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Exploratory Data Analysis of Self-Consumption Units in Portugal's Energy Transition

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Master's in Computer Engineering

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Universidade de Aveiro

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TECHNOLOGY
AND ARCHITECTURE

Department of Information Science and Technology

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Resumo

A transição energética é fundamental para a redução das emissões de carbono e para o reforço da sustentabilidade energética. Em Portugal, a rápida adoção de fontes renováveis em particular a produção descentralizada de energia solar através de sistemas UPAC tem vindo a transformar o panorama energético nacional. No entanto, persistem disparidades regionais na disponibilidade de recursos, bem como uma dependência contínua da energia importada, que representam desafios importantes para a resiliência a longo prazo. Este estudo adota uma abordagem baseada em dados para analisar as dinâmicas geográficas e temporais da energia renovável em Portugal. Recorre a dados da E-REDES, AMA, Eurostat e IPMA para explorar a distribuição da radiação solar, a evolução da capacidade instalada em UPAC e os padrões de consumo local. São aplicados métodos estatísticos e geoespaciais para avaliar de que forma fatores regionais como a irradiância solar e a densidade populacional influenciam a adoção e o potencial de produção. Os resultados demonstram que os distritos do sul, com maior exposição solar, apresentam condições técnicas e económicas mais favoráveis à geração descentralizada, enquanto as regiões do norte revelam limitações comparativas. A variabilidade sazonal reforça ainda a importância de integrar fontes complementares e soluções de armazenamento. Estas conclusões oferecem uma perspetiva atualizada sobre o progresso de Portugal rumo à sustentabilidade energética, ao mesmo tempo que evidenciam os constrangimentos geográficos, infraestruturais e sistémicos que devem ser superados para garantir um futuro energético robusto e independente.

Palavras-Chave: *Renováveis, Energia, Autoconsumo, Portugal, Radiação Solar, Sustentabilidade*

Abstract

The energy transition is central to reducing carbon emissions and strengthening energy sustainability. In Portugal, the rapid adoption of renewable sourcesparticularly decentralized solar production through UPAC systems–has reshaped the national energy landscape. However, regional disparities in resource availability and the continued reliance on imported energy highlight important challenges for achieving long-term resilience. This study adopts a data-driven approach to examine the geographic and temporal dynamics of renewable energy in Portugal. Using datasets from E-REDES, AMA, Eurostat and IPMA, the analysis explores the distribution of solar radiation, the evolution of installed UPAC capacity, and patterns of local consumption. Statistical and geospatial methods are applied to assess how regional factors – such as solar irradiance and population density – influence adoption and production potential. The results show that southern districts, with higher solar exposure, present stronger technical and economic conditions for decentralized generation, while northern regions remain comparatively limited. Seasonal variability further underscores the importance of integrating complementary sources and storage solutions. These findings provide an updated perspective on Portugal's progress toward energy sustainability, while highlighting the geographic, infrastructural, and systemic constraints that must be addressed to secure a robust and independent energy future.

Keywords: *Renewables, Energy, Self-Consumption, Portugal, Sustainability*

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List of Acronyms

UPAC: Self-consumption Production Unit

EV: Electrical Vehicle

PV: Photovoltaic

FPV: Floating Photovoltaic

NECP: National Energy and Climate Plan

PtG: Power-to-Gas

DC: Direct Current

AC: Alternating Current

MIBEL: Iberian Electricity Market

CHAPTER 1

Introduction

1.1. Background

The Energy Transition is a fundamental pillar of the global decarbonization strategy, and Portugal has played a leading role in the adoption of renewable energy. However, for this transformation to be efficient and sustainable, it is essential to understand how the different factors affect the evolution of energy production and consumption in the country.

Portugal has made significant progress in increasing the share of renewable energy sources in its electricity mix [**Baptista and Vargas, 2020**], reducing its dependence on fossil fuels. The country has set ambitious targets for carbon neutrality, with the aim of phasing out coal-fired power plants and expanding solar, wind and hydroelectric capacity. Despite these efforts, challenges remain in balancing production with consumption, integrating renewable sources into the grid, and reducing reliance on imported energy [**IEA, 2025a**].

A central aspect of this transformation is the electrification of consumption. Electricity is the most versatile and efficient energy carrier, since it can be produced from multiple renewable sources, transmitted through existing infrastructure, and used across sectors such as mobility, heating and industry. For this reason, the path to decarbonization is increasingly dependent on the expansion of electricity as the primary vector of the energy system [**IEA, 2025b**].

The increasing digitalization of the energy sector and the availability of open energy datasets provide an opportunity to analyze trends, identify challenges, and optimize decision making. Data-driven analysis of the energy transition enables a more precise understanding of how regional disparities in production and consumption impact energy security and sustainability.

1.2. Motivation

The transition to a low-carbon energy system is one of the most pressing global challenges. In Portugal, the rapid deployment of solar and wind energy has positioned the country as a leader in the adoption of renewable energy [**Nunes, 2018**]. As the country continues this transition, an important question arises: how evenly is renewable energy production distributed across regions, and what factors influence this distribution? While some areas have seen significant clean energy investments, others may still rely more on imported electricity. Investigating these dynamics is essential for optimizing the country's energy infrastructure and ensuring a more balanced and resilient energy system.

Furthermore, the role of imported energy in Portugal's electricity mix raises important questions about its sustainability and composition. Is the imported energy predominantly clean, or does it rely on fossil fuels? Addressing these questions through data analysis will provide a clearer picture of Portugal's energy transition and highlight areas where improvements can be made [**Ana Fontoura Gouveia, Gonzalo Escribano, Ignacio Urbasos Arbeola, João Fachada, 2025**].

At the same time, distributed renewable generation has emerged as a complementary dimension of the transition. Self-consumption Production Units (UPACs) allow households, businesses and institutions to generate and consume their own electricity, turning consumers into active participants in the energy system. This decentralized approach not only contributes to reducing pressure on centralized production but also opens new opportunities for resilience and local autonomy. For these reasons, the analysis of the adoption of UPAC and its potential impact is an essential component in understanding Portugal's energy transition.

1.3. Goals

The primary objectives of this study over a span of four years (2022–2025) are:

- Analyze the temporal evolution of UPAC installations and installed capacity in Portugal.
- Examine the geographical distribution of UPAC adoption, highlighting regional disparities and spatial diffusion over time.
- Identify factors that may influence adoption patterns, including solar radiation, demographic characteristics, and public incentives.
- Assess the relationship between decentralized self-consumption and national electricity consumption, in order to understand whether UPACs alter demand composition.
- Estimate the potential contribution of UPACs to local energy production using solar irradiance data as a proxy.
- Provide data-driven insights to inform policymakers and stakeholders on the role of decentralized generation in supporting Portugal's carbon neutrality goals.

1.4. Research Questions

To guide the analysis, the study is structured around four main research dimensions:

Temporal Dynamics

- How has the adoption of UPACs evolved over the analysis period?
- What growth patterns can be observed?

Geographical Dimension

- Are there significant regional disparities in the distribution of installations?
- Which regions lead in UPAC adoption?

Energy Contribution

- What is the relationship between decentralized energy generation and national electricity consumption?

Production Potential

- What is the estimated production potential based on solar radiation of each region?

1.5. Research Approach and Timeline

To address the research questions outlined in this study, a data-driven approach will be adopted, combining geospatial analysis, statistical modeling, and energy system evaluation. The research will be conducted in several phases, following a structured timeline.

- **October–January**: Literature Review and Exploration of Technical Options
  A comprehensive review of existing literature was carried out to establish the theoretical foundation of the study. This phase also included the definition of the research scope, focusing on decentralized generation and the adoption of UPACs in Portugal.
- **February–March/April**: Data Collection and Preprocessing
  Relevant datasets on renewable energy production and distribution will be collected from official sources. The focus will be on organizing and preparing the data for further analysis, ensuring its quality and consistency.
- **April/May–June**: Data Analysis and Visualization
  The processed data was explored through descriptive statistics, temporal series analysis, and geospatial mapping. This stage highlighted the evolution of UPAC adoption, regional disparities, and potential production estimates based on solar irradiance.
- **November–July**: Writing of the Thesis and Preparation of an Academic Article
  The writing was developed in parallel with the analysis. Initial drafts were started early to structure ideas and record results as they emerged. By June, a research article summarizing key findings was prepared.
- **September–October**: Finalization and Defense
  The dissertation was revised and formatted, incorporating feedback from supervisors. The final version was submitted for evaluation, followed by the oral defense.

1.6. Structure of the Dissertation

The remainder of this dissertation is organized as follows.

- **Chapter 2** reviews the state of the art, summarizing recent research and policy developments on renewable energy and self-consumption in Portugal and Europe.
- **Chapter 3** presents the contextual background, including national energy strategies, regulatory frameworks, and the role of decentralized production through UPACs.

- **Chapter 4** details the methodological approach and data exploration procedures, explaining the datasets, processing steps, and analytical methods applied.
- **Chapter 5** reports the results of the analysis, focusing on temporal trends, regional disparities, and the evolving characteristics of UPAC adoption.
- **Chapter 6** concludes the dissertation by revisiting the research questions, discussing limitations, and outlining directions for future work.

CHAPTER 2

Literature Review

2.1. Background and Scope of the Review

This chapter provides an overview of the existing research on Portugal's energy transition, focusing on renewable energy production, energy imports, and self-consumption. The literature review aims to identify the key influencing factors in Portugal's transition toward sustainability and assess the current state of knowledge, trends, and gaps.

Portugal has made significant strides in adopting green energy, with policies encouraging the expansion of wind, solar, and hydroelectric power. However, challenges remain in grid integration, decentralized energy production, and reliance on energy imports. Understanding these elements through a systematic literature review might help build a comprehensive perspective on the country's energy transition.

2.2. Methodology for the Systematic Review

A systematic review methodology following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework is used to ensure transparency and reproducibility in the selection and analysis of relevant literature. The search strategy involves querying Scopus to extract studies focused on renewable energy production, decarbonization, and energy imports in Portugal.

- Query Used: (TITLE-ABS-KEY(energy AND production AND decarbonization) AND TITLE-ABS-KEY(portugal))
- Inclusion Criteria: Studies published in the last ten years, focused on renewable energy production, geographical energy distribution, and energy imports in Portugal.
- Exclusion Criteria: Studies focusing solely on energy policy or unrelated energy sectors.

Additionally, Scopus AI is employed to analyze the current status and future trends in Portugal's energy transition. The AI-driven query: What is the current state of green energy production in Portugal? is used to gather insights into the latest developments and predictions for Portugal's energy sector.

2.3. Results

The systematic review yielded a total of 22 studies from the Scopus database using the query. Additionally, 7 more results were obtained from Scopus AI, providing insights into the current status and future trends of Portugal's energy transition.

This resulted in an initial dataset of 29 studies. However, after filtering:

- 1 study was identified as duplicate and removed.
- 3 studies were excluded due to lack of access to the full text.
- 5 studies were removed for not being relevant to the literature review.

After applying these filters, the final dataset consisted of 20 studies. To consolidate the main insights from the literature, Table 2.1 summarizes a selection of the most relevant studies addressing Portugals energy transition. These works cover a variety of perspectives, ranging from technical challenges in renewable deployment to infrastructural, policy, and systemic issues. The table highlights both the scope of each contribution and its specific relevance to the broader decarbonization process.

In addition to these research contributions, it is also important to contextualize Portugals energy transition by comparing its current status with its future targets. Table 2.2 provides an overview of key dimensions, including renewable electricity, hydropower and wind, solar energy, and green hydrogen. This complement allows the literature findings to be read alongside Portugals strategic objectives, reinforcing both the achievements already made and the goals that still lie ahead.

2.4. Discussion

This section analyzes the key findings from the literature review, focusing on the main trends shaping Portugal's energy transition.

2.4.1. Production Trends

Portugal has made substantial progress in increasing the share of renewable energy in its electricity mix, with a strong emphasis on solar, wind, and hydroelectric power. The country has set ambitious goals under the National Energy and Climate Plan (NECP), aiming to achieve 80% renewable electricity by 2030 and full decarbonization by 2050 [**Baptista and Vargas, 2020**]. Recent developments in Photovoltaic (PV) energy, green hydrogen production, and offshore wind energy highlight the key production trends shaping Portugal's energy transition.

One of the major trends in renewable energy production is the rapid expansion of photovoltaic solar energy, both on land and in floating installations. The expansion of large-scale solar farms has introduced territorial challenges, particularly regarding land competition and environmental impacts. Studies suggest that site selection for PV plants has prioritized technical and economic factors over sustainability considerations, highlighting the need for improved spatial decision-making tools [**Alves et al., 2023**] Additionally, Floating Photovoltaic (FPV) systems are emerging as a solution to land constraints, integrating solar energy with hydropower facilities to enhance renewable capacity while minimizing land use conflicts [**Baptista and Vargas, 2020**].

Offshore wind energy is another area gaining attention, with Portugal exploring hybrid wind-solar offshore systems to stabilize energy supply. The Western Iberian coast, with its strong wind resources, is considered a promising location for large-scale offshore projects.

Research indicates that integrating offshore solar PV with wind power can mitigate intermittency issues, improving the overall reliability of renewable energy production [**Costoya et al., 2022**].

In addition to expanding renewable electricity generation, Portugal is investing in green hydrogen production as a key component of its energy transition strategy. Hydrogen is being considered both as a fuel for transport and as a means to support energy security. Studies indicate that hydrogen-fueled thermoelectric plants can provide grid stability, particularly in scenarios where solar and wind generation fluctuate. However, different production strategies come with some trade-offs, since hydrogen expansion incurs higher costs, while a more moderate approach could balance affordability with long-term decarbonization goals [**Bairrão et al., 2023**].

At the system level, integrating these new renewable energy sources presents technical and infrastructural challenges. Studies emphasize the need for flexibility measures to ensure energy security, particularly in cases of extreme drought when hydropower generation is significantly reduced. The growing reliance on renewables requires additional investment in grid infrastructure and interconnection capacity to balance production across different energy sources [**Bento et al., 2024**].

Finally, Portugal faces challenges related to interconnection and energy market integration with Spain. With the phase-out of coal-fired power plants, Portugal has increased its reliance on imported energy, particularly during periods of low renewable output. Studies suggest that strengthening cross-border transmission capacity could enhance energy security and mitigate supply risks, especially during extreme weather conditions [**Santos et al., 2023**].

In summary, the primary trends in Portugal's renewable energy production involve the rapid expansion of photovoltaic energy, increasing interest in offshore wind projects, and the integration of green hydrogen as a strategic energy carrier.

2.4.2. Other trends

Beyond the production of renewable energy, Portugal's energy transition is also shaped by key structural and systemic changes that influence the efficiency, security, and resilience of the national energy system. These trends include the need for enhanced grid integration, improved interconnections within the Iberian electricity market, energy storage solutions, and the role of electrification in decarbonization.

One of the main challenges in integrating renewable energy is grid stability and flexibility. The increasing penetration of intermittent energy sources such as wind and solar requires enhanced infrastructure to ensure reliable electricity distribution. Studies indicate that Portugal and Spain face technical and infrastructural constraints in managing high levels of renewable energy integration. The intermittency of solar and wind energy, combined with seasonal hydropower variations, underscores the need for greater flexibility measures to balance the grid. Offshore wind and hydrogen-based storage solutions have been proposed as complementary technologies to improve system resilience [**Bento et al., 2024**].

Interconnections with Spain through the Iberian Electricity Market (MIBEL) also play a crucial role in ensuring energy security. Periods of low renewable generation have increased the importance of electricity imports, highlighting Portugal's dependence on interconnections with Spain. Studies highlight concerns about the current transmission capacity between Portugal and Spain, as energy imports are already operating close to maximum limits during peak demand periods. Strengthening interconnection infrastructure could help stabilize the system, reducing the risk of supply shortages and price volatility in the Iberian market [**Santos et al., 2022**].

Another significant trend is the expansion of energy storage technologies to address fluctuations in renewable production. Studies explore Power-to-Gas (PtG) as a promising solution for storing surplus renewable energy in the form of hydrogen, which can later be used for electricity generation or industrial applications. Portugal has the potential to leverage its growing renewable energy capacity to develop a more flexible grid through PtG and other long-term storage solutions [**Miguel et al., 2018**].

The electrification of transport is also a key factor in Portugal's energy transition, as decarbonization efforts extend beyond electricity generation to include transportation. The adoption of EVs is expected to increase electricity demand, requiring additional renewable capacity and grid reinforcement to accommodate this shift. Studies indicate that while EV adoption aligns with Portugal's carbon neutrality goals, the current pace of deployment may be insufficient to meet 2030 targets. Expanding charging infrastructure and ensuring grid resilience are necessary steps to support transport electrification [**Khatiwada et al., 2022**].

Finally, the economic and policy dimensions of the energy transition remain crucial. While Portugal has ambitious decarbonization goals, studies highlight the financial and regulatory challenges associated with scaling renewable energy and storage projects. The NECP Roadmap 2050 outline key investment areas, but long-term energy planning must balance cost efficiency with environmental sustainability [**Gomes et al., 2023**].

In summary, Portugal's energy transition is not only driven by production capacity expansion but also by the need for robust infrastructure, improved interconnections, energy storage development, and electrification strategies. Addressing these challenges will be essential for ensuring a stable and resilient energy system capable of supporting the country's long-term sustainability goals.

Table 2.1. Relevant Studies for Energy Transition in Portugal

Document	Summary	Key Contribution
[**Alves et al., 2023**]	Location Challenges for Photovoltaic Solar Energy in Portugal	Analyzes land competition and environmental concerns for large-scale PV projects using multi-criteria analysis. Highlights the need for better spatial decision-making in renewable expansion.
[**Baptista and Vargas, 2020**]	Floating Photovoltaic Systems in Portugal	Evaluates the potential of FPV systems to expand solar energy capacity without land constraints. Focuses on their role in grid stability and hybrid hydropower integration.
[**Bento et al., 2024**]	Challenges and Opportunities in Renewable Energy Integration	Discusses technical and infrastructural barriers to large-scale wind and solar energy integration in Portugal and Spain. Suggests offshore wind and hydrogen as complementary solutions.
[**Costoya et al., 2022**]	Offshore Renewable Energy Assessment in Western Iberia	Assesses the viability of offshore wind and solar along the Western Iberian coast, highlighting their potential to mitigate onshore renewable intermittency.
[**Gomes et al., 2023**]	Carbon Neutrality Roadmap 2050 Energy Transition Strategies	Examines Portugal's long-term energy decarbonization plan, with emphasis on renewable electricity expansion and hydrogen utilization in industry and transport.
[**Khatiwada et al., 2022**]	Electrification of the Transport Sector in Portugal	Investigates the impact of Electrical Vehicle (EV) adoption on electricity demand, energy security, and decarbonization goals, aligning with PNEC 2030 targets.
[**Miguel et al., 2018**]	Renewable Energy Expansion and Power-to-Gas Potential in Portugal	Explores the feasibility of Power-to-Gas as a solution for surplus renewable energy storage, emphasizing Portugal's potential for grid flexibility.
[**Santos et al., 2023**]	Impact of Coal Phase-Out and Drought on Portugal's Energy System	Analyzes energy system vulnerabilities following coal decommissioning, focusing on hydroelectric dependency and the role of offshore wind in compensating for drought periods.
[**Santos et al., 2022**]	Energy Market and Transmission Challenges in Portugal and Spain	Examines Portugal's electricity transmission challenges post-coal phase-out, highlighting interconnection constraints with Spain and their impact on grid stability.

Table 2.2. Summary of Current Status and Future Targets for Key Energy Transition Aspects in Portugal

Aspect	Current Status	Future Targets
Electricity from Renewables	53% of electricity consumption from renewables [**Baptista and Vargas, 2020**]	80% by 2030 [**Baptista and Vargas, 2020**]
Hydropower and Wind	Significant contributions to reducing fossil fuel reliance [**Miguel et al., 2018**] [**Nunes, 2018**]	Continued expansion and integration [**Nunes, 2018**]
Solar Energy	Plans for an eightfold increase in capacity by 2030 [**Alves et al., 2023**]	Major focus on photovoltaic systems [**Alves et al., 2023**]
Green Hydrogen	Potential to meet European goals for 2030-2050 [**Bairrão et al., 2023**]	National Hydrogen Strategy implementation [**Cardoso et al., 2021**]

CHAPTER 3

Context

As Portugal undergoes a major transformation in its energy system, understanding the broader context of its transition toward renewable energy is essential. This chapter outlines the national strategies, technologies, infrastructures, and structural challenges that define the country's evolving energy landscape. Particular attention is given to decentralized production models such as UPACs, the role of imported energy, and the indicators that allow for data-driven assessment of progress. The contextual information presented here serves as the foundation for interpreting the empirical results and analyses described in the following chapters.

3.1. The Energy Transition in Portugal

The transition to renewable energy is a cornerstone of Portugal's national decarbonization strategy and reflects a broader global movement toward sustainability. As part of the European Union, Portugal has committed to ambitious climate and energy targets outlined in the NECP and the National Hydrogen Strategy, aiming for 80% of its electricity to be generated from renewable sources by 2030 and full carbon neutrality by 2050 [**IEA, 2025a**].

Over the last decade, the Portuguese energy system has undergone significant transformation. The closure of coal-fired power plants, expansion of solar photovoltaic (PV) and wind capacity, and increased grid interconnection with Spain are all part of this transition. These changes are supported by regulatory measures, financial incentives, and infrastructure modernization. However, challenges remain, including grid flexibility, intermittency of renewable sources, and regional disparities in adoption [**IEA, 2025b**].

In this broader transformation, decentralized energy production has emerged as a crucial component. One of the most widespread mechanisms enabling this shift in Portugal is the adoption of self-consumption production units.

3.2. UPAC – Self-Consumption Production Units

An UPAC (Production Unit for Self-Consumption, originally: Unidade de Produção para Autoconsumo) is a decentralized energy system that enables individuals, businesses, or institutions in Portugal to generate their own electricity for direct use, thereby reducing their dependence on the public grid and lowering energy costs. Although UPACs can be based on different technologies, they are predominantly solar photovoltaic systems, reflecting Portugal's high solar potential and favorable policy framework.

A typical UPAC consists of several key components: photovoltaic panels, which capture solar radiation and convert it into Direct Current (DC) electricity; an inverter, which transforms DC into Alternating Current (AC) suitable for immediate use in households or businesses; protection equipment to ensure system safety; and energy meters, which register the electricity produced and consumed. In some cases, battery storage may be added to accumulate surplus energy for later use, increasing self-sufficiency and reducing reliance on the grid during periods of low solar generation.

The operation of UPACs can follow different configurations. In grid-connected systems, electricity produced on-site is consumed directly, while any surplus not used instantaneously can either be injected into the grid or, depending on the contractual arrangement, sold or offset against future consumption. In off-grid systems the surplus production must be stored in batteries for later consumption, as there is no connection to the public grid [**ADENE, 2025a**].

UPACs provide several benefits to their users and to the energy system as a whole. For self-consumers, they allow a reduction in electricity bills, increase energy independence, and contribute to environmental sustainability by lowering greenhouse gas emissions. At the system level, they can reduce load during daylight hours and inject clean energy into the grid, supporting decarbonization targets.

In Portugal, legislation distinguishes between different types of self-consumers. Individual self-consumers are those who own and operate a UPAC for their own consumption, typically in residential contexts. Collective self-consumers, on the other hand, are groups of individuals or entities – such as residents of a condominium – that share a single production unit and distribute the generated electricity among themselves. This legal framework enables wider participation in decentralized renewable generation and encourages collaborative models of energy sharing [**ADENE, 2025b**].

3.3. The Role of UPACs in the National Grid

Portugal's electricity grid is part of the MIBEL, which facilitates cross-border energy exchange with Spain. As the number of UPACs increases, the grid must adapt to a new paradigm of bidirectional energy flows. Traditionally designed for centralized generation, the grid is now facing operational changes due to decentralized and intermittent production.

Key challenges include:

- Managing local voltage stability and load balancing;
- Absorbing surplus energy injected into the grid during peak solar hours;
- Ensuring reliability and resilience, particularly in rural or underdeveloped areas.

These developments require upgrades to grid infrastructure and smarter control systems to maintain stability. The role of UPACs in reducing load on the grid during the day is generally positive, but their collective effect must be carefully monitored and integrated.

3.4. Imported Energy: Dependency and Implications

Although Portugal has increased its domestic renewable production, it continues to import electricity, especially during periods of low generation (e.g., droughts affecting hydropower or low wind conditions). Imports are often used to stabilize the grid, particularly in winter or high-demand periods.

This reliance introduces two concerns:

(1) Energy security – Over-dependence on external suppliers may expose the country to geopolitical and market volatility. [**International Energy Agency (IEA), 2025**]
(2) Decarbonization consistency – Imported energy is not always from renewable sources, potentially undermining national emissions targets. [**IEA, 2021**]

3.5. Key Indicators for Analysis

This thesis relies on several quantitative indicators to assess the progress and characteristics of the energy transition in Portugal:

- Number of UPACs installations per quarter and per municipality
- Installed power per UPAC and categorized by power class;
- Electricity consumption data
- Energy injected into the grid

3.6. The Role of Public Incentives in the Energy Transition

Public incentive programs have been a central tool in Portugal's strategy to accelerate renewable energy adoption, especially among households and small businesses. The Fundo Ambiental [**Fundo Ambiental, 2025**], managed by the Ministry of Environment and Climate Action, has offered financial support for energy efficiency improvements, including photovoltaic systems for self-consumption. In recent editions, the program covered up to 85% of the investment cost, up to 7,500 per household, for systems with or without storage.

These programs are designed to reduce the financial barrier to entry for renewable technologies and to promote distributed energy generation. Funding is typically allocated through application rounds with defined eligibility criteria, which can include technical specifications, installation deadlines, and budget ceilings. The initiatives are aligned with national energy and climate goals and are often adjusted based on budget availability and political priorities.

Although the effectiveness of such programs is an area of ongoing evaluation, they are generally seen as important enablers of early adoption, particularly in the residential segment. Nevertheless, public incentives are often limited in scope and duration, raising concerns about the long-term sustainability of adoption patterns and the risk of regional disparities in uptake. [**Qadir et al., 2021**]

3.7. Grid Infrastructure and Limitations

Portugal's electricity grid, traditionally designed for centralized generation, is adapting to the challenges posed by increasing levels of decentralized energy production, including self-consumption units [**IEA, 2025a**]. As part of the Iberian interconnected system, Portugal's grid must accommodate both large-scale renewable energy plants and smaller distributed producers.

The integration of distributed generation introduces bidirectional power flows, requiring upgrades in voltage regulation, transformer capacity, and system monitoring. In particular, low-voltage distribution networks in older or rural areas may be more susceptible to technical constraints, such as voltage deviations or saturation of transformer capacity. Additionally, smart grid technologies, are being deployed to improve observability and flexibility [**E-REDES, 2025c**].

E-REDES, the distribution system operator, provides public information on grid reception capacity by substation, which helps indicate where new self-consumption units can be more easily integrated.

Even with these improvements, the grid still faces operational and infrastructural challenges in supporting a high volume of small producers. These challenges are widely recognized in literature as key technical limitations in scaling decentralized renewable energy systems.

3.8. Technical and Economic Barriers to Self-Consumption Expansion

The expansion of Self-Consumption systems across Portugal is subject to a variety of barriers that affect both individual decision-making and broader policy implementation. These barriers are often economic, technical, or regulatory in nature [**ERSE, 2025a**].

Economically, the upfront cost of installing a photovoltaic system can be significant, even when partially offset by incentives. Some consumers may lack access to financing or may be unaware of the long-term cost savings associated with self-consumption. Additionally, incentive programs typically require pre-financing, which can exclude lower-income households from participating [**ERSE, 2025a**].

Technically, not all buildings are equally suitable for solar installations. Variables such as roof orientation, shading, structural condition, and shared ownership structures in multi-family buildings can complicate installation or reduce efficiency. In rural or remote areas, limited access to qualified installers or technical support services can also delay or prevent adoption [**ADENE, 2024**].

From a regulatory perspective, although recent reforms have simplified the legal process for UPAC registration and grid connection, administrative procedures can still pose difficulties, especially for non-specialist users [**ADENE, 2024**].

These barriers are the subject of ongoing discussion in Portuguese and European policy circles, as they influence the equitable expansion of renewable energy and the achievement of national decarbonization targets.

CHAPTER 4

Exploration Data Analysis

This chapter outlines the methodological approach used to investigate the evolution of renewable energy adoption in Portugal, with a particular emphasis on UPACs. The study employs a data-driven strategy, combining descriptive statistics, temporal analysis, and geographic comparisons to identify patterns in energy production, adoption trends, and the broader implications for the national grid.

The methodology is structured around four main stages: data collection, data preprocessing, quantitative analysis, and synthesis of insights. All steps were designed to be reproducible using publicly available data sources.

This dissertation adopts an exploratory and data-driven approach. The datasets used were not collected directly but obtained from E-REDES and other official institutions through their open data platforms. The focus of the work is therefore on processing, cleaning, and structuring these datasets, followed by statistical analysis, comparison, and visualization to highlight relevant trends. Rather than developing predictive models or controlled experiments, the study emphasizes descriptive exploration and graphical representation, which are appropriate to the scope of a Master's degree in computer engineering.

This methodological choice also reflects the characteristics of the available data, which is heterogeneous, incomplete, and often limited in granularity. The emphasis is therefore placed on extracting insights through reproducible analysis, providing a basis for further research and potential policy evaluation.

4.1. Objectives of the Experiments

The experiments aim to:

- Analyze the temporal evolution and adoption of UPACs in Portugal;
- Identify regional disparities in self-consumption;
- Examine how the growth of decentralized energy production relates to national electricity consumption;
- Identify factors that may influence adoption patterns, including solar radiation, demographic characteristics, and public incentives.
- Estimate the potential energy production of UPACs based on installed capacity.

4.2. Data Sources

This study relies on official, publicly available datasets from national and European institutions. These sources provide the basis for the quantitative analyses of UPAC adoption, electricity consumption, demographic normalization, and geographic representation. All datasets were accessed between April and June 2025 and exported primarily in .csv, .parquet, and .xlsx formats. Before analysis, the datasets were cleaned, harmonized, and reformatted to ensure compatibility across sources.

- E-REDES Open Data Platform – E-REDES, the Portuguese electricity distribution system operator, provides detailed datasets on electricity consumption and decentralized production. The following datasets were used:
  - *New production units for self-consumption* and *Total production units for self-consumption*, which provide the number of UPACs installed by municipality and quarter. These datasets were essential to track temporal adoption and regional disparities.
  - *Total national consumption* and *Monthly consumption by municipality*, which detail electricity demand patterns at both national and local levels. These datasets supported the comparison between consumption trends and the growth of self-consumption.

    Preparation involved aggregating the quarterly records, handling missing values, and aligning municipal identifiers with other sources.
- AMA (Agência para a Modernização Administrativa) – Geographic delimitation data was obtained through shapefiles of Portuguese parishes. These files were used to produce thematic maps of UPAC adoption. Preparation steps included converting shapefiles into GeoDataFrames and ensuring consistency with municipal codes from other datasets.
- Eurostat – European statistical datasets were used to provide a standardized geographic and statistical framework.
  - The shapefiles for NUTS territorial units and the correspondence tables for NUTS classification levels allowed for analyses and visualizations at regional and supra-municipal levels.

    These files were harmonized with AMA geographic data to ensure spatial consistency.
- INE (Instituto Nacional de Estatística) – Demographic data from the Portuguese National Statistics Institute was used to normalize UPAC adoption across municipalities.
  - Specifically, the dataset Resident population (No.) by place of residence at the time of the Census [2021] was employed to compute indicators such as UPACs per 1,000 inhabitants.

    Data preparation involved extracting population values by municipality and merging them with E-REDES installation data.
- IPMA (Instituto Português do Mar e da Atmosfera) – Solar radiation datasets were used as a proxy for estimating potential production from UPACs, since the majority of installations rely on photovoltaic technology. These datasets provide long-term average values of solar irradiance across Portugal. The information was

employed to compare regional solar potential with observed installation patterns, and to approximate possible electricity output.

4.3. Procedures and Experiments

The analytical workflow adopted in this study was designed to systematically explore the available datasets and extract insights into the evolution of decentralized energy production in Portugal. The procedures followed can be summarized in four main stages:

(1) Data Preprocessing and Cleaning [**Valadares, 2025**]
- Raw datasets from E-REDES, INE, AMA, Eurostat, and IPMA were imported in various formats (.csv, .xlsx, .parquet, and shapefiles).
- Missing or inconsistent records (e.g., municipalities with incomplete quarterly data) were identified and handled through imputation, aggregation, or removal, depending on their relevance.
- Temporal coverage was harmonized by aggregating monthly records into quarterly intervals to align with the reporting frequency of UPAC adoption.
- Geographic identifiers (municipality and parish codes) were standardized across datasets to ensure accurate joins.

(2) Descriptive and Temporal Analysis
- The evolution of UPAC installations and installed capacity was examined over time, using line graphs and quarterly variation rates to highlight periods of acceleration or slowdown.
- Growth patterns were compared with national electricity consumption trends, in order to explore whether decentralized generation had any visible relationship with overall demand.
- Temporal fluctuations in both the number of installations and the installed capacity were contrasted, enabling identification of structural changes such as the emergence of larger-scale systems.

(3) Geographic and Demographic Exploration
- Installation data was combined with AMA and Eurostat shapefiles to generate thematic maps of UPAC adoption across municipalities and districts.
- By integrating INE population statistics, adoption was normalized per 1,000 inhabitants, allowing fairer comparisons between densely populated urban areas and smaller municipalities.
- Geographic analyses highlighted spatial disparities, showing both concentrations of adoption and the gradual reduction of municipalities without any UPAC presence.

(4) Estimation of Production Potential
- Since direct production data for UPACs is not publicly available, solar radiation datasets from IPMA were employed as a proxy for estimating potential generation.

- Average irradiance values were aggregated at the municipal level and compared against installed capacity, providing an approximation of regional production potential.
- This analysis enabled the exploration of whether regions with higher solar potential also exhibited higher adoption rates, and whether the installed capacity was consistent with resource availability.

All procedures were carried out using reproducible data analysis workflows in Python, with libraries such as pandas and geopandas for data handling, matplotlib for visualization, and shapely for spatial operations.

4.4. Limitations and Difficulties

Several limitations affect the precision and scope of the analysis:

- There is no access to measured production data for UPACs, so energy estimates rely on irradiance assumptions and average performance ratios;
- Financial incentive data is available at national level but not linked to specific installations, preventing causal attribution;
- Installation and consumption data are available at the municipal level, but infrastructure and grid data are not available, so no analysis can be performed in that regard.
- The temporal scope of the available data (2022–2025) constrains the ability to assess long-term trends or pre-incentive baselines.
- As the work is exploratory and descriptive, results should be interpreted as indicative rather than causal; correlations observed between UPAC growth, consumption, and solar potential do not imply direct causality.

4.5. Code Availability

The code and reproducible materials for the analyses presented in this chapter are publicly available in the project repository:

`https://github.com/MLValadares/portugal-energy-analysis`

The repository contains the scripts and resources necessary to reproduce data processing, statistical analyses, geospatial visualizations, and the figures reported in this thesis. Key contents include:

- Jupyter notebooks and Python scripts used for data cleaning, analysis, and visualization.
- Data processing pipelines and intermediate data.
- Scripts to reproduce figures included in this document.
- Documentation (README) with usage notes and a short guide to reproduce the main results.

CHAPTER 5

Results

This chapter presents the main results of the exploratory analysis. It examines the evolution of UPAC installations and capacity over time, their as geographic distribution, adoption relative to population, and potential production based on solar radiation. The findings are shown through descriptive statistics and visualizations that highlight key trends and regional differences.

5.1. Temporal Evolution of UPACs Installations

The number of UPAC installations exhibits visible growth between 2022 and 2025. As shown in Figure 5.1, there is a noticeable increase in quarterly installations beginning in 2022, with a marked rise through 2023. Some fluctuations are visible between quarters, with periods of acceleration followed by slower growth.

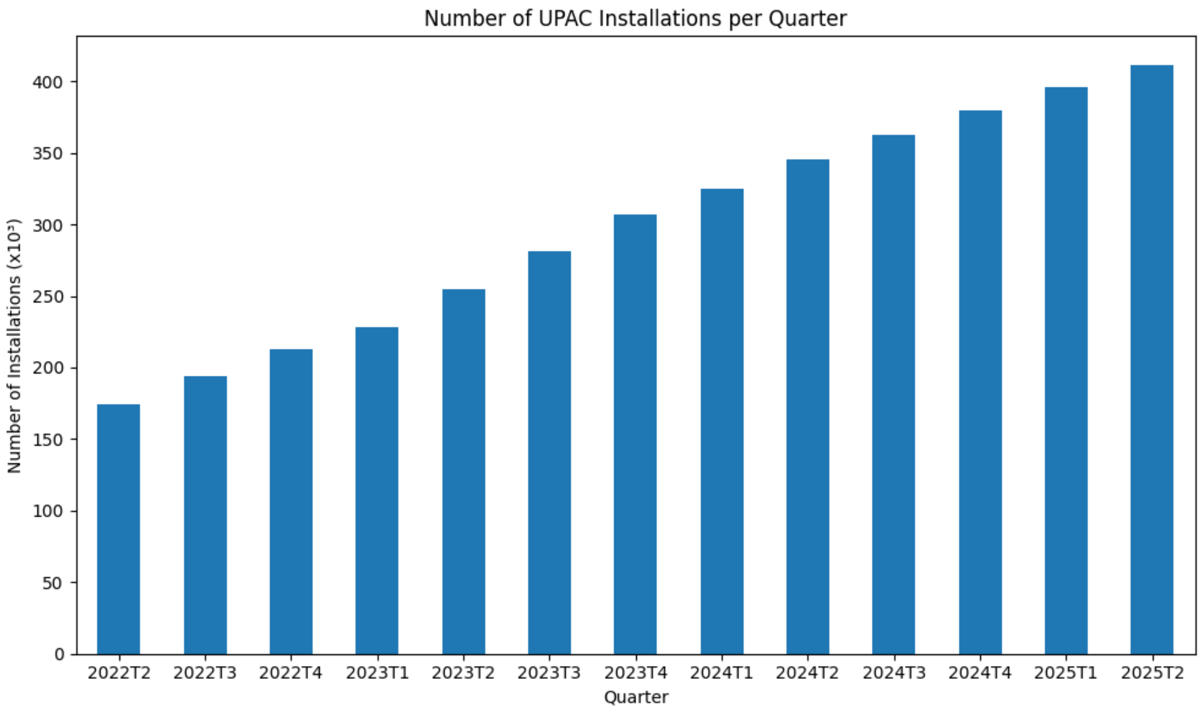

FIGURE 5.1. Number of UPAC Installations per Quarter

In terms of power classes (Figure 5.2), the majority of installations fall within the]0, 4] kW range, reflecting the predominance of small-scale residential systems. Other ranges, such as]4, 20.7] kW and]30, 1000] kW, are present but represent a much smaller share of total installations. Nevertheless, these categories show a gradual increase over time, particularly from 2023 onwards, signaling a diversification of system sizes. By contrast, power classes above 1000 kW are almost nonexistent, indicating that very large-scale self-consumption projects remain marginal in the Portuguese context.

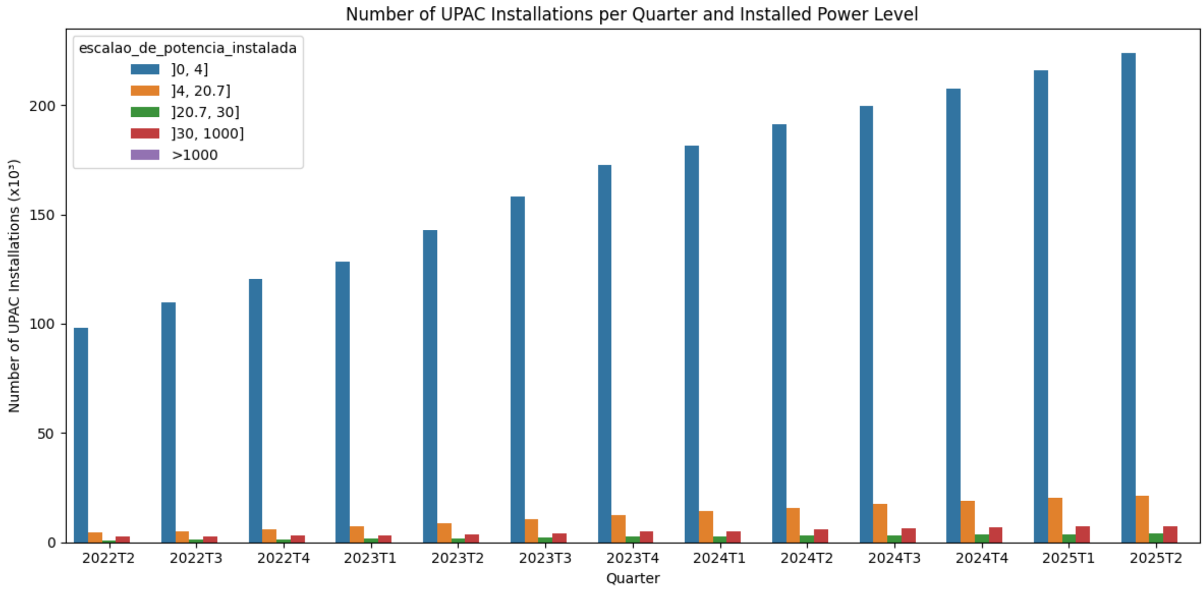

FIGURE 5.2. Number of UPAC Installations per Quarter and Installed Power Level

5.2. Installed Capacity Growth

Figure 5.3 displays the evolution of total installed capacity over time. Alongside the increasing number of installations, there is also a steady upward trend in total installed power. The data shows that capacity accumulates progressively, and the slope of the curve varies slightly across quarters.

It is also observable that some periods of high installation growth coincide with sharper increases in capacity, while others show more modest gains. This may reflect differences in the average size of installed systems across quarters.

Disaggregating capacity by power class (Figure 5.4) reveals that the bulk of installed power originates from the]30, 1000] kW range, which contributes disproportionately to total capacity, despite representing a smaller number of installations. The]0, 4] kW class, while dominant in terms of the number of installations, accounts for a much smaller share of total capacity. This contrast highlights a dual dynamic: on the one hand, widespread adoption of small-scale residential systems; on the other, the significant contribution of medium-scale projects to the overall expansion of installed power.

5.3. Geographic Penetration of UPAC

The spatial distribution of UPAC installations reveals both an increase in the absolute number of units and a gradual reduction of areas without any recorded adoption. As illustrated in Figure 5.5, the initial register (Q2 2022) shows several municipalities and parishes with no installations, visible as blank or holes in the map. These areas reflect

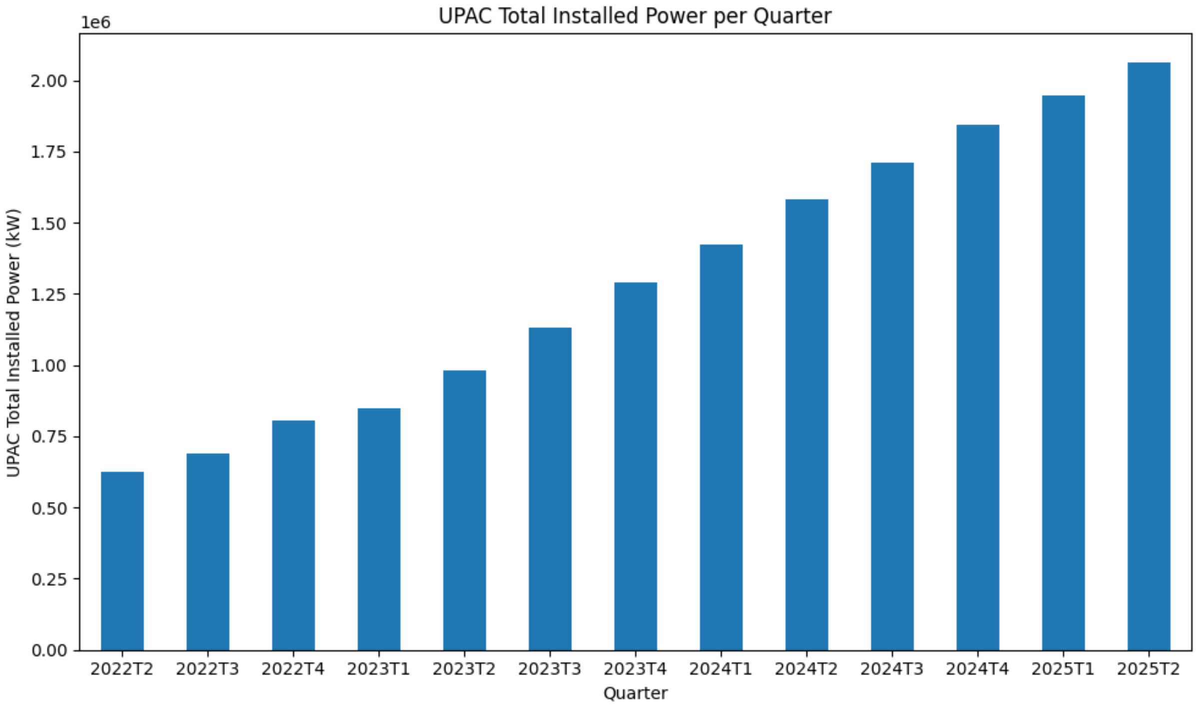

FIGURE 5.3. UPAC Total Installed Power per Quarter

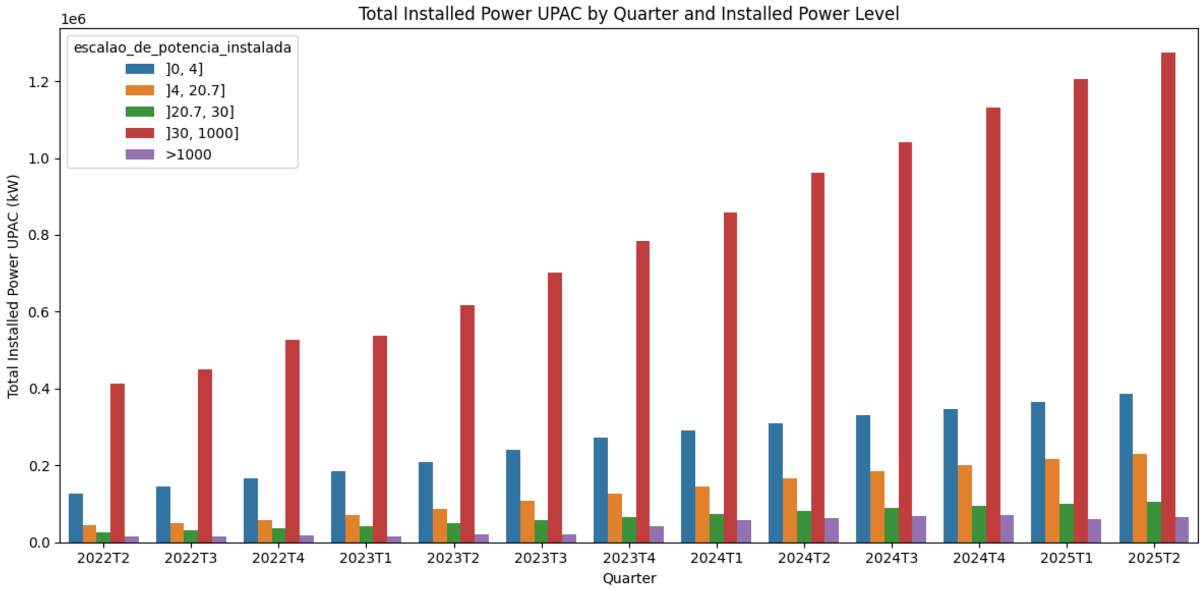

FIGURE 5.4. UPAC Total Installed Power per Quarter and Installed Power Level

the early stage of adoption, when UPAC penetration was highly uneven and concentrated in specific regions, particularly in the south of the country.

By contrast, in the later period (Q2 2025), not only do the regions with existing installations show significantly higher values, but the number of parishes with zero installations has markedly decreased. This suggests a broader territorial diffusion of self-consumption

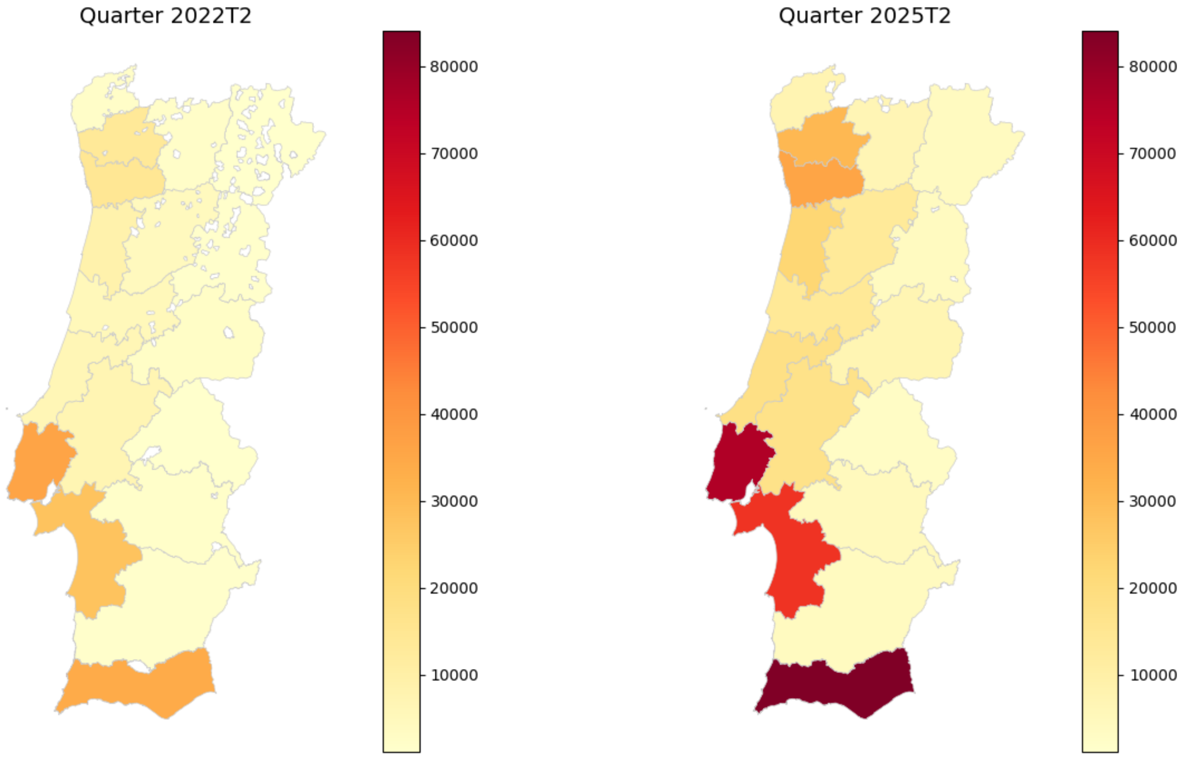

FIGURE 5.5. Spatial distribution of UPAC installations across Portugal

systems, with UPAC reaching areas that initially showed no adoption. The maps therefore highlight both the intensification of installations in already active regions and the gradual filling of previously empty areas, contributing to a more homogeneous national coverage.

5.4. Temporal Dynamics of UPAC Deployment

The temporal evolution of UPAC deployment can also be examined through two complementary indicators: the total connection power of newly completed units and the number of processes concluded. Both are aggregated at the municipal level and observed with monthly granularity.

As illustrated in Figure 5.6, the total connection power of completed UPACs displays a fluctuating yet overall upward trajectory between 2021 and early 2025. Peaks are particularly visible in the first semester of 2024, when the aggregated connection power surpassed 180,000 kW, reflecting a wave of medium- to large-scale projects being finalized during that period. Conversely, semesters such as the second half of 2023 and the beginning of 2025 show comparatively lower totals, indicating potential slowdowns in project approvals or implementation bottlenecks. Despite these oscillations, the general trend highlights a substantial reinforcement of installed capacity, pointing to the growing impact of UPACs on national electricity production.

Figure 5.7 complements this perspective by focusing on the number of completed processes, regardless of installed capacity. Here, the dynamics differ: the peak is reached

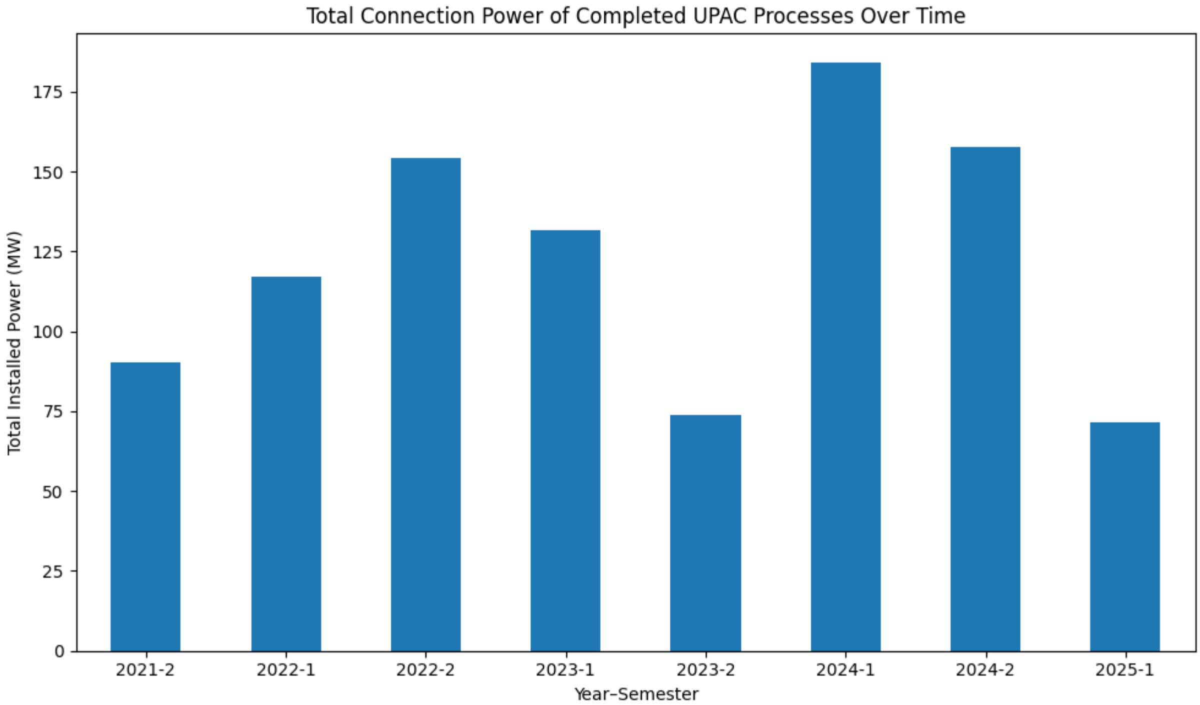

FIGURE 5.6. Total Connection Power of Completed UPAC Processes over Time

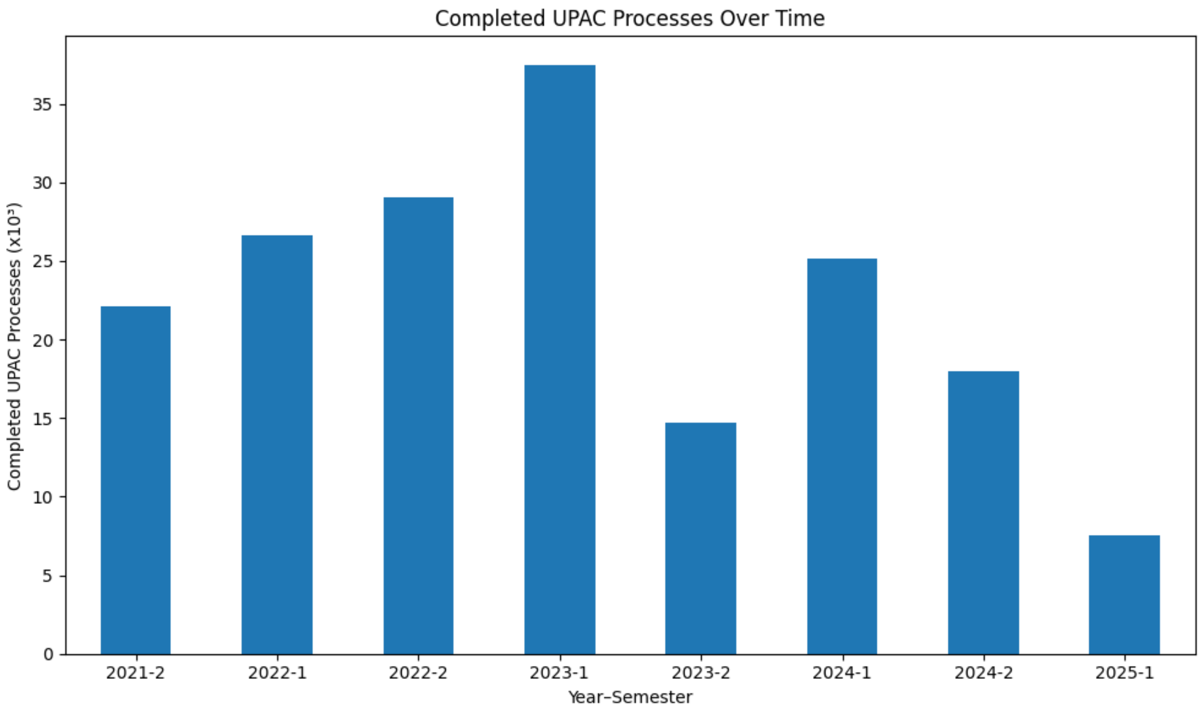

FIGURE 5.7. Completed UPAC Processes over Time

earlier, in the first semester of 2023, with nearly 38,000 processes concluded. This suggests that while many small-scale units were connected during this period, the following semesters saw fewer but often more powerful installations, explaining the divergence with the connection power trend. One possible factor behind this surge in 2023 is the availability of public incentives, particularly the "Programa de Apoio a Edifícios Mais Sustentáveis (PAE+S)", funded by the Fundo Ambiental, which had calls for applications open during this period and closed in October 2023 [**Fundo Ambiental, 2023**]. These incentives were primarily directed at small-scale residential systems, helping explain the concentration of installations in that timeframe. Conversely, the decline observed in Q2 2024 and Q1 2025 in process counts, together with relatively high power values in 2024, reinforces the interpretation that the UPAC market is evolving from being dominated by numerous small systems to gradually including larger-scale connections, a shift that also aligns with the reduction of subsidies for small-scale units.

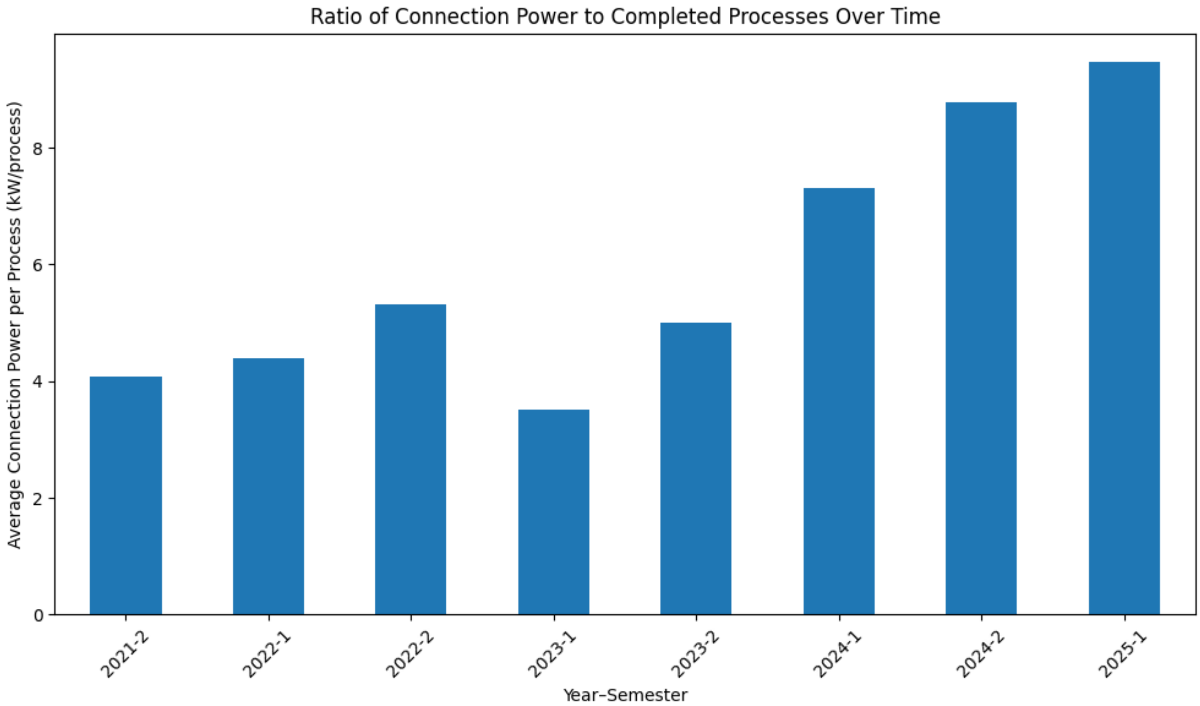

FIGURE 5.8. Ratio of Connection Power to Completed Processes over Time

This interpretation is further strengthened by Figure 5.8, which plots the ratio between total connection power and the number of concluded processes. The indicator remained relatively stable and moderate until 2023, fluctuating between 3 and 5 kW per process. However, from 2024 onwards it increased sharply, reaching almost 10 kW per process by the first semester of 2025 (2025-1). This shift highlights a structural change: new installations are on average becoming more powerful, suggesting that medium- and large-scale systems are gaining ground within the national portfolio of UPACs.

Taken together, these graphs reveal that UPAC expansion is not only growing in absolute terms but also transforming in structure: from an initial phase of mass small-scale adoption to a more balanced scenario where fewer but higher-capacity projects increasingly shape the overall capacity trajectory. This dual dynamic confirms both the widespread diffusion of self-consumption at the household level and the growing importance of larger systems for meeting renewable energy targets.

5.5. Regional Dynamics of UPAC Adoption

In addition to national-level trends, the quarterly maps of UPAC adoption reveal important differences across districts. Figures A.1 and A.2 present the evolution of, respectively, the number of UPAC installations and the total installed capacity between Q2 2022 and Q2 2025.

The first set of maps (Figure A.1) shows a gradual intensification of installations throughout the country. Initially, adoption was highly concentrated in southern districts such as Faro, Beja, and Évora, where both solar potential and early engagement were strongest. Over time, more northern districts also began registering higher numbers of installations, reducing the number of areas with little or no activity. By the end of 2024, the maps indicate a more widespread penetration, though still with significant regional variation.

The second set of maps (Figure A.2), which display total installed power, highlights a somewhat different dynamic. While southern districts remain prominent, particularly Faro and Setúbal, other areas such as Lisbon and Porto show higher increases in installed capacity despite comparatively lower installation counts. This suggests that in these districts, UPAC growth has been driven not only by numerous small-scale systems but also by the connection of larger units.

Taken together, these results emphasize that the regional expansion of UPACs is characterized by two parallel processes: a diffusion of installations into previously underrepresented districts, and a consolidation of capacity in certain areas through medium and large-scale projects.

5.6. Variation of UPACs

An important dimension of the energy transition in Portugal is the regional distribution of new UPAC installations and their associated capacity. To capture this, the analysis presents complementary perspectives on quarterly percentage changes in both installed power and the number of installations across districts, each benchmarked against the national average. This dual view helps distinguish between structural growth driven by large projects and widespread adoption resulting from smaller, distributed systems.

The first graph, Figure 5.9, highlights quarterly changes in installed capacity by district. While the national average exhibits moderate growth rates, generally ranging between 5% and 20%, certain districts display significant volatility, with isolated quarters showing sharp spikes or drops. For example, some districts experienced surges above 80–100% growth in specific quarters, suggesting the commissioning of large-scale projects or the completion of clusters of medium-sized installations. Conversely, abrupt declines, such as those observed in 2024T2, may reflect project delays, grid connection constraints, or administrative bottlenecks. These fluctuations indicate that, although national growth

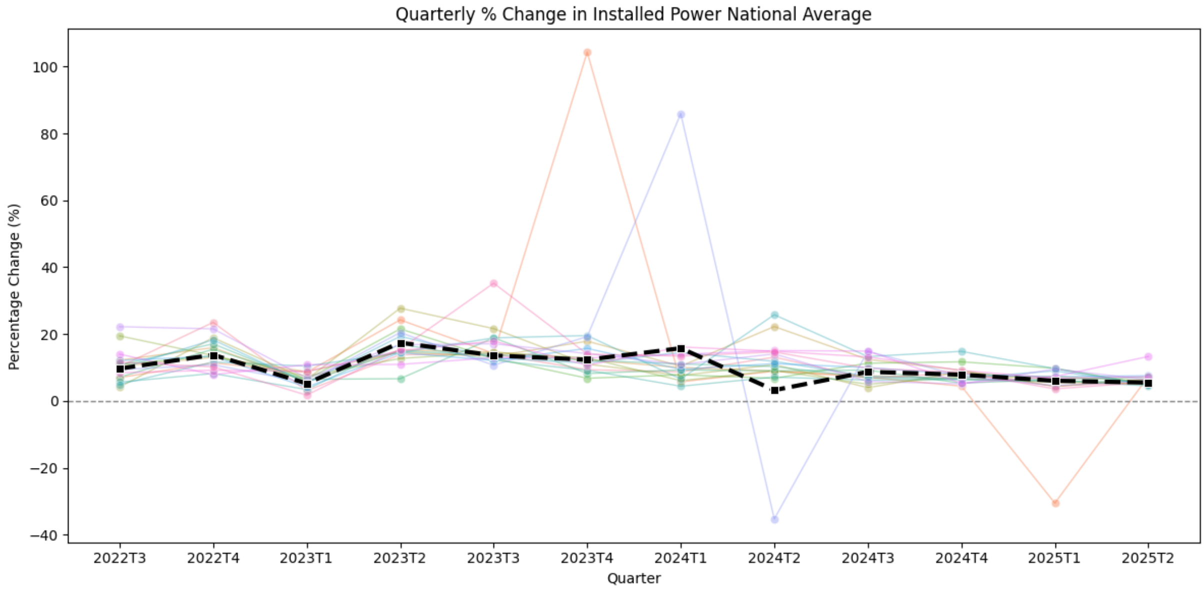

FIGURE 5.9. Quarterly Change in Installed Power National Average

appears relatively stable, local dynamics can be highly uneven, shaped by both structural and circumstantial factors.

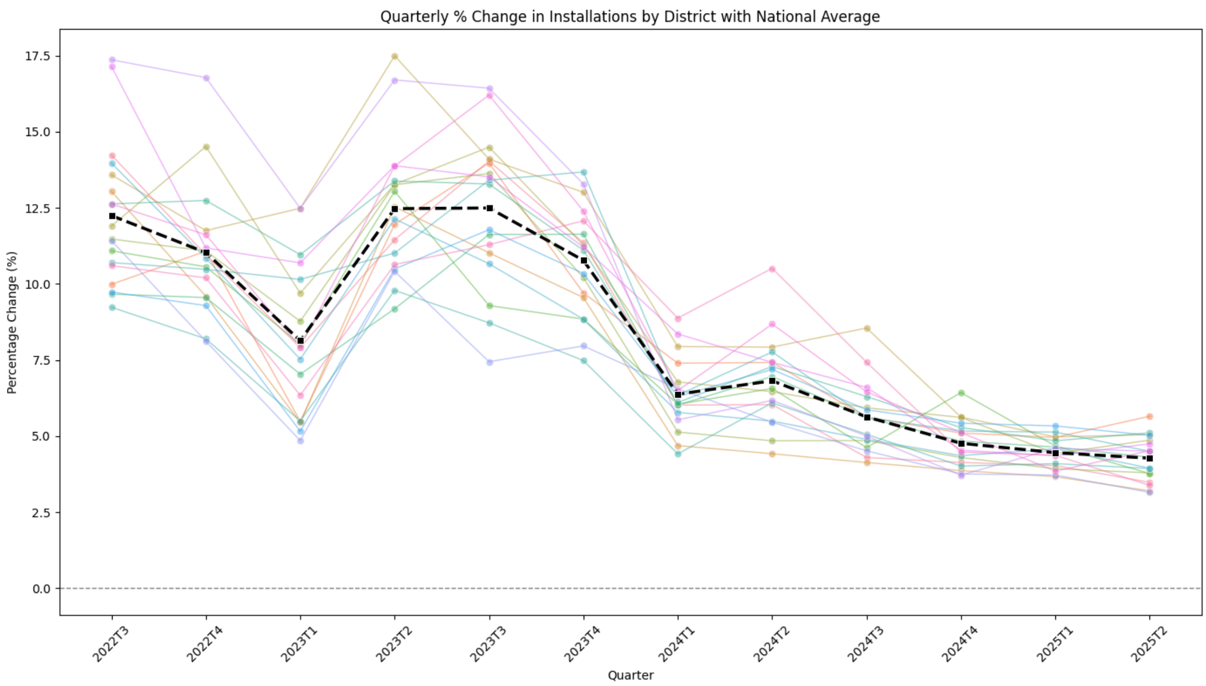

FIGURE 5.10. Quarterly Change in Installations by District with National Average

The second graph, Figure 5.10, focusing on the number of installations, portrays a smoother and more homogeneous pattern across districts. Most regions follow the national trajectory, which peaked around 2022–2023 with growth rates exceeding 10% per quarter, before gradually stabilizing below 5% by 2024. This reflects a broad diffusion of small-scale self-consumption systems, where individual households and small businesses drive steady increases in adoption. Compared to installed power, the variation in the number of installations shows fewer extreme outliers, underscoring that capacity growth is more susceptible to large, isolated projects, whereas installation growth reflects a mass adoption trend.

5.7. Distribution of UPAC Installations by Technology

This section examines the quarterly evolution of UPAC installations broken down by technology type. While installed capacity reflects the scale of generation, the count of installations provides complementary insight into how different renewable technologies are being adopted over time.

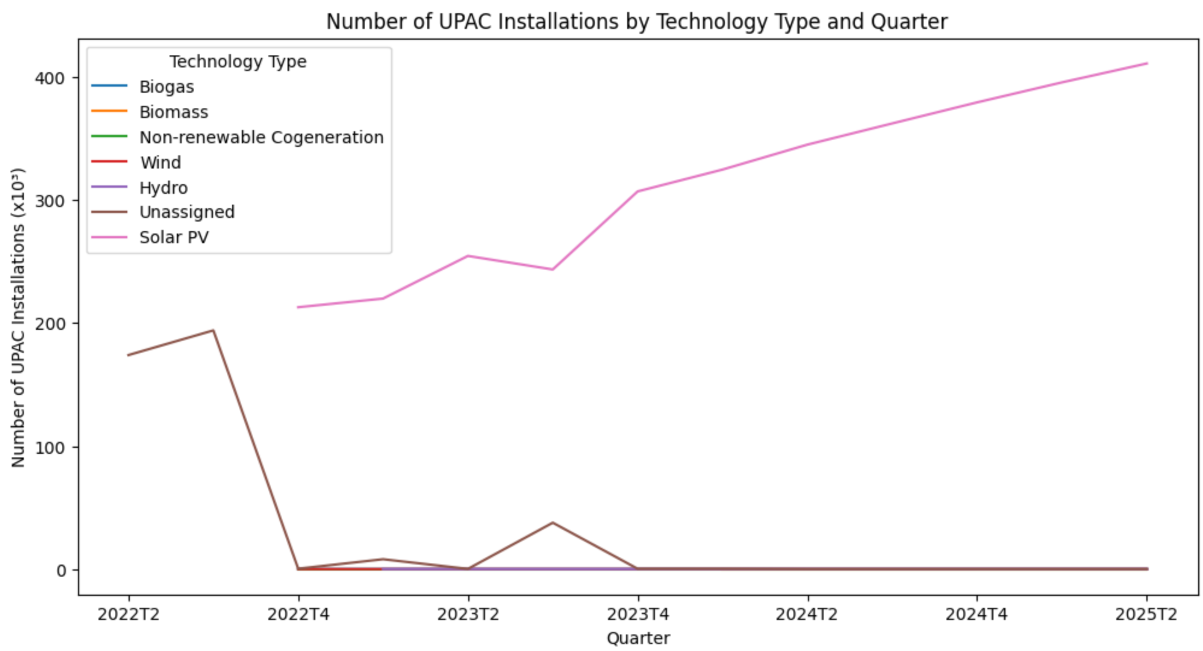

FIGURE 5.11. Active Energy Consumption by Voltage Level

The results show that solar technology dominates overwhelmingly, consistent with Portugal's climatic conditions and the economic competitiveness of photovoltaic systems. Other technologies such as biomass, biogas, cogeneration, wind, and hydro appear only sporadically and represent a negligible share of total installations. Their limited presence highlights that UPACs in practice function almost exclusively as a mechanism for distributed solar self-consumption.

This confirms that both market incentives and policy frameworks are strongly aligned toward solar deployment, reinforcing its central role in Portugal's decentralized energy transition.

5.8. UPAC Adoption Normalized by Population

To account for demographic differences across districts, Figures A.3 and A.4 present the evolution of UPAC adoption normalized by resident population. The first map series (Figure A.3) illustrates the number of UPAC installations per population by district and quarter, while the second series (Figure A.4) shows the percentage of total installed power per population by district and quarter.

When normalized by population, the results reveal patterns distinct from those observed in absolute terms. As shown in Figure A.3, the districts with the highest relative number of installations are not the large metropolitan areas such as Lisbon or Porto, but rather smaller and less densely populated northern regions, including Viana do Castelo, Braga, and Vila Real. These districts consistently register higher per-capita installation ratios, indicating that households in these areas are proportionally making greater use of self-consumption systems. This contrast suggests that rural and semi-rural areas, despite their smaller populations, are leading in relative adoption of UPACs.

In terms of installed power per population (Figure A.4), the distribution highlights the growing role of Beja, where the ratio of installed capacity per resident shows a marked increase over the study period. While other districts also demonstrate steady growth, Beja's trajectory is particularly prominent, suggesting the deployment of larger-scale systems in proportion to its population base. This indicates that beyond household-level installations, medium- and large-capacity projects are contributing significantly to the district's per-capita figures.

Taken together, these normalized indicators demonstrate that UPAC adoption in Portugal is not only a phenomenon of scale concentrated in urban areas, but also one of relative intensity in rural districts. While cities account for larger absolute numbers, smaller districts show greater proportional engagement, reinforcing the importance of considering demographic normalization when assessing the national diffusion of self-consumption.

5.9. Patterns of Electricity Consumption

In addition to production dynamics, it is important to assess the evolution of electricity consumption across different consumer categories. Figure 5.12 presents the daily active energy consumption disaggregated by voltage level, distinguishing between low-voltage demand – associated with residential and small commercial consumers – and medium to very high-voltage demand, which corresponds mainly to industrial and large commercial users.

The series reveals two distinct patterns. Consumption at low voltage exhibits stronger variability and pronounced peaks, particularly visible in early 2021, early 2023, and early 2025. These peaks are likely linked to seasonal effects, such as increased heating and cooling needs, which disproportionately affect residential and small commercial consumers. Despite fluctuations, there is a noticeable upward tendency, with recent values surpassing 2.3 billion kWh, suggesting sustained growth in household and small-scale electricity demand.

By contrast, consumption at medium to very high voltages is more stable, oscillating around 1.92.1 billion kWh. This reflects the steadier nature of industrial and commercial demand, which is less subject to short-term climatic variations and more influenced by structural economic activity. The relative flatness of this curve suggests that industrial

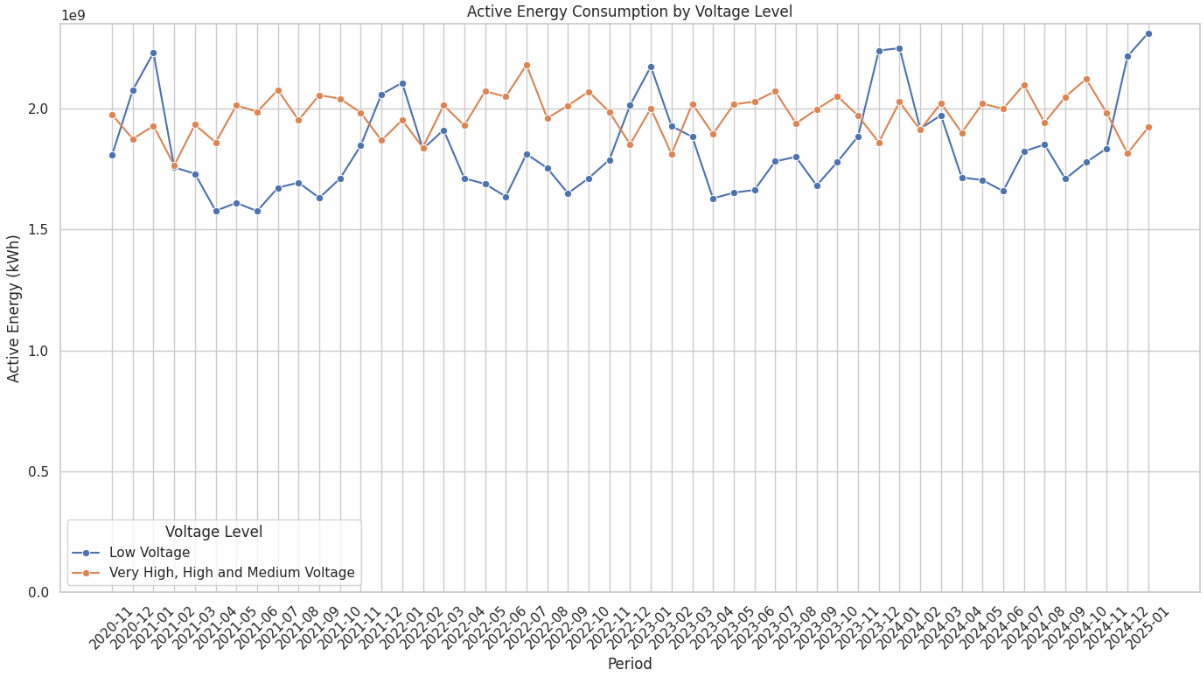

FIGURE 5.12. Active Energy Consumption by Voltage Level

demand has remained stable, with limited expansion compared to the residential and small commercial sector.

Overall, the comparison highlights an important shift in the Portuguese electricity system: while industrial demand remains a backbone of consumption, the growing importance of low-voltage demand underscores the rising role of households and small businesses in driving national electricity usage. This reinforces the significance of policies directed at residential energy efficiency and the integration of self-consumption solutions at the low-voltage level, which directly interact with the patterns observed in UPAC deployment.

Beyond long-term trends, electricity consumption also follows recurring intra-week patterns, reflecting differences between working days and weekends. Figure 5.13 presents the average hourly consumption across weekdays, offering a clearer view of how demand evolves within a typical week.

The heatmap reveals three key aspects:

- Working days (Monday–Friday):
  - Demand begins rising sharply around 07:00–08:00, aligned with morning residential activity and the start of the workday.
  - Consumption then stabilizes at elevated levels throughout the afternoon.
  - The most pronounced peak consistently occurs between 18:00 and 21:00, driven by residential usage during evening hours, when households return home and industrial/commercial activity is still ongoing.
- Weekends (Saturday–Sunday):
  - The morning ramp-up is delayed, beginning closer to 09:00–10:00, consistent with later household activity.

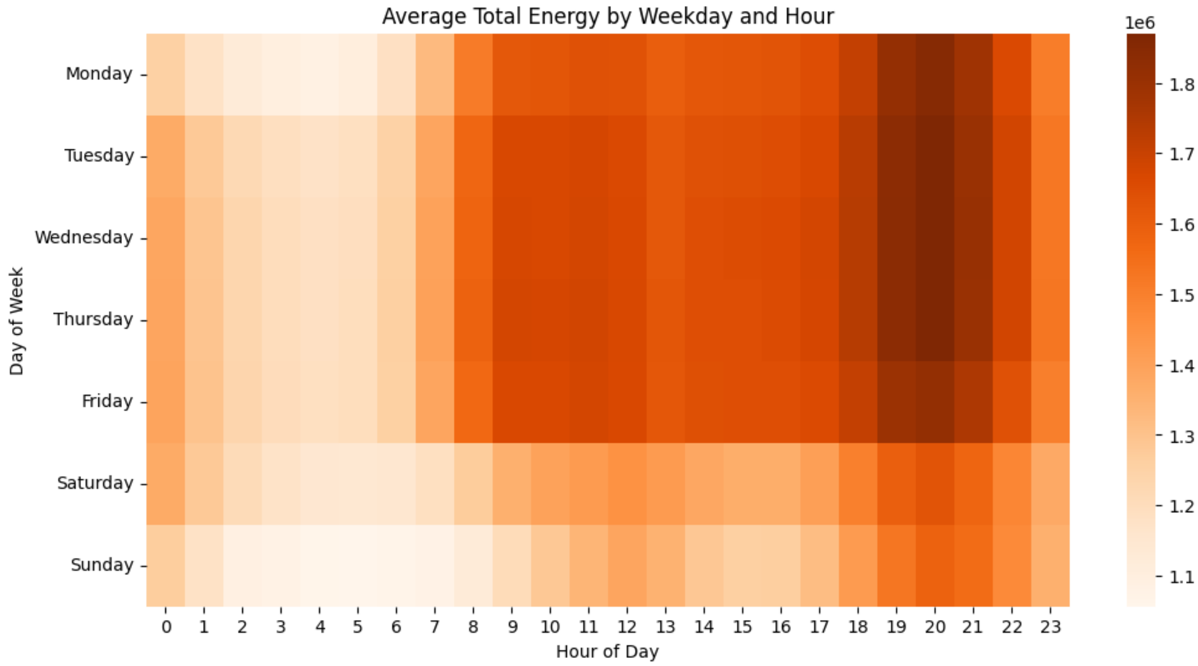

FIGURE 5.13. Average Active Energy Consumption by Weekday and Hour

  – Evening peaks remain visible but are less intense, reflecting reduced industrial/commercial demand and more residentially driven load.

- System-wide implications:
  – The persistence of strong evening peaks highlights the structural misalignment between demand and solar generation, since photovoltaic output typically declines after 18:00.
  – This underlines the importance of flexibility measures such as storage systems, demand-side management, and tariff incentives to better match consumption with renewable production.

Overall, the weekly analysis shows that Portugal's electricity consumption retains a dual nature: weekdays are characterized by the superposition of industrial/commercial and residential loads, while weekends shift more toward residential dominance. These patterns are fundamental for assessing the adequacy of UPAC, since household-oriented self-consumption technologies must address precisely these evening peaks where renewable supply is weakest.

5.10. Potential Production Based on Solar Radiation

Because real production data from UPAC installations is not publicly available, the potential production of these systems was explored indirectly through solar radiation data provided by IPMA. The assumption is that most UPACs in Portugal rely on photovoltaic technology, meaning their generation capacity is directly related to the amount of solar irradiance received in each region.

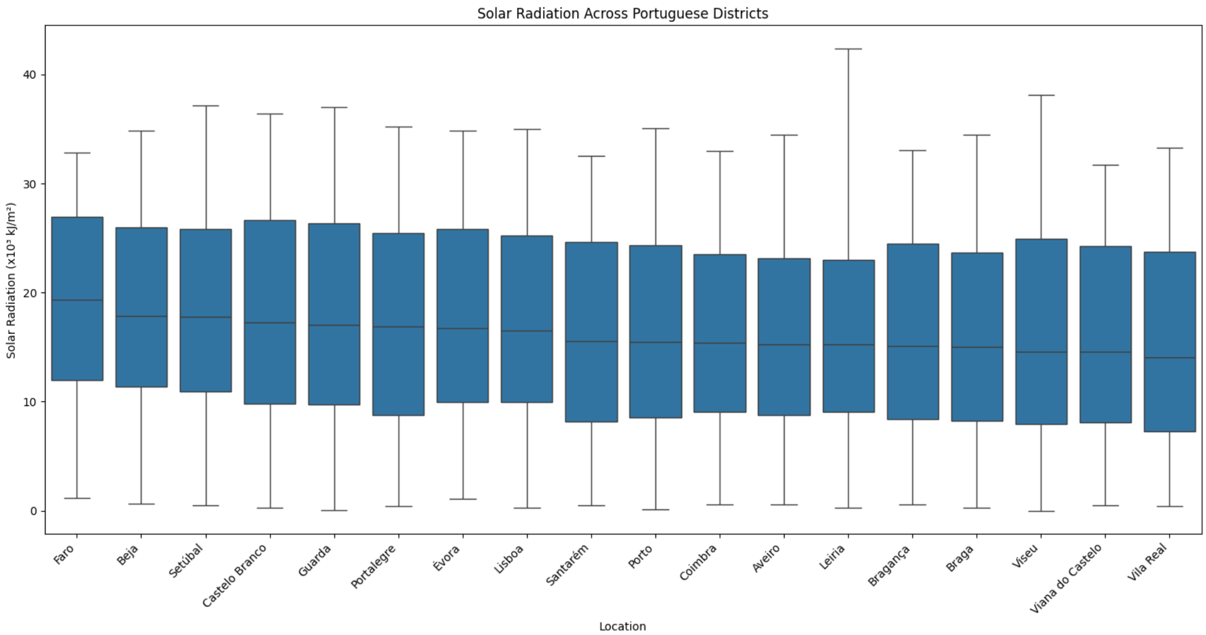

FIGURE 5.14. Solar Radiation Across Portuguese Districts

Figure 5.14 presents the distribution of solar radiation values across Portuguese districts. Even after outliers are removed, the variability between locations is evident. Southern districts such as Faro, Beja, and Setúbal tend to register higher median values, reflecting their advantageous solar exposure. Conversely, northern regions such as Viana do Castelo, Vila Real, and Braga show lower distributions, consistent with their less favorable climatic conditions. This geographic disparity highlights that while UPAC adoption is increasing nationwide, the technical potential for production is strongly shaped by regional solar resources.

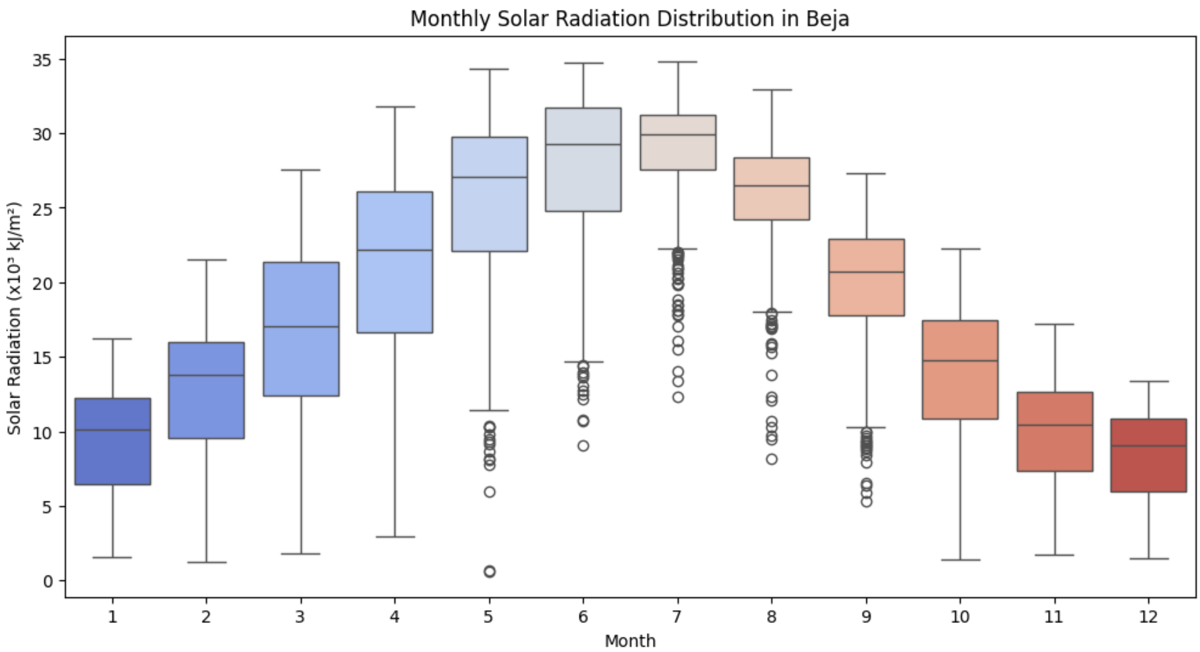

FIGURE 5.15. Monthly Solar Radiation Distribution in Beja

Figure 5.15 focuses specifically on Beja, a district that has already shown significant growth in per-capita installed UPAC power. The monthly distribution of solar radiation values shows a clear seasonal pattern: production potential increases steadily from February to June, peaking in May and July, before declining through the late summer and winter months. The interquartile range also widens during spring and summer, reflecting greater variability in solar conditions but also greater opportunities for high generation. In contrast, the winter months (November to January) show consistently lower values with less dispersion, underscoring the reduced potential in this period.

Taken together, these results suggest that regional solar irradiance is a critical driver in both the adoption and expected performance of UPACs. Districts with higher radiation levels not only present better economic conditions for investment but also explain, at least in part, why areas like Beja are emerging as leaders in installed capacity per capita. While this analysis cannot replace direct production data, it provides a valuable approximation of the seasonal and geographic dynamics that shape the contribution of UPACs to the national energy system.

CHAPTER 6

Conclusion

This study set out to explore the evolution and distribution of UPACs in Portugal using publicly available datasets and descriptive data-driven analysis. The work applied temporal analysis, geographic normalization, and production estimation to identify patterns in decentralized renewable energy adoption. By focusing on exploratory methods, the dissertation contributes to a clearer picture of how UPACs are spreading across Portugal and what this might imply for the energy transition.

Overall, the results indicate a steady increase in the number and capacity of UPAC installations between 2022 and 2025. Growth was not evenly distributed across the territory: larger urban areas recorded higher absolute numbers, while smaller municipalities often stood out when normalized by population or housing stock. Maps further highlighted how areas that initially had no UPAC presence gradually began to register installations, suggesting a process of spatial diffusion. Estimated production values also show a growing contribution from UPACs to local consumption, though with significant regional differences, aligning with public incentive programs.

6.1. Research Questions Revisited

This dissertation was structured around four main research dimensions. The results obtained allow revisiting each of them as follows:

Temporal Dynamics

The analysis showed a consistent increase in the number and installed capacity of UPACs, with marked acceleration during 2022 and 2023. These peaks coincide with periods of active public support programs, suggesting a strong responsiveness of adoption to incentive availability (Subsection 5.1). Although the growth rate slowed slightly in 2024, cumulative capacity continued to expand steadily, reflecting the consolidation of self-consumption as a mainstream energy practice.

Geographical Dimension

Spatial patterns reveal a dual dynamic: in absolute terms, installations are concentrated in more populous districts such as Lisbon and Porto, while normalized indicators – such as installations or capacity per capita – highlight smaller districts in the North (e.g., Viana do Castelo, Braga, and Vila Real) and South (e.g., Évora and Beja) as leading adopters (Subsections 5.3 and 5.5). This indicates that population density and solar resource availability jointly shape the geography of decentralized energy adoption.

Energy Contribution

At the national level, total electricity consumption remained relatively stable throughout the study period (Subsection 5.9). However, the increasing share of self-consumption systems suggests a gradual shift in the composition of electricity supply. While UPAC adoption has not yet driven major changes in overall demand, it has begun to displace grid-supplied electricity, particularly in the residential and small commercial segments.

Production Potential

Given the absence of real production data, potential output was estimated based on regional solar radiation provided by IPMA (Subsection 5.10). The results show that southern districts such as Beja, Faro, and Évora possess the most favorable solar conditions, aligning with higher per–capita installed capacity. This reinforces the idea that solar irradiance is a key driver of both adoption feasibility and expected performance of decentralized systems.

6.2. Future Work

Future studies could expand on this work by:

- Improved data availability: Incorporating real production and self-consumption measurements from smart meters or pilot projects would allow for more accurate estimation of UPAC contributions.
- Socio-economic analysis: Examining the demographic and economic drivers of adoption at the municipal level could reveal the social and regional factors that shape diffusion patterns.
- Technical assessment: Investigating the effects of UPAC growth on grid stability, flexibility, and local distribution infrastructure would provide insights into operational challenges and potential solutions.
- Policy evaluation: Linking detailed incentive program data to installation records would enable a stronger assessment of the effectiveness of subsidies and regulatory frameworks.
- Broader scope of analysis: Extending the study to other decentralized generation technologies, such as community energy projects, collective self-consumption schemes, or storage systems, would offer a more comprehensive picture of distributed energy's role in the transition.

Another relevant aspect is that the open datasets provided by E-REDES are continuously evolving. For instance, in August 2025 a new dataset on "Comunidades de Energia" was released, containing detailed information on collective self-consumption (ACC) and renewable energy communities (CER), disaggregated by date, region, and type of collectivity. These developments highlight the importance of ongoing updates in open data platforms, which can enable future research to address questions that were not possible to explore at the time of this study.

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APPENDIX A

Additional Figures

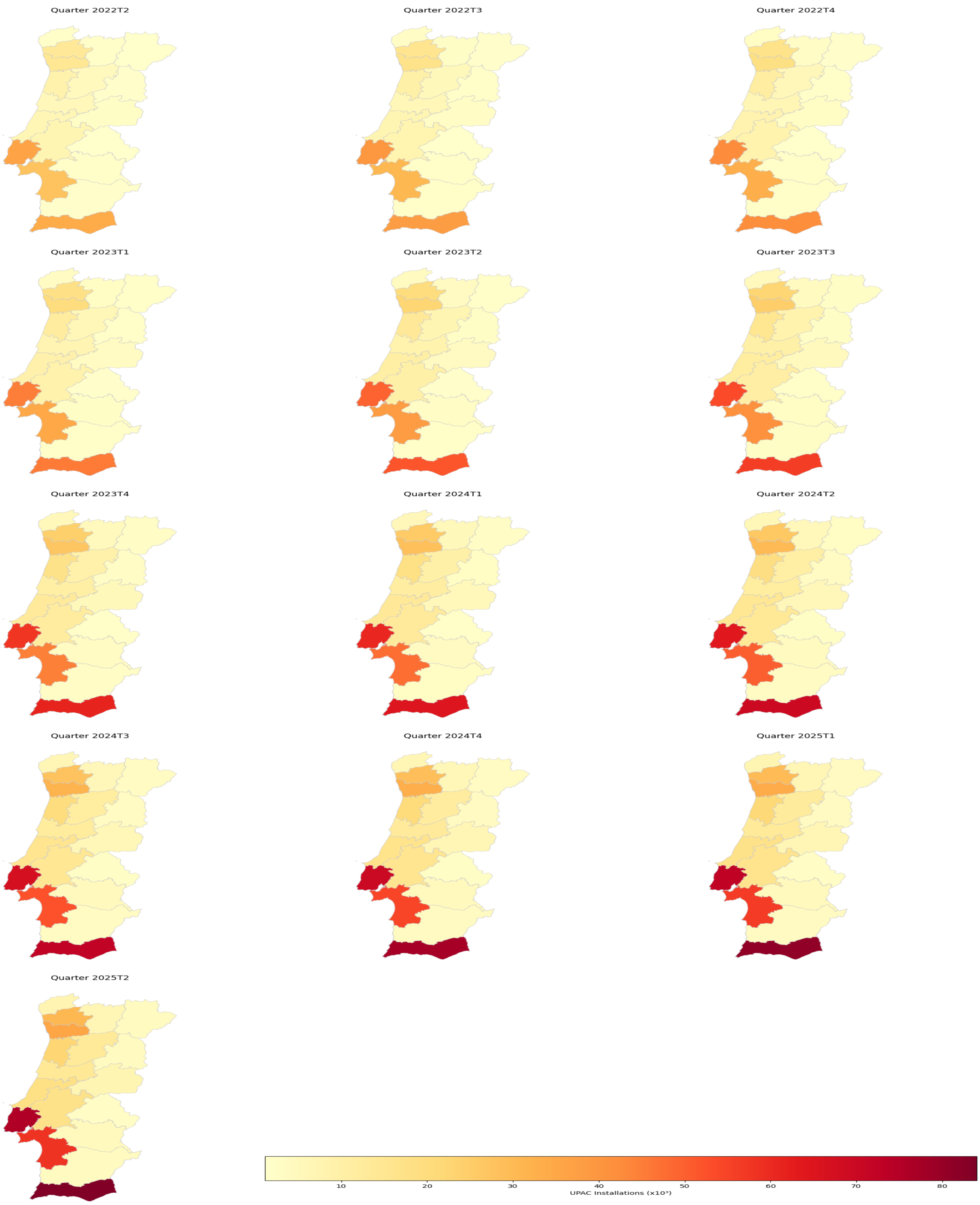

FIGURE A.1. Number of UPAC Installations by District and Quarter

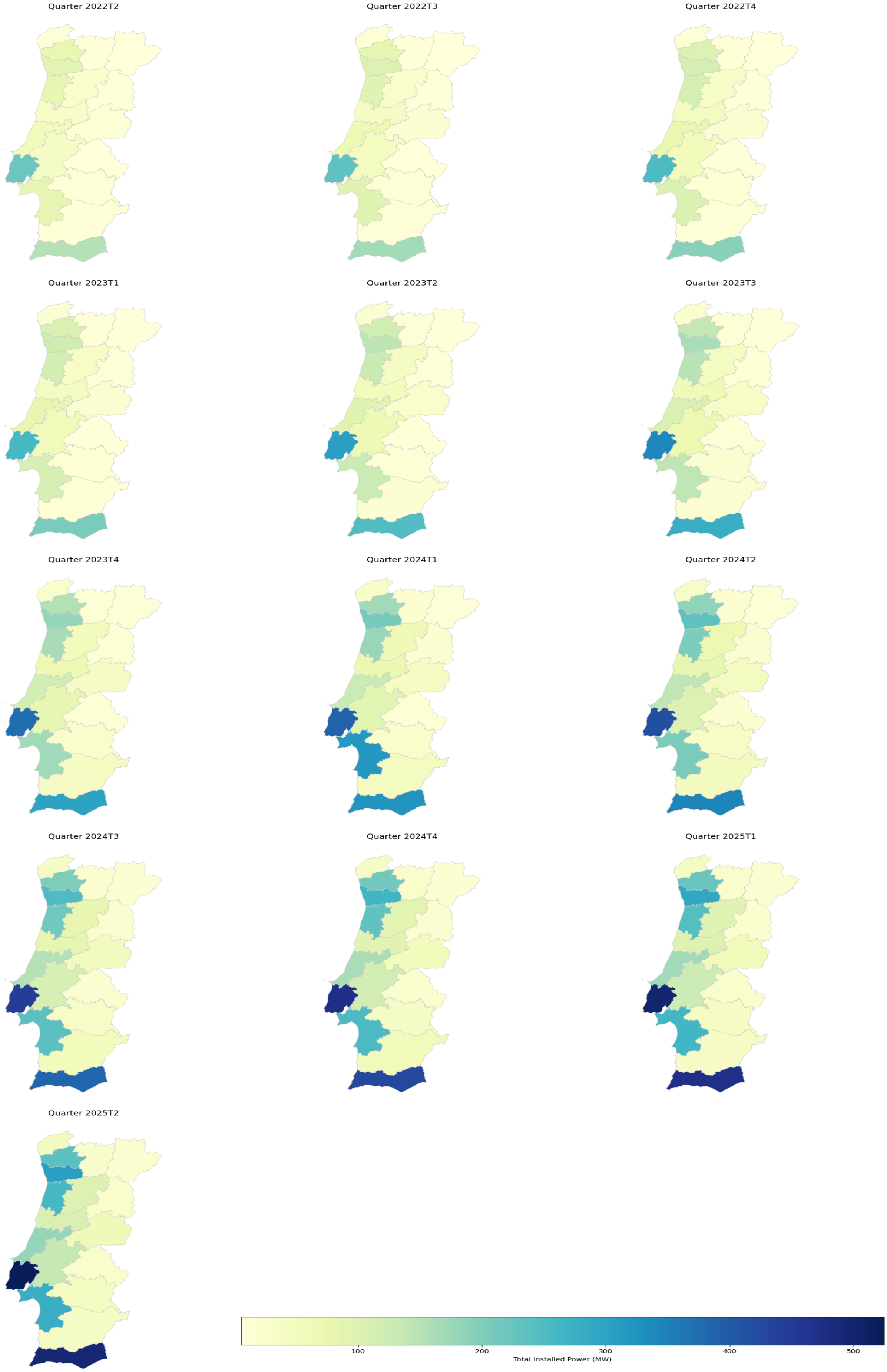

FIGURE A.2. UPAC Total Installed Power by District and Quarter

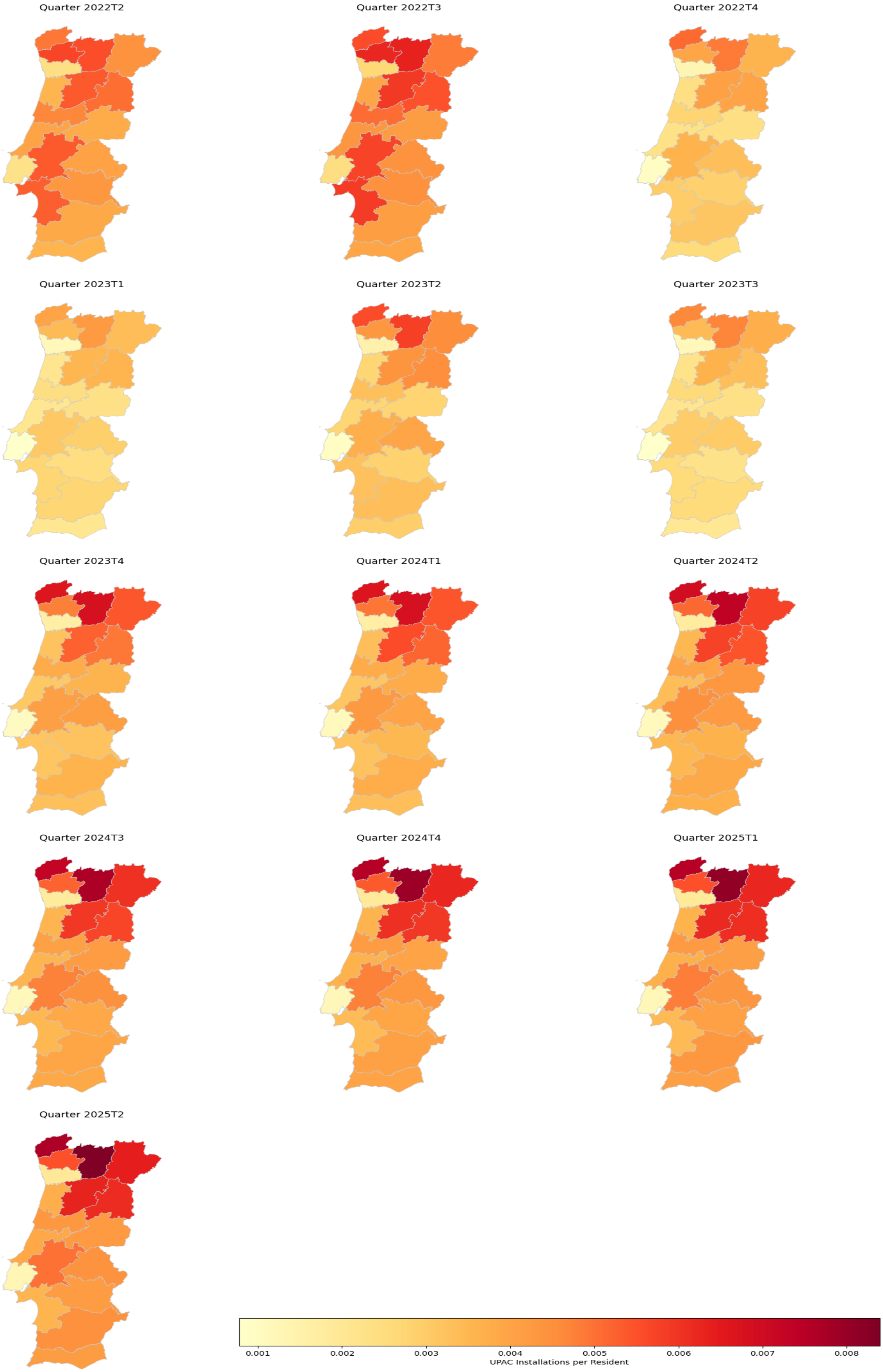

FIGURE A.3. Number of UPAC Installations per Resident Population by District and Quarter

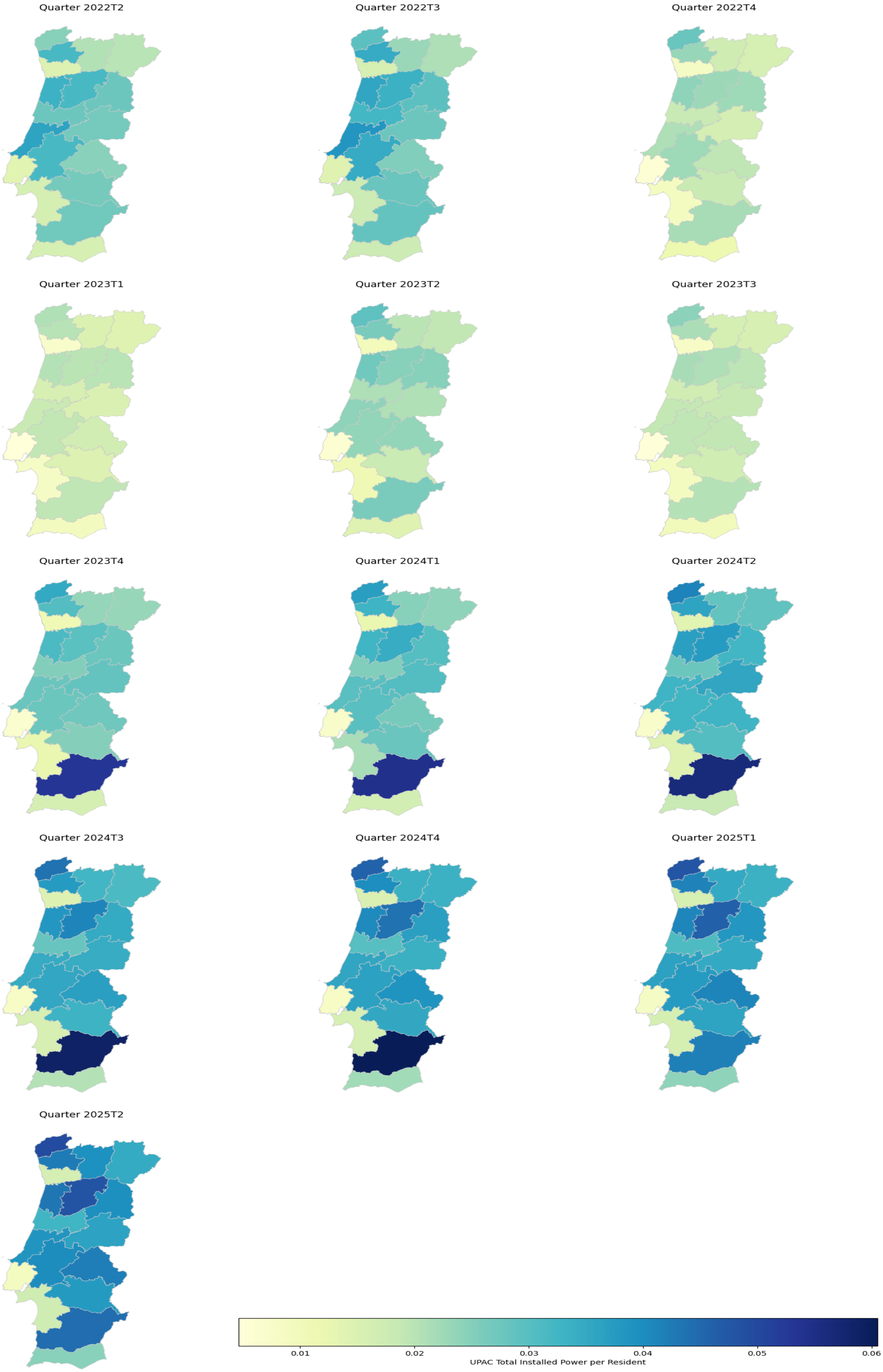

Figure A.4. UPAC Total Installed Power per Resident Population by District and Quarter