandbox arrangements should specifically prioritise pilots that link DLT components, such as MRV registries or trusted DBLs, to EPBD national renovation schemes and EEOS programmes.

On the financial side, InEExS identifies the absence of standardised financing models and the high upfront costs of smart technology deployment as barriers that are structurally significant (InEExS 2024). The roadmap proposes three complementary mechanisms, specifically National Green Energy Funds that pool public, private and international capital to finance distributed energy resources, energy efficiency and DLT innovation; standardised incentive schemes for pay-for-performance contracts and demand flexibility services; and substantially simplified access pathways to EU and national funds for Small and Medium Enterprises (SMEs), ESCOs and energy communities, including streamlined digital application portals and dedicated local technical assistance (InEExS 2024). Article 8 of Directive 2023/1791/EU requires Member States to mobilise investment in energy efficiency, including through innovative financing instruments and targeted support for vulnerable customers (European Union 2023). Renovation Wave-related instruments (Cohesion Policy funds, InvestEU, the Social Climate Fund) provide existing channels through which these mechanisms could be operationalised, provided their eligibility criteria are explicitly extended to reward DLT integration that meets EPBD alignment, data governance and distributional impact requirements (European Commission 2020; European Commission 2022). Governance and funding programmes for DLT pilots should further include provisions for cross-country knowledge sharing and capacity building, given that the scarcity of EU-based, fully scaled DLT case studies is itself identified by InEExS as a market barrier that depresses regulatory and investor confidence (InEExS 2024; UNDP 2025).

6.4 DESIGN PRINCIPLES FOR JUST AND EFFECTIVE DLT INTEGRATION

Four principles, based in EU law, peer reviewed literature and empirical evidence, should govern the integration of DLT into EPBD building decarbonisation roadmaps.

- Optional: Member States should establish well-designed, inclusive and interoperable BRP and DBL schemes before introducing DLT as an optional integrity or coordination layer. DLT should complement, not substitute, EPBD's mandatory digital instruments (D2EPC 2023; Li and Kassem 2021; InEExS 2024).
- Interoperability: Any DLT solution deployed in buildings or energy contexts must adopt the data models, schemas and APIs already established for EPCs, BRPs, DBLs and SRI services, rather than creating parallel, incompatible structures. The Digitalisation Action Plan's emphasis on a standardised EU energy data space and ENTSO-E's insistence on alignment with existing market platforms make this a non-negotiable design condition (European Commission 2022; ENTSO-E 2024).

- Privacy: Architectures should combine off chain data storage with on chain cryptographic hashes, permissioned ledger access and role-based controls, reconciling the auditability that DLT provides with GDPR data minimisation obligations and Data Governance Act principles. This pattern, exemplified by the Trusted DBL and supported by MRV literature, is a legal compliance necessity, not merely a design preference (Woo et al. 2021; Li and Kassem 2021; European Union 2022).
- Inclusion: The EPBD requires BRP schemes to be implemented affordably and with targeted support for vulnerable households (European Commission 2024a). DLT applications that serve only digitally literate, asset-owning prosumers while displacing administrative burden onto less resourced actors would contradict the distributional logic of the Renovation Wave. InEExS evidence on financial, awareness and regulatory barriers facing households, SMEs and cooperatives confirms that DLT models must be designed and evaluated against distributional impact criteria, favouring public or regulated governance for national BRP/DBL systems and community governed platforms in local markets (InEExS 2024; Kloppenburg and Boekelo 2019; UNDP 2025).

7 DISCUSSION

The analysis brings together EU legislation and policy documents, peer reviewed literature on DLT in energy and construction, and empirical data from five InEExS business cases. The overall finding is that DLT has real, yet limited roles to play in building decarbonisation, and that most of those roles depend on regulatory and governance conditions that are not yet fully in place across EU Member States.

The EPBD recast and its associated instruments establish a structured digital governance framework for buildings, organised around BRPs, DBLs, SRI, BACS and national energy performance databases. Within this framework, the specific contributions DLT can make (i.e. record-keeping, programmable contracts, transparent attribution of savings and flexibility) are most relevant where data integrity and trust are genuine constraints, rather than as general replacements for conventional digital tools (Andoni et al. 2019; EU Blockchain Observatory and Forum 2020; ENTSO-E 2024). The Trusted DBL architecture and the IOTA-based network security work both illustrate this in technical terms (Li and Kassem 2021; Priyadarshini et al. 2025), and InEExS business cases confirm this empirically, where DLT functions best as a secondary backend layer, not as a standalone market infrastructure (InEExS 2024).

The barrier analysis makes clear that the binding constraints on DLT adoption in buildings are not primarily technical. Scalability and consensus algorithm design, the dominant focus of much blockchain research, are secondary to regulatory fragmentation, data governance ambiguity and distributional barriers. The incomplete transposition of aggregator rights under the electricity market Directive (EU) 2019/944/EU and of energy community provisions of Directive (EU) 2018/2001/EU means that the regulatory foundation required for DLT-enabled flexibility services and community energy architectures is absent at national level in several Member States (InEExS 2024; Andoni et al. 2019). Egunjobi et al. (2024) confirm from a broader literature perspective that standardisation and IoT interoperability remain the most persistently unresolved barriers across post 2021 DLT-in-energy research. The absence of standardised MRV frameworks for performance contracts (e.g. for PV self-consumption, legacy boiler efficiency or aggregated savings) was a shared constraint across all examined business cases (InEExS 2024; Woo et al. 2021).

Data governance raises structural problems that reach beyond regulatory fragmentation. GDPR rights of rectification and erasure may be fundamentally incompatible with blockchain immutability (European Parliament Research Service 2019). While permissioned, hybrid off chain/on chain architectures offer a recognised technical mitigation, they do not resolve underlying ambiguities about data controllership, consent validity in automated smart contract environments, or territorial jurisdiction (EPRS 2019; Woo et al. 2021). Across all five business cases, stakeholders reported persistent uncertainty about which data they could lawfully share, on what legal basis, and through what technical means (InEExS 2024). The incomplete national implementation of the Data Governance Act and the Digitalisation of the Energy System Action Plan's dataspace frameworks compounded these difficulties at the time of deployment (European Union 2022; European Commission 2022).

At the same time, the findings do point to conditions under which DLT can make a genuine contribution. Where data integrity constraints limit participation in performance-based contracts or EEOS programmes, where trust is required across many parties to settle community self-consumption accounts, or where an auditable provenance record is needed to link renovation interventions to MEPS compliance or financial eligibility, DLT provides specific capabilities that are harder to achieve with conventional centralised databases (Woo et al. 2021; Li and Kassem 2021). These capabilities, however, are only as useful as the regulatory and governance framework that gives the underlying data and records legal standing.

Two methodological limits should be acknowledged. The empirical basis of five business cases across four Member States offers a rich qualitative picture but is not designed for statistical generalisation. The cases varied in sector, energy carrier and technology maturity, and all operated where national DLT and energy community regulatory frameworks were at early stages. Additionally, while the paper addresses the EU context, its conclusions are not directly transferable to regulatory settings with different property rights regimes, data governance laws or energy market structures.

8 CONCLUSIONS

This paper has examined how Distributed Ledger Technology can be integrated into building decarbonisation pathways in a way that reinforces the regulatory provisions already in place. It becomes evident from the analysis that DLT can deliver specific, bounded value, primarily as a backend integrity and coordination layer, but only where the primary digital infrastructure of Building Renovation Passports, Digital Building Logbooks, Smart Readiness Indicators and Building Automation and Control Systems is already functioning, and where the regulatory conditions for the intended application have actually been met at national level.

The five InEExS business cases show that whether DLT is used to verify pay-for-performance contracts, record token-based incentives for cooperative self-consumption, support machine learning-driven measurement and verification, ensure transparent compensation for load shifting, or support the financial flows of an aggregated savings model, the performance of each DLT component depends not on the architecture itself, but on standardised baselines, recognised MRV protocols, defined aggregator roles and functioning energy community legal frameworks, conditions that were absent or incomplete across all deployment contexts (InEExS 2024). The core finding is therefore regulatory and governance in character, and DLT cannot substitute for the policy reforms its own operation requires. Where a single trusted authority already exists and multiple stakeholder verification is not required, a conventional centralised database can meet the same auditability needs at lower complexity and cost. The advantage of DLT across the five business cases lies in that evidence cannot be tampered, and records are shared among parties (DSOs, aggregators, ESCOs, energy communities) that might not otherwise need to trust a common intermediary (Andoni et al. 2019).

Three strategic priorities follow from this analysis. First, Member States should treat BRP and DBL implementation as the immediate task, building the interoperable, machine-readable digital building infrastructure that EPBD guidance already mandates, and into which DLT components can later be selectively embedded (D2EPC 2023; Li and Kassem 2021; European Commission 2024a). Second, consistent transposition of Clean Energy Package provisions (specifically aggregator rights under the electricity market Directive (EU) 2019/944/EU, energy community frameworks under Directive (EU) 2018/2001/EU, and nationally defined VPP standards) is a necessary prior condition for any DLT-enabled flexibility or community energy service to function as intended (InEExS 2024; Eurelectric 2020). Third, the design of any DLT component must respect four principles, namely (i) BRP-first ordering, (ii) interoperability with pre-existing standards and APIs, (iii) privacy-preserving transparency through permissioned off chain storage combined with on chain cryptographic hashes, and (iv) explicit provision for inclusion and distributional fairness (Woo et al. 2021; Li and Kassem 2021; Kloppenburg and Boekelo 2019; UNDP 2025).

Several research priorities merit attention beyond this paper's scope. Quantitative studies of how DLT-enabled MRV affects actual renovation investment decisions and rates would move the debate beyond the qualitative plausibility arguments that currently dominate.

Institutional analysis of long term governance arrangements for DLT-based DBLs and MRV registries (including questions of ownership, liability and version control) is needed before these architectures can be deployed at scale with confidence. Empirical evaluation of distributional and justice outcomes in real world DLT-based community energy and renovation programmes would then test whether the inclusion safeguards proposed here are sufficient in practice (Li and Kassem 2021; Kloppenburg and Boekelo 2019; UNDP 2025).

Meeting EU climate targets by 2030 and 2050 requires raising annual renovation rates well above their current trajectory (European Commission 2020; Müench et al. 2022). That depends far more on regulatory certainty, accessible finance and inclusive governance than on any specific digital technology. DLT's contribution to this transition will be durable only where it is embedded in, and actively supports, the broader institutional infrastructure the building sector needs.

ABBREVIATIONS

ABBREVIATION	FULL TERM
ACER	Agency for the Cooperation of Energy Regulators
BACS	Building Automation and Control Systems
BC1–BC5	Business Case 1–5
BIM	Building Information Modelling
BRP	Building Renovation Passport
CEN-CENELECT	European Committee for (Electrotechnical) Standardization
DBL	Digital Building Logbook
DEEPP	Decentralised Energy Efficiency Power Plant
DLT	Distributed Ledger Technology
DSO	Distribution System Operator
EED	Energy Efficiency Directive
EEA	European Economic Area
EEOS	Energy Efficiency Obligation Scheme(s)
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
ESCO	Energy Service Company
ETS2	(EU) Emissions Trading System extended to buildings and transport
IEC	International Electrotechnical Commission
IoT	Internet of Things
IOTA	distributed ledger platform
MEPS	Minimum Energy Performance Standard(s)
ML	Machine Learning
MRV	Measurement, Reporting and Verification
RED III	Renewable Energy Directive (recast III)
SRI	Smart Readiness Indicator
SWOT	Strengths, Weaknesses, Opportunities, Threats (analysis framework)
VPP	Virtual Power Plant
ZEB/nZEB	(nearly) Zero Energy Building

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