

Article

Towards a Sustainable Future: Assessing the Adaptation of Madrid's Markets to New Energy Regulations

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Abstract

Food markets represent a public good essential for urban supply and as intergenerational spaces supporting the small-scale economy, yet they face growing challenges in adapting to sustainability regulations and circular economy requirements. This study examines the current state of sustainability in Madrid's municipal markets through interviews and questionnaires administered to market managers, analyzing building characteristics, renewable energy systems, passive savings strategies, and energy costs across different market typologies. Results reveal that in December 2025, only 9% of markets had solar thermal installations, while merely 11% were planning photovoltaic solar panel projects—figures insufficient to meet current EU energy efficiency mandates. The findings demonstrate a significant gap between existing infrastructure and the requirements of the Directive (EU) 2023/1791, which supersedes previous directives. These results indicate an urgent need for accelerated implementation of renewable energy systems in market buildings to achieve sustainability targets. The study contributes baseline data for developing intervention strategies that can reduce energy consumption and align Madrid's market network with European decarbonization goals for 2030 and 2050.

Keywords: energy efficiency; sustainability; supply markets; thermal envelope; energy consumption; energy demand; air conditioning; ventilation; renewable energies; European directives



Academic Editors: Lefki Papada and
Dimitris Damigos

Received: 15 April 2026

Revised: 11 May 2026

Accepted: 13 May 2026

Published: 17 May 2026

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1. Introduction

Food markets represent essential urban infrastructure with multifaceted functions extending beyond mere commercial exchange. Historically conceptualized as public goods, these facilities serve as critical supply nodes for cities, intergenerational social spaces, and supports for small-scale economies [1]. However, contemporary food markets face an unprecedented dual challenge: adapting to rapidly evolving consumer behaviors while simultaneously complying with increasingly stringent European sustainability regulations and circular economy mandates [2]. This tension is particularly acute given that many

municipal markets occupy historically significant buildings, creating complex trade-offs between heritage preservation and energy performance obligations [3].

The European regulatory landscape has undergone substantial acceleration since 2021, driven by geopolitical disruptions and climate imperatives. In July 2021, the European Commission proposed amendments to the Renewable Energy Directive (EU) 2018/2001, subsequently consolidated by Directive (EU) 2023/2413, establishing a binding renewable energy target of 42.5% by 2030 [4]. The REPowerEU plan, introduced in May 2022 following Russia's invasion of Ukraine, further accelerated this transition by establishing additional measures to phase out fossil fuel dependence while proposing an aspirational target of 45% renewable energy share [5]. Simultaneously, the Energy Performance of Buildings Directive (EU) 2024/1275 and the Energy Efficiency Directive (EU) 2023/1791—which supersedes the previous Directive (EU) 2018/2002—mandate that Member States achieve highly energy-efficient and decarbonized building stocks by 2050 [6]. These directives impose specific obligations: all new public buildings must achieve zero-energy performance from 2027, while existing non-residential buildings must undergo staged renovations to improve their energy classification, with G-class buildings requiring upgrade to at least F-class by 2027 and E-class by 2030 [7].

For contextual clarity, Directive (EU) 2023/1791 entered into force in October 2023 and required Member States to transpose its provisions by 11 October 2025, while Directive (EU) 2024/1275 entered into force in May 2024 and must be transposed by 29 May 2026. Therefore, the December 2025 dataset captures a pre-transposition baseline, and the present analysis should be interpreted as a reference point to guide and evaluate subsequent compliance-focused retrofit programmes.

Despite these ambitious regulatory targets, the scholarly literature on food markets has predominantly focused on sociocultural and commercial dimensions, often neglecting the technical and architectural aspects of building energy performance [8]. Recent studies have begun addressing this gap, proposing assessment frameworks for energy efficiency in food retail buildings that integrate environmental sustainability and cost-saving measures [9]. However, research specifically examining energy retrofit strategies for food markets housed in historic buildings remains limited, even as the literature on heritage building energy retrofitting has expanded considerably [10]. Studies demonstrate that heritage buildings can achieve carbon neutrality through carefully implemented photovoltaic installations and shared renewable generation systems [11], yet these solutions require nuanced approaches that balance conservation requirements with technical performance [12].

The intersection of circular economy principles with food market operations represents another emerging research frontier. Recent scholarship has reconceptualized open municipal markets as networked ecosystems within food supply chains, emphasizing their potential role in facilitating circular economy transitions through waste reduction, local supply chain optimization, and sustainable resource management [13]. These frameworks highlight how strategic interactions between market actors influence the development of circular economy initiatives, yet empirical assessments of actual implementation remain scarce [14]. Furthermore, while the relationship between circular economy metrics and agri-food system sustainability has been analyzed at macro scales, building-level energy efficiency in market infrastructure receives limited attention [15].

The specific challenges of retrofitting historic market buildings have garnered increasing scholarly attention. Energy improvements in heritage structures present unique difficulties: interventions must preserve architectural integrity while achieving substantial reductions in energy consumption and carbon emissions [16]. Recent systematic reviews identify key research clusters around passive design strategies, high-performance envelopes, and efficient HVAC systems for historic buildings, yet note persistent gaps

regarding the integration of these measures in actively functioning commercial facilities such as food markets [17]. Digital documentation approaches (e.g., BIM/HBIM workflows) have been proposed in the literature to support energy-performance enhancement in heritage assets; however, the present study does not implement HBIM. Instead, we focus on a replicable, survey-based portfolio assessment that can be complemented by detailed audits or digital twins in subsequent phases [18].

This research addresses these interconnected gaps by presenting the first comprehensive survey-based assessment of energy-efficiency and sustainability conditions across Madrid's municipal market network, Figure 1, based on interviews and structured questionnaires completed by facility managers (35 of 45 markets; 77.8% coverage). The study is designed as a baseline snapshot (December 2025) to support subsequent audit campaigns and retrofit programmes aligned with the recast EU Energy Efficiency Directive (Directive (EU) 2023/1791) and the recast Energy Performance of Buildings Directive (Directive (EU) 2024/1275).

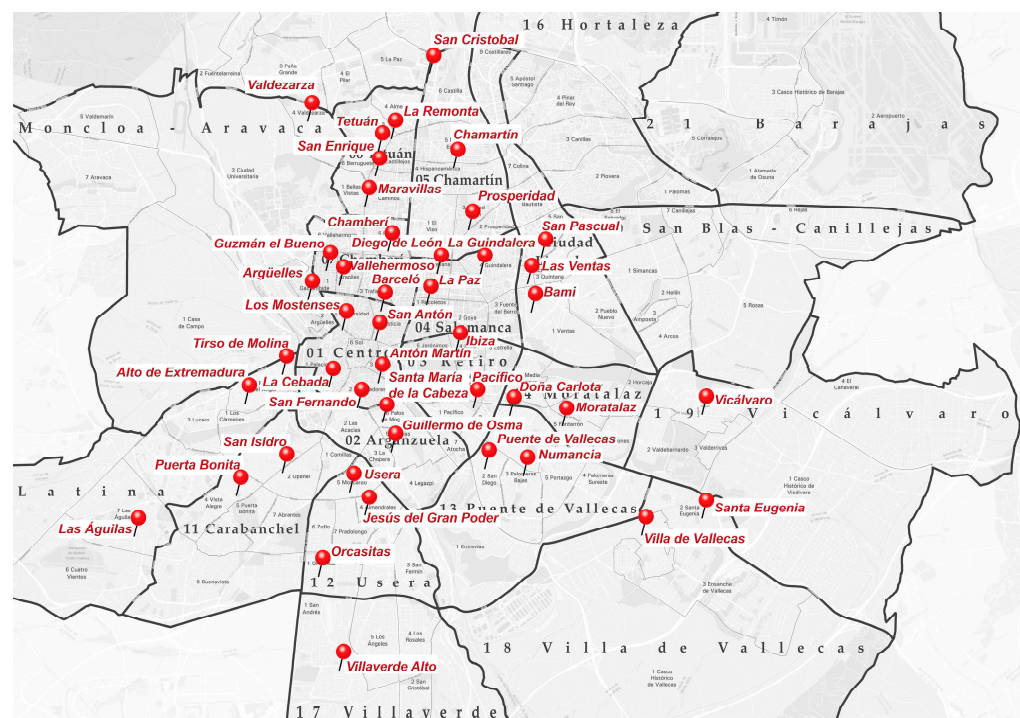


Figure 1. Municipal Food Market Network of Madrid.

The analysis reveals a substantial implementation deficit: as of December 2025, only 9% of markets utilized solar thermal panels and merely 11% had photovoltaic projects in development—figures demonstrably insufficient to meet current EU mandates requiring accelerated deployment of renewable energy systems [19].

The principal aim of this work is to establish a comprehensive baseline assessment of energy efficiency compliance in Madrid's municipal markets and identify actionable pathways for architectural intervention that align with the EU's 2030 and 2050 decarbonization targets [20]. The findings demonstrate that municipal markets, often housed in publicly owned buildings with cultural heritage classification, require urgent yet carefully calibrated retrofitting strategies that reconcile conservation obligations with performance requirements. This study contributes essential empirical data for developing national building renovation plans under the revised Energy Efficiency Directive [21] and establishes a replicable methodology for assessing food market infrastructure across European

cities, addressing a critical knowledge gap at the intersection of food systems, heritage conservation, and sustainable building transition [22].

Key contributions are:

- A system-level baseline dataset for 35 markets (77.8% of the municipal network) obtained directly from facility managers, covering envelope condition, HVAC/ventilation, water and electricity use, and renewable energy adoption.
- A transparent aggregation rubric that translates multi-domain indicators into a portfolio screening metric, enabling benchmarking and identification of priority retrofit pathways.
- Policy-relevant recommendations that link observed gaps to municipal levers (procurement, lease/investment horizons, audit programmes, and financing) to accelerate alignment with EU directives.

2. Materials and Methods

2.1. Research Design and Data Collection

This study employed a quantitative-descriptive methodology based on structured questionnaire surveys administered to facility managers of municipal food markets in Madrid, Spain. The questionnaire instrument was designed following established protocols for energy consumption analysis in public buildings [23] and adapted for food retail environments. Data collection was conducted in December 2025 through face-to-face and telephone interviews with market managers, who were selected as key informants based on their direct responsibility for building operations and maintenance [24].

The study population comprised all 45 municipal food markets operating in Madrid at the time of data collection. From this total population, data were successfully obtained from 35 markets, Table 1 (77.8% response rate), with non-response attributed to scheduling conflicts, managerial turnover, or temporary closure for renovation works. The sample represents a comprehensive cross-section of Madrid's municipal market infrastructure, encompassing diverse typologies (covered markets, open-air markets, mixed-use facilities) and construction dates ranging from the early 20th century to contemporary structures.

Non-response assessment:

To evaluate potential non-response bias, we compared responding markets ($n = 35$) with the non-responding subset ($n = 10$) using publicly available portfolio descriptors (district membership) from municipal market directories. Non-response was concentrated in a limited number of districts, while the responding sample retained broad geographic coverage across the municipal network. Because district is a coarse proxy for structural/operational heterogeneity, we retain non-response as a limitation and recommend targeted follow-up outreach to improve coverage in under-represented districts in future waves.

Based on the directory listing by district, the following markets did not provide responses during the survey campaign: Puerta Bonita (Carabanchel), San Cristóbal (Chamartín), Bami/Las Ventas/San Pascual (Ciudad Lineal), Mediodía-Entrevías (Puente de Vallecas), La Remonta/Maravillas (Tetuán), and Orcasitas/Orcasur (Usera).

Table 1. Municipal food markets analyzed in Madrid by district.

ID	Market	District
01-ADE	Alto de Extremadura	Latina
02-AM	Antón Martín	Centro
03-AR	Argüelles	Moncloa-Aravaca
04-BAR	Barceló	Centro
05-CHA	Chamartín	Chamartín
06-CHAM	Chamberí	Chamberí
07-DDL	Diego de León	Salamanca
08-DC	Doña Carlota	Puente de Vallecas
09-GDO	Guillermo de Osma	Arganzuela
10-GEB	Guzmán el Bueno	Chamberí
11-IBI	Ibiza	Retiro
12-JDGP	Jesús del Gran Poder	Usera
13-LC	La Cebada	Centro
14-LG	La Guindalera	Salamanca
15-LP	La Paz	Salamanca
16-LA	Las Águilas	Latina
17-LM	Los Mostenses	Centro
18-MO	Moratalaz	Moratalaz
19-NU	Numancia	Puente de Vallecas
20-PA	Pacífico	Retiro
21-PROS	Prosperidad	Chamartín
22-PDV	Puente de Vallecas	Puente de Vallecas
23-SA	San Antón	Centro
24-SE	San Enrique	Tetuán
25-SI	San Isidro	Carabanchel
26-SEU	Santa Eugenia	Villa de Vallecas
27-SMC	Santa María de la Cabeza	Arganzuela
28-TE	Tetuán	Tetuán
29-TDM	Tirso de Molina	Latina
30-USE	Usera	Usera
31-VAL	Valdezarza	Moncloa-Aravaca
32-VALLE	Vallehermoso	Chamberí
33-VI	Vicálvaro	Vicálvaro
34-VDV	Villa de Vallecas	Villa de Vallecas
35-VILLA	Villaverde Alto	Villaverde

Note: Data collected through interviews with market managers (2025).

2.2. Questionnaire Instrument

The survey instrument consisted of 12 structured questions organized into four analytical domains: (1) building envelope characteristics, (2) HVAC and ventilation systems, (3) water and energy consumption patterns, and (4) renewable energy installations. The questionnaire was developed referencing established assessment tools for residential building envelopes [25] and adapted for commercial food market environments, considering the specific operational requirements of fresh food storage and retail spaces [26].

The specific questionnaire items were as follows:

2.2.1. Building Envelope (Items 1–3)

1. Is the market adequately insulated against cold, heat, and noise?
2. Do the market walls/roof incorporate air/insulation chambers?
3. Do windowpanes include air/thermal break chambers?

2.2.2. Facilities: HVAC and Ventilation (Items 4–6):

4. Does the market have heating or cooling systems? What type?

5. Does the market have any specific ventilation requirements?
6. How is the market ventilated (natural, mechanical, mixed)?

2.2.3. Water and Energy Consumption (Items 7–10):

7. What is the monthly water consumption in liters?
8. Are water-saving systems installed in taps or toilets?
9. What is the monthly electricity consumption in kW?
10. What type of lighting is used in common areas?

2.2.4. Renewable Energy Systems (Items 11–12):

11. Does the market have photovoltaic solar panels installed? If yes, in what year?
12. Does the market have solar thermal panels installed? If yes, in what year?

All responses were recorded in a standardized digital database with categorical coding for qualitative answers and numerical entry for quantitative metrics. Energy consumption data were validated through cross-reference with available utility billing records where accessible.

2.3. Analytical Framework

Data analysis followed a mixed-approach framework combining descriptive statistics for quantitative variables (energy consumption, installation dates) and categorical analysis for qualitative variables (insulation presence, system types). The assessment methodology was validated through reference to established building energy analysis models [27] and demand-side management frameworks [28], with particular attention to flexible energy demand behaviors applicable to commercial buildings [29].

Global Assessment: AHP-Derived Weights and Reproducible Scoring Rubric

To improve methodological rigor and transparency, we formalize the portfolio-level ‘Global Assessment’ as a multi-criteria decision model. Each of the seven indicators (insulation, air conditioning, ventilation, water, electricity, photovoltaic, solar thermal) is first mapped to an ordinal score $x_{ij} \in \{0, 1, 2\}$ (Table 2). Criterion weights are derived using the Analytic Hierarchy Process (AHP), and the composite score is computed as a weighted sum. This makes the classification fully reproducible.

Table 2. Scoring mapping scheme and AHP-derived criterion weights.

Criterion	Response Levels	Score (x_{ij})	Weight (w_j)
Insulation (Chamber/Insulation)	YES/NR/DK/NO	2/0/0	0.20
Air conditioning	Efficient/Average/Inefficient/NR/DK	2/1/0/0	0.15
Ventilation	Efficient/Average/Inefficient/NR/DK	2/1/0/0	0.15
Water	Limited/Average/High/NR/DK	2/1/0/0	0.10
Electricity	Limited/Average/High/NR/DK	2/1/0/0	0.10
Photovoltaic	YES/Project/NO	2/1/0	0.20
Solar thermal	YES/NO	2/0	0.10
Level/response	Mapped score	Examples	
Best	2	Good; Efficient; YES	
Intermediate	1	Improvable; Average; Limited; Project	
Worst/unknown	0	Bad; Inefficient; NO; NR/DK	

Note: NR = No response; DK = Don’t know.

AHP weighting: Let $w = [w_1, \dots, w_7]$ be the criterion weight vector. We define a pairwise-comparison matrix A where a_{jk} expresses the relative importance of criterion j over k . Weights are obtained from the principal right-eigenvector of A ($Aw = \lambda_{\max} w$), normalised such that $\sum_j w_j = 1$. Consistency is checked using the consistency ratio $CR = CI/RI$, where $CI = (\lambda_{\max} - n)/(n - 1)$ and RI is Saaty’s random index. In our

implementation, the comparison matrix is constructed to be consistent with the adopted weight vector ($a_{jk} = w_j/w_k$), yielding $CR \approx 0$ [30], (Figure 2).

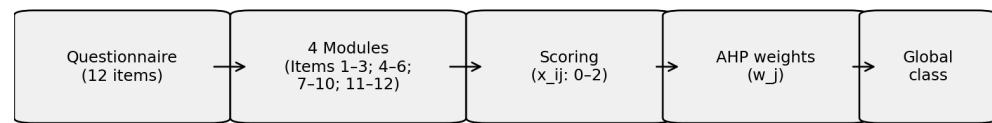


Figure 2. Overall methodological framework (questionnaire → modules → scoring → AHP weighting → classification).

The resulting AHP weight set is:

- insulation 0.20,
- air conditioning 0.15,
- ventilation 0.15,
- water 0.10,
- electricity 0.10,
- photovoltaic 0.20,
- solar thermal 0.10.

The AHP formulation is included to document and justify the adopted weight set; the numerical weights used in the composite index are unchanged, and therefore Table 3 classifications remain unchanged.

As a robustness check, objective weights can also be derived from Shannon-entropy weighting, which determines criterion importance based on information dispersion in the decision matrix [31].

Composite score: For each market i , we compute $S_i = 100 \cdot \sum_j w_j \cdot (x_{ij}/2)$, where division by 2 normalises scores to $[0, 1]$. Classification follows fixed, pre-defined thresholds:

- Good if $S_i \geq 70$;
- Improvable if $40 \leq S_i < 70$;
- Bad if $S_i < 40$.

The four analytical blocks were processed as follows:

- Envelope assessment: Categorical scoring of insulation adequacy (adequate/partial/inadequate).
- Facilities analysis: Classification of HVAC and ventilation system types and efficiency ratings.
- Consumption metrics: Normalization of water and electricity consumption per square meter of market surface area to enable comparative analysis across different market sizes.
- Renewable energy penetration: Calculation of installation rates and temporal distribution of adoption.

Rationale for weights:

The AHP comparisons were defined a priori to reflect (i) decarbonization relevance and (ii) retrofit leverage in this building typology. Photovoltaic adoption and envelope insulation receive the highest weights (0.20 each) because they directly address renewable-energy integration and heat-loss reduction pathways that dominate compliance-oriented retrofit planning under current EU decarbonization objectives. Air-conditioning and ventilation (0.15 each) are weighted next given their central role in operational energy demand and indoor environmental quality in food retail settings. Water and electricity monitoring/efficiency (0.10 each) are weighted to reflect enabling, cross-cutting improvements (metering, benchmarking, low-regret upgrades) that support prioritization and governance. Solar thermal (0.10) is weighted lower because DHW demand in most markets is

limited and alternative DHW solutions (e.g., heat pumps) are commonly deployed. The AHP framework (including consistency checks) is provided to ensure transparency and replicability of the weighting procedure [32].

Sensitivity analysis:

To test robustness, we performed a sensitivity check by perturbing the weights within a reasonable range ($\pm 20\%$) and verifying that the main portfolio conclusions and the identity of the best-performing markets remain stable under these variations [33].

2.4. Data Availability

The raw questionnaire data and anonymized manager responses supporting this study will be made available upon reasonable request to the corresponding author. Due to commercial sensitivity agreements with Madrid City Council, complete market-level consumption data cannot be publicly deposited; however, aggregated datasets and analysis scripts will be provided during the review process and made available through the institutional repository upon publication.

2.5. Use of Generative Artificial Intelligence

The authors declare that no generative artificial intelligence (GenAI) tools were used for data collection, analysis, interpretation, or manuscript drafting in this study. Standard text editing software was employed solely for grammar and spelling correction.

3. Results

With $n = 35$ responses from a population of $n = 45$ markets, reported proportions should be interpreted as descriptive shares of the surveyed portfolio; sampling uncertainty is limited but non-zero (e.g., a 50% share corresponds to an approximate $\pm 15\%$ margin of error at 95% confidence under simple random sampling assumptions).

3.1. Building Envelope Insulation

Interpretation: The dominance of thermal (vs. acoustic) deficiencies likely reflects the markets' operational sensitivity to temperature control (comfort for occupants and refrigeration loads for vendors), making heat/cold issues more salient and costly than noise. Moreover, the high share of 'NR/DK' on envelope composition indicates information asymmetry that can bias perceived performance, supporting audit-first retrofit planning.

Analysis of manager surveys revealed significant discrepancies between perceived and actual thermal performance. While 46% of managers reported adequate envelope insulation, 40% acknowledged deficiencies, indicating substantial knowledge gaps regarding building fabric performance (Figure 3). Thermal deficiencies were identified as the predominant envelope problem, with acoustic insulation representing a secondary concern. Notably, 21% of markets hold historical preservation status, presenting structural constraints for retrofitting interventions.

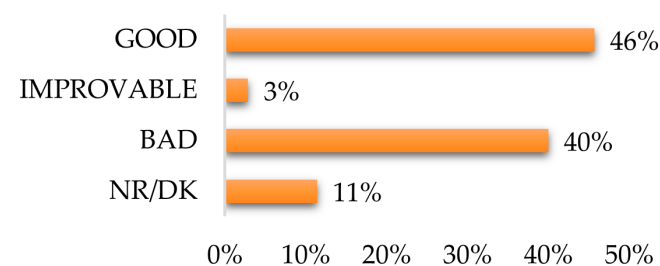


Figure 3. Insulation condition.

It is worth (Figure 4) noting that 21% of the markets analyzed are subject to varying levels of historical preservation, which poses significant challenges when addressing the identified deficiencies. Notably, the results reveal a higher prevalence of thermal deficiencies compared to acoustic ones, suggesting that insulation against external noise is a relatively minor concern in these market buildings. This finding underscores the need to prioritize strategies aimed at improving thermal performance, in order to achieve an appropriate balance between heritage conservation requirements and contemporary energy efficiency objectives.

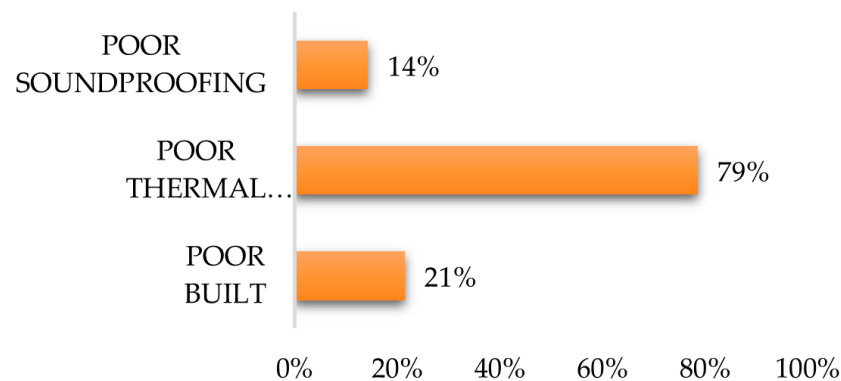


Figure 4. Poor insulation.

Investigation of envelope composition showed that 50% of managers lacked knowledge regarding wall construction details, including air chamber or insulation layer presence (Figure 5). Among managers with documented envelope information, buildings with verified thermal protection features (air chambers or insulation layers) doubled compared to those with unknown specifications. However, measured insulation thicknesses in these buildings frequently failed to meet current regulatory standards, indicating compliance gaps in the existing building stock.

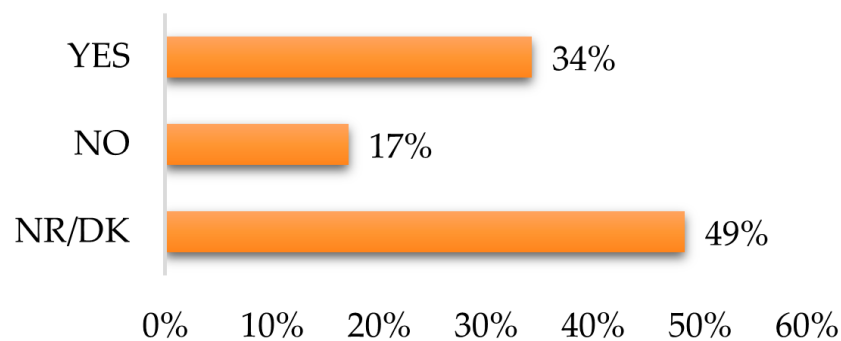


Figure 5. Enclosure with air cavity and insulation.

Window systems analysis revealed widespread thermal bridge issues: the majority of existing carpentry lacked thermal breaks, and double-glazed units with air chambers were scarce (Figure 6). While manager awareness of glazing specifications exceeded that of wall construction details, significant information deficits persisted, constraining accurate energy performance assessments.

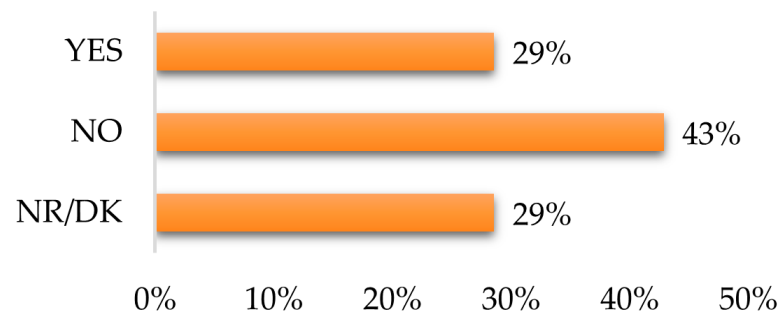


Figure 6. Double glazing with thermal break.

3.2. HVAC and Ventilation Systems

Interpretation: The ventilation perception gap (low perceived need vs. low heat-recovery adoption) suggests that ventilation benefits are less visible to managers than HVAC and lighting. In practice, odor-extraction is often conflated with adequate ventilation, while heat-recovery retrofits face space, duct-routing and maintenance constraints; these factors help explain the mismatch between perceived need and best-practice adoption.

Mechanical systems survey indicated progressive technology adoption, with 69% of markets utilizing heat pump-based air conditioning, predominantly retrofitted due to original construction without integrated climate control (Figure 7). System efficiency varied significantly by installation vintage, reflecting technological evolution. Evaporative cooling constituted the second most prevalent technology (sustainable cooling without heating capability), while cooling towers remained rare (3%) due to specialized maintenance requirements including anti-legionella protocols.

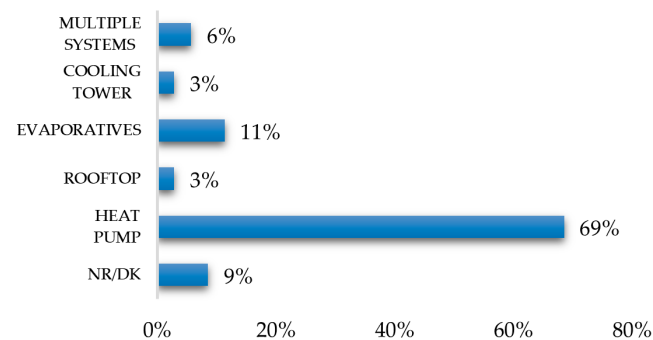


Figure 7. Air conditioning system.

Ventilation assessment revealed concerning gaps in indoor air quality management: 86% of managers did not perceive ventilation system installation as necessary (Figure 8). Despite this perception, only 6% of markets employed heat recovery ventilation systems, representing best-practice energy-efficient air renewal (Figure 9).

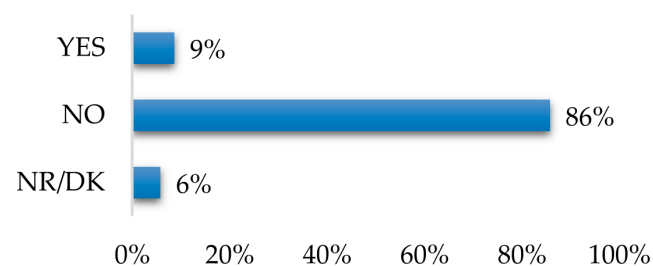


Figure 8. Ventilation system required.

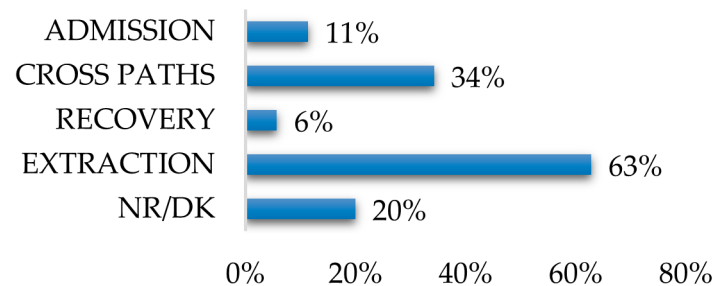


Figure 9. Ventilation system.

Extraction systems for odor control were present in 63% of facilities, though cross-ventilation mechanisms suitable for natural air renewal existed in merely 34% of markets. This configuration of trade-off between thermal energy conservation and ventilation efficacy highlights optimization challenges in market environments.

3.3. Water and Electrical Consumption

Interpretation: Heterogeneous consumption intensities and the presence of ‘NR/DK’ responses indicate uneven monitoring maturity across the portfolio. Improving metering and reporting is a low-regret action because it enables benchmarking and targeted identification of outliers before capital-intensive retrofits.

Water consumption normalized by floor area showed 57% of markets operating within 100–500 L/m² monthly range (Figure 10). Knowledge deficits affected 17% of respondents unable to report consumption data. High-consumption outliers (>500 L/m², 3%) suggest potential efficiency improvements, while low-consumption facilities (<100 L/m², 23%) warrant investigation for conservation best practices.

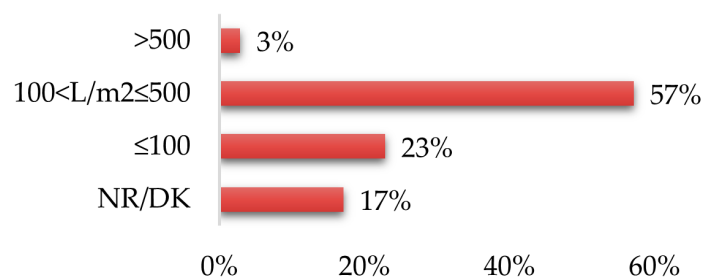


Figure 10. Water consumption L/m².

Water-saving technology adoption remained limited: 66% of markets lacked sensor-equipped faucets or timed push-button dispensers, while 29% had implemented such measures (Figure 11). Age of construction and market typology strongly correlated with infrastructure modernization status.

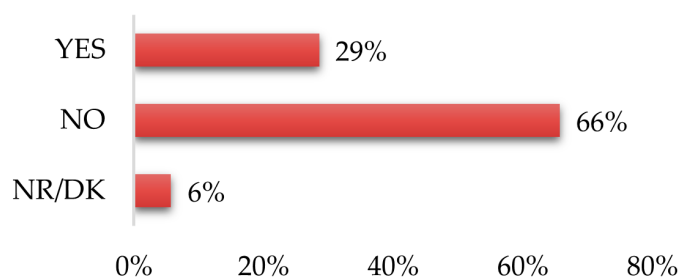


Figure 11. Water-Saving System.

Electrical consumption analysis demonstrated heterogeneous efficiency profiles (Figure 12). High-consumption facilities (>5 kWh/m²) comprised 9% of the sample, while efficient operations (<1 kWh/m²) represented 23%, typically associated with recent technology adoption. The majority operated at intermediate levels (<5 kWh/m²). Notably, 14% of managers lacked awareness of monthly electricity consumption despite its operational cost significance.

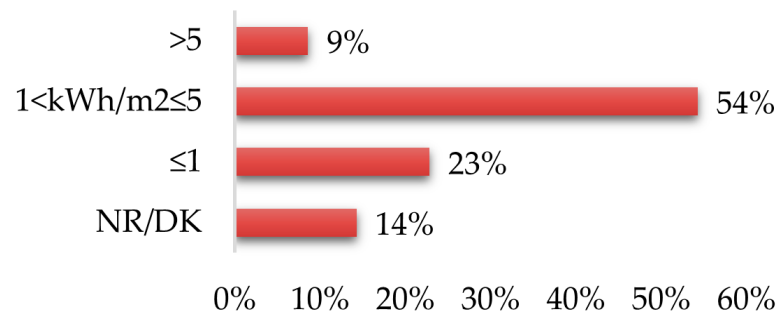


Figure 12. Electricity Consumption (kWh/m²).

Lighting technology assessment showed successful LED transition in 72% of markets, though 14% retained less efficient fluorescent systems, and 11% maintained hybrid configurations (Figure 13). Manager knowledge of lighting infrastructure was substantially higher than for passive building elements, reflecting the visible and maintainable nature of active systems.

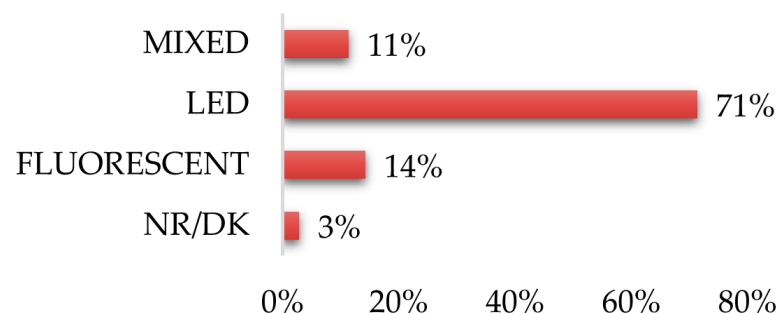


Figure 13. Type of lighting.

3.4. Renewable Energy Penetration

Interpretation: The low PV uptake is consistent with a feasibility–governance barrier pattern rather than resource scarcity. Roof constraints (geometry, shading, heritage) and investment horizons under lease/ownership arrangements likely dominate decision-making; the existence of ‘Project’ cases suggests that administrative pathways exist but require scaling and standardisation.

Photovoltaic system adoption was critically low: as of December 2025, only 11% of markets had active installation projects, while 9% had operational systems (Figure 14). The remaining 80% showed no renewable generation capacity. Barriers included architectural constraints (roof morphology, heritage protection status), shading from adjacent structures, and economic disincentives related to temporary use agreements where investment amortization periods exceeded remaining lease durations.

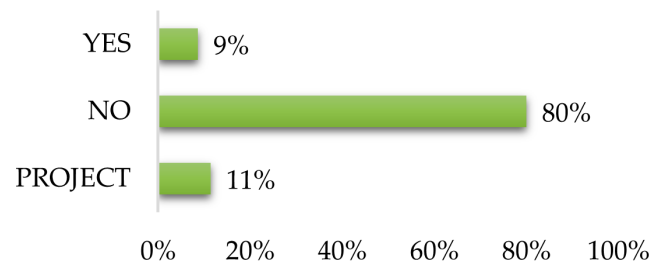


Figure 14. Solar Photovoltaic (PV) System.

Solar thermal installations for domestic hot water provision were similarly limited (9% penetration, Figure 15). Given minimal hot water demand in market operations (restricted primarily to sanitary facilities), this low adoption rate aligns with functional requirements. The 2006 Spanish Technical Building Code mandate for solar thermal systems in new construction primarily influenced post-2006 buildings; regulatory language revisions in 2019 shifted preference toward aerothermal systems, further reducing thermal panel relevance for low-demand commercial typologies.

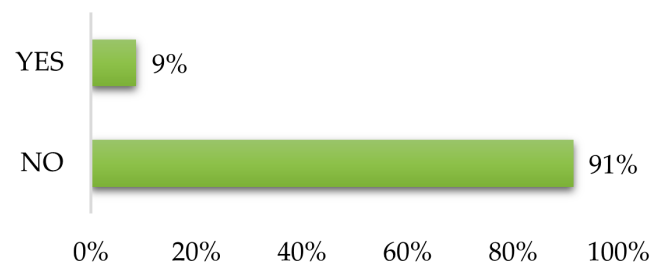


Figure 15. Solar Thermal System for Domestic Hot Water (DHW).

3.5. Synthesis of Findings

Portfolio benchmarking indicates that the best-performing cases (Markets 16-LA and 21-PROS, classified as “Good” in Table 3) combine at least one renewable-energy pathway (operational PV or an active PV project) with generally adequate performance in HVAC/ventilation and consumption domains. Conversely, the worst-performing group (“Bad”) typically combines envelope uncertainty or lack of insulation with absent renewables and either high electricity use or inefficient ventilation. These contrasts support a staged retrofit roadmap: (1) audits and envelope upgrades, (2) ventilation heat recovery and controls, and (3) PV deployment where feasible.

The diagnostic assessment reveals systemic energy efficiency deficits across Madrid’s municipal market network. Critical vulnerabilities include: (i) envelope thermal performance deficiencies compounded by managerial knowledge gaps; (ii) ventilation inadequacies despite high perceived air quality; (iii) incomplete water and energy monitoring infrastructure; and (iv) negligible renewable energy penetration. These findings establish baseline conditions prior to EU Directive (EU) 2023/1791 and Directive (EU) 2024/1275 implementation, demonstrating substantial retrofit requirements to achieve 2030 decarbonization targets.

The marked disparity between manager awareness of active systems (HVAC, lighting) versus passive elements (envelope composition) suggests targeted educational interventions and building audits are prerequisite to effective efficiency planning. Historic preservation status affecting 21% of facilities necessitates nuanced retrofit strategies reconciling heritage conservation with thermal performance improvements.

4. Discussion

4.1. Thermal Envelope Performance and Managerial Knowledge Deficits

The diagnostic findings reveal substantial inefficiencies in the thermal envelope performance of Madrid's municipal markets, corroborating broader European patterns of energy deficit in publicly owned commercial buildings. The documented 40% inadequacy rate in envelope insulation and the widespread lack of managerial knowledge regarding building fabric composition (50% unknown wall construction) align with the systematic literature identifying knowledge gaps as primary barriers to effective energy management in public buildings [34]. Prioritizing improvements in envelope thermal performance through passive retrofit strategies has been demonstrated to significantly enhance energy-saving and carbon-reduction outcomes in comparable building typologies [35], supporting our interpretation that envelope upgrades represent the most cost-effective intervention pathway for these facilities.

The heritage protection status affecting 21% of markets presents a recognized challenge across European cities. Research on energy retrofitting of public buildings confirms that envelope thermal properties constitute the most sensitive parameter for retrofit optimization, yet historic preservation constraints frequently limit intervention options [36]. The incongruence between perceived and actual thermal performance identified in our study underscores the necessity of empirical building audits rather than reliance on managerial assessments, consistent with findings that occupant perception frequently misaligns with measured performance in heritage buildings [37].

Window system deficiencies, particularly the prevalence of single-glazing and thermal bridges in carpentry, represent readily addressable improvements. Current research on residential and commercial envelope systems emphasizes that advanced glazing solutions with low-emissivity coatings and thermal break frames can achieve transmittance reductions of 50–70% [38]. The disconnect between available technologies and their deployment in municipal markets suggests structural barriers—including procurement protocols, lease duration limitations, and fragmented ownership responsibilities—that warrant future investigation.

4.2. HVAC Systems and Ventilation Strategies

The predominant adoption of heat pump technology (69% of markets) reflects successful alignment with European decarbonization trajectories, consistent with sector-wide transitions documented in recent building energy assessments [39]. However, the high prevalence of ventilation systems without heat recovery (94%) represents a critical efficiency gap. Our findings show that only 6% of markets employ heat recovery ventilation while 86% of managers perceive mechanical ventilation as unnecessary indicate substantial misalignment between operational practices and indoor air quality requirements. This observation is particularly relevant given post-pandemic heightened awareness of airborne pathogen transmission in crowded retail environments.

Cross-ventilation deployment (34%) offers passive air renewal potential, yet the documented thermal energy trade-offs highlight the fundamental tension between ventilation efficacy and thermal conservation. Future research should investigate hybrid ventilation strategies incorporating demand-controlled mechanical systems with heat recovery for peak occupancy periods, complementing natural ventilation during standard operations. Such adaptive approaches have demonstrated success in reducing HVAC energy consumption by 25–40% in comparable commercial buildings while maintaining air quality standards [40].

4.3. Water and Energy Consumption Patterns

Water consumption analysis revealed manageable baseline consumption in most facilities (57% within 100–500 L/m² range), yet the 17% knowledge gap regarding water metering among managers indicates monitoring infrastructure deficiencies. The limited adoption of water-saving technologies (29%) and complete absence of greywater recycling systems represent significant circular economy implementation gaps [41]. Greywater recycling for non-potable applications—particularly toilet flushing in market sanitary facilities—has been demonstrated to achieve 30–50% reductions in potable water demand in commercial buildings [42], directly supporting circular economy principles through resource cascading [43].

The heterogeneity in electrical consumption profiles, with 9% of markets exceeding 5 kWh/m² while 23% operate below 1 kWh/m², suggests the existence of replicable best practices within the network that could be disseminated through benchmarking initiatives. The near-complete transition to LED lighting (72%) demonstrates that technology adoption succeeds when economic incentives align; however, the residual fluorescent installations (14%) in markets with high electricity consumption indicate persistent implementation gaps requiring targeted intervention. The documented 14% managerial unawareness of electricity consumption—despite its direct financial impact—highlights the need for enhanced monitoring infrastructure and data transparency as prerequisites for energy efficiency governance.

4.4. Renewable Energy Deployment Barriers

The critically low photovoltaic penetration (9% operational, 11% planned) presents the most significant compliance gap relative to EU Directive (EU) 2023/2413 requirements mandating substantial renewable energy integration in public buildings by 2030 [44]. This deficit is particularly concerning given Madrid's high solar resource availability (approximately 1800 equivalent peak sun hours annually). The identified barriers—architectural constraints, heritage protection, shading from adjacent structures, and lease duration limitations affecting investment amortization—mirror structural challenges documented in commercial building renewable energy transitions [45].

Emerging technological solutions, including bifacial photovoltaic panels capable of capturing diffuse light from suboptimal orientations and building-integrated photovoltaics compatible with heritage facades, offer pathways to overcome installation constraints in dense urban contexts [46]. Furthermore, hybrid solar thermal–photovoltaic systems warrant investigation for markets with moderate hot water demand, potentially consolidating renewable generation infrastructure.

The negligible solar thermal adoption (9%) appropriately reflects the minimal domestic hot water demand in market operations. Contemporary regulatory frameworks, including the revised Spanish Technical Building Code, increasingly prioritize heat pump-based aerothermal systems over solar thermal for low-demand applications—a trend validated by our observation that aerothermal integration with heat pumps effectively meets residual hot water requirements while providing heating capacity.

4.5. Integration and Future Research Directions

The comprehensive assessment presented in Table 3 reveals that no municipal market currently achieves “Good” classification across all evaluated domains, and only two facilities (5.7%) attain this rating in the overall assessment. This baseline condition, established in December 2025, indicates substantial retrofit requirements to achieve compliance with Directive (EU) 2023/1791 (energy efficiency) and Directive (EU) 2024/1275 (building performance) implementation timelines.

Table 3. Summary of the Analyzed Parameters.

ID	INSULATION	AIR CONDITIONING AND VENTILATION SYSTEMS		WATER AND ENERGY CONSUMPTION		USE OF RENEWABLE ENERGY		GLOBAL ASSESSMENT
	Chamber/Insulation	Air Conditioning	Ventilation	Water	Electricity	Photovoltaic	Solar Thermal	
01-ADE	NR/DK	Efficient	Average	Average	Average	NO	NO	Bad
02-AM	NO	Efficient	Average	Average	High	NO	NO	Bad
03-AR	NO	Efficient	NR/DK	Average	Average	NO	YES	Improvable
04-BAR	NR/DK	Average	Inefficient	Limited	High	NO	NO	Bad
05-CHA	YES	NR/DK	NR/DK	NR/DK	NR/DK	NO	NO	Bad
06-CHAM	NR/DK	Efficient	Average	Limited	Average	NO	NO	Improvable
07-DDL	NR/DK	Efficient	Average	Average	Limited	NO	NO	Improvable
08-DC	NR/DK	Efficient	NR/DK	Average	Average	NO	NO	Bad
09-GDO	NR/DK	Efficient	Average	Average	Limited	NO	NO	Improvable
10-GEB	NR/DK	Efficient	Average	Limited	Limited	NO	NO	Improvable
11-IBI	YES	Efficient	Inefficient	Limited	NR/DK	NO	YES	Improvable
12-JDGP	YES	Inefficient	Average	Limited	Limited	NO	NO	Improvable
13-LC	NR/DK	Average	NR/DK	Average	Average	NO	NO	Bad
14-LG	NR/DK	Efficient	Average	NR/DK	Average	NO	NO	Bad
15-LP	YES	Average	Average	High	Average	Project	NO	Bad
16-LA	YES	Average	Average	Average	Average	YES	NO	Good
17-LM	NR/DK	Inefficient	Inefficient	Average	Average	NO	NO	Bad
18-MO	NR/DK	NR/DK	NR/DK	Average	Average	NO	NO	Bad
19-NU	NR/DK	Efficient	Inefficient	Limited	Limited	NO	NO	Improvable
20-PA	YES	Efficient	Average	NR/DK	NR/DK	NO	NO	Improvable
21-PROS	NR/DK	Efficient	Efficient	Average	Average	Project	YES	Good
22-PDV	NR/DK	Efficient	Inefficient	Average	Average	YES	NO	Improvable
23-SA	YES	Efficient	Inefficient	NR/DK	NR/DK	YES	NO	Improvable
24-SE	NR/DK	Efficient	Inefficient	Limited	Limited	NO	NO	Improvable
25-SI	NR/DK	Efficient	Inefficient	Average	Average	NO	NO	Bad
26-SEU	YES	Efficient	Average	NR/DK	Average	NO	NO	Improvable
27-SMC	YES	Efficient	Average	Average	Average	Project	NO	Improvable
28-TE	NR/DK	Efficient	Inefficient	Average	Limited	Project	NO	Improvable
29-TDM	NO	Efficient	Efficient	Average	High	NO	NO	Improvable
30-USE	YES	Average	NR/DK	Average	Average	NO	NO	Bad
31-VAL	YES	NR/DK	NR/DK	Average	NR/DK	NO	NO	Bad
32-VALLE	NO	Efficient	Average	NR/DK	Limited	NO	NO	Improvable
33-VI	NO	Efficient	Inefficient	Limited	Average	NO	NO	Improvable
34-VDV	NO	Efficient	Average	Average	Average	NO	NO	Bad
35-VILLA	YES	Efficient	Average	Average	Average	NO	NO	Improvable
SUMMARY								Summary counts ($n = 35$): Global Good = 2, Improvable = 19, Bad = 14. PV: YES = 3, Project = 4, NO = 28.

Note: NR = No response; DK = Don't know.

Future research priorities should address: (i) longitudinal monitoring of retrofit implementation effectiveness following 2026 transposition and subsequent national implementation milestones; (ii) economic analysis of lease structure modifications enabling long-term renewable energy investments; (iii) occupant comfort and indoor environmental quality validation in retrofitted markets; and (iv) the potential of electric vehicle charging infrastructure—powered by surplus photovoltaic generation—to enhance market attractiveness and support transport electrification objectives while creating new revenue streams for market operations. The integration of building-level efficiency improvements with

district-scale energy systems and urban circular economy platforms represents a critical frontier for municipal infrastructure sustainability transitions.

5. Conclusions

5.1. Overall Market Valuation

The comprehensive assessment presented in Table 3 reveals that only two municipal markets (5.7%) achieve a “Good” overall rating based on evaluated sustainability and energy efficiency parameters, while fourteen markets (40%) receive “Bad” classifications. This distribution indicates substantial systemic deficiencies across Madrid’s municipal market network, with the majority (54.3%) rated as “Improvable” requiring targeted interventions. These findings establish a critical baseline demonstrating significant compliance gaps relative to Directive (EU) 2023/1791 and Directive (EU) 2024/1275 requirements.

The interaction of multiple energy efficiency measures demonstrates synergistic potential: envelope thermal improvements [47] combined with heat pump optimization and photovoltaic generation [48] can achieve compound reductions in operational energy consumption and carbon emissions. However, implementation feasibility varies substantially across the portfolio due to structural heterogeneity—building age ranging from early 20th century to contemporary construction, heritage protection status affecting retrofit options, and diverse ownership/lease structures influencing investment horizons. The documented knowledge deficits among facility managers further complicate optimization, highlighting the necessity of systematic audit protocols and capacity-building programs as prerequisites for effective building performance governance.

Real-world effectiveness of proposed interventions requires longitudinal monitoring following implementation, with particular attention to climate-adaptive performance validation and user behavior impacts on actual versus predicted energy consumption. The Madrid market network’s diversity—encompassing open-air, covered, and mixed-use typologies with varying climatic exposure—necessitates customized rather than standardized retrofit approaches, introducing complexity to municipal-scale program deployment [49].

5.2. Strategic Implications and Future Directions

This diagnostic assessment contributes empirical baseline data for public building energy efficiency transitions, demonstrating methodologies applicable to municipal facility portfolios beyond food markets [50]. The integration of digital technologies for monitoring, optimization, and user engagement represents a critical enabling infrastructure for achieving sustained performance improvements. Recent research on smart building integration into smart city frameworks emphasizes that building-level digitalization serves as foundational infrastructure for urban-scale sustainability transitions, enabling real-time performance optimization and predictive maintenance capabilities that can reduce energy consumption by 15–30% beyond hardware retrofit benefits [51].

The integration of digital technologies for monitoring, optimisation, and user engagement can act as enabling infrastructure for sustained performance improvements (e.g., asset-management dashboards, metering integration, and data-sharing protocols). Complementary governance mechanisms—such as dedicated roles to coordinate circular-economy initiatives and retrofit planning across stakeholders—may help translate technical findings into operational action at the municipal level [52]. The documented success of comparable pilot projects in European municipal markets suggests that cooperative replication strategies, sharing best practices across city networks, could accelerate transformation trajectories beyond individual municipality capacities [53].

Beyond immediate energy efficiency improvements, strategic priorities should incorporate: (i) electric vehicle charging infrastructure powered by surplus photovoltaic generation

to enhance market accessibility and revenue diversification [54]; (ii) advanced metering infrastructure enabling demand-response participation in grid balancing services; and (iii) circular resource platforms extending beyond water recycling [55] to encompass organic waste valorization and packaging reduction initiatives. These integrated approaches position municipal markets as multifunctional urban infrastructure—simultaneously serving food security, climate adaptation, and community cohesion functions—thereby justifying public investment in their comprehensive modernization despite competitive pressures from conventional retail formats.

5.3. Limitations

Several methodological limitations should be acknowledged. First, historical data availability for energy consumption and building envelope characteristics varied across markets, potentially constraining longitudinal analysis. Second, the study scope is geographically bounded to municipal food markets in Madrid; consequently, findings may not be directly generalizable to other building typologies or geographic contexts with different climatic or regulatory conditions. Third, self-reported data from facility managers may introduce reporting bias, particularly regarding subjective assessments of envelope adequacy. Fourth, external factors including subsequent regulatory changes (implementation of Directive (EU) 2023/1791 and Directive (EU) 2024/1275 post-dating the data collection period) may impact the long-term applicability of recommendations, though these evolutions are explicitly addressed in the Discussion section.

This study does not include a quantitative rooftop-based PV potential assessment (e.g., using GIS/cadastral roof-area estimates), as it would require additional market-level data and site verification (shading, structural capacity, and heritage constraints). We identify this as a priority extension for future work to benchmark technical potential against current PV uptake.

Author Contributions: Conceptualization, M.B.-A. and J.G.S.-T.; methodology, M.B.-A., C.G.-G., E.R.C.-L. and J.G.S.-T.; software, M.B.-A.; validation, M.B.-A., C.G.-G., E.R.C.-L. and J.G.S.-T.; formal analysis, M.B.-A., C.G.-G., E.R.C.-L. and J.G.S.-T.; investigation, M.B.-A., J.L.P.R., M.A.F.N. and J.G.S.-T.; resources, M.B.-A., J.L.P.R., M.A.F.N. and J.G.S.-T.; data curation, M.B.-A., J.L.P.R., M.A.F.N. and J.G.S.-T.; writing—original draft preparation, M.B.-A.; writing—review and editing, M.B.-A., C.G.-G., E.R.C.-L. and J.G.S.-T.; visualization, M.B.-A.; supervision, M.B.-A., C.G.-G., E.R.C.-L., J.L.P.R., M.A.F.N. and J.G.S.-T.; project administration, M.B.-A., J.L.P.R. and J.G.S.-T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Ethical approval was not required for this study, in accordance with Regulation (EU) 2016/679 (General Data Protection Regulation) and Spanish Organic Law 3/2018 on the Protection of Personal Data and Guarantee of Digital Rights (LOPDGDD). The study involved non-interventional, voluntary, and anonymized interviews and questionnaires with professionals, with no collection of identifiable or sensitive personal data.

Informed Consent Statement: Informed consent was obtained verbally from all participants prior to their voluntary participation. Participants were informed about the purpose of the study, the anonymous treatment of the data, and its use for research purposes.

Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy or ethical restrictions.

Acknowledgments: The authors wish to express their gratitude to the Extraordinary Chair of Circular Economy in the Management of Public Markets at Francisco de Vitoria University for their administrative and technical support in promoting and facilitating this research on the municipal markets of Madrid. We extend our sincere thanks to the facility managers of all 45 municipal markets in the Madrid network for their cooperation in completing the questionnaires and providing the operational data that served as the empirical foundation for this analysis. Their willingness to share detailed information on building characteristics and energy consumption patterns was essential for the comprehensive assessment presented in this study.

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

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