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The Influence of Decarbonization on Electricity Demand

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Abstract

This paper analyzes the impact of key decarbonization and economic factors on electricity consumption supplied through the power grid in Portugal, between 1995 and 2023. Energy efficiency surges as one of the variables with the most significant coefficients, as a result of the policies that encourage the reduction of energy/electricity consumption. Though self-consumption generally reduces pressure over the grid demand, its effect remains small and sometimes statistically insignificant. However, continuous monitoring is essential to anticipate its future impact on grid-supplied electricity. Additionally, as Portuguese regions shift towards the service sector, electricity consumption is increasing, likely driven by electric-intensive service subsectors and increased digitalization. Electrification also shows a positive impact on the electricity demand. A comprehensive approach to assess long-term electricity demand that manages these many confounding effects, will better guide investment decisions in grid infrastructure, provide clearer insights into the future evolution of allowable revenues and grid tariffs, and help meet the EU's decarbonization targets.

Keywords: decarbonization, electrification, energy efficiency, electricity demand, income elasticity; **JEL codes**: Q41;Q43;Q48[1]

1. Introduction

Understanding the drivers of electricity consumption is important to ensure a stable, efficient, and sustainable power grid. Rising decarbonization and economic factors need to be taken into consideration by governments, regulatory authorities and private players in

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order to optimize the planning and development of the electricity infrastructure (ENTSO-E, 2025) and help to define the recovery of allowed revenues and to set tariffs. In this context, the European Parliament (EP, 2019) states that the assessment of resource adequacy in Europe, at the transmission level, shall include projections of electricity demand and cover a 10 years period from the date of the assessment.

(DGEG, 2025) acknowledges the impact of decarbonization drivers on the electricity supplied over the national power grid, with emphasis on energy efficiency, electric mobility, self-consumption and green hydrogen. In this report, the forecasts that support energy policy decisions, especially concerning national security of supply, project electricity consumption between 56 439 GWh and 73 332 GWh by 2040. This range is highly dependent on the chosen decarbonization scenario, highlighting the critical need for accurately assessing the impact of decarbonization factors on electricity demand.

Thus, this paper aims to provide insights on the impact of energy efficiency policies, self-consumption development, electrification and economic structural shifts in the grid-supplied electricity consumption, by extending and providing a complementary perspective to the work conducted by (Cruz, 2024). While (Cruz, 2024) focused on the time-varying income elasticity that could arise from decarbonization and economic factors, this paper investigates the direct impact of key decarbonization and economic drivers directly on electricity consumption using a methodological framework that addresses endogeneity. It also explores the existence of spatial spillovers, key differences between low-voltage and high-voltage consumers, as well as the impact on income elasticity that may come from business cycles or unusual weather conditions.

Decarbonization requires the deployment of technologies with significant upfront investment costs. According to the European Commission (EC, 2023a) and the European Investment Bank, the green transition, will require additional investment of EUR 620 billion, annually, throughout this decade. For the coming decades, investment needs are estimated to be between EUR 520 billion and EUR 575 billion, per year (EC, 2020), according to models supporting the EC's long-term vision for 2050. As per (EC, 2023b) EUR 584 billions are necessary for the electricity grids in this decade. Additionally, a majority of this investment must come from private funding (EC, 2023a).

Private sector, represented by Eurelectric and EY, emphasizes the urgent need for modernizing Europe's distribution grids to facilitate extensive electrification of transportation, heating, and industrial sectors (Eurelectric and EY, 2024), as well as to integrate renewable energy sources and enhance resilience against more frequent extreme weather events and cyber threats. (Eurelectric and EY, 2024) indicate that investment in distribution grids should rise to EUR 67 billion annually between 2025 and 2050, twice the current amount, but less than the amount spent on implicit fossil fuel subsidies and far below the amount spent on fossil fuel imports.

Following this initial overview, the paper is structured as follows: the literature review chapter examines the main factors that may contribute to changes in the electricity supplied over the power grid. The chapter on data and methods describes the variables used, the methods applied and the relevant assumptions, transformations and limitations. The "Results" chapter presents the quantitative analysis of the study for all estimated models. Following this, there are the policy recommendations where a set of policies is evaluated regarding the results obtained. The "Conclusions" chapter summarizes the key messages on the determinants of the electricity demand and outlines further research needs.

2. Literature Review

The results of (Csereklyei, 2020), (Liddle et al., 2023) and the broad meta-analysis conducted by (Zhu et al., 2018) and (Mubiinzi et al., 2024) show that, established determinants, such as income, remain significant drivers of electricity consumption, especially in the long run. Therefore it is still relevant that network operators, as well as national public institutions (DGEG or ERSE) use income data in their assessments to meet decarbonization goals, flexibility procurement, security of supply and linkages with other energy sectors.

Next it is presented the relevant literature review regarding four main decarbonization factors: electrification, energy efficiency, self-consumption and the share of services in the economy[1].

2.1 Electrification of the Economy

The electrification hypothesis refers to the replacement of fossil fuel-based technologies or processes with electrically powered equivalents. With significant potential to reduce emissions and decarbonize energy supply chains, electrification is an important strategy for achieving net zero targets. As stated by International Energy Agency (IEA), as more energy end-uses become electrified, the share of electricity in total final energy consumption is estimated to increase from 20% in 2022 to over 27% in 2030 in the Net Zero Emissions scenario (NZE) by 2050 (IEA, 2024).

Portugal is a country highly dependent on energy imports (78%), with the largest energy vector being oil and petroleum products (68%), mainly used in the transport sector, where the electrification of the sector is expected to increase gradually until 2050 (Martins et al., 2022). The main conclusions of (Felício et al., 2024) reflect that there is still a long way to go (similar results can be found in (Martins et al., 2022)), much like

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[1] A note about hydrogen: hydrogen is a flexible energy carrier that can be produced from various sources for multiple applications (IRENA, 2025). Green hydrogen, generated via electrolysis using renewable electricity, can enhance grid flexibility, complement storage alternatives, support demand response, and strengthen vehicle-to-grid integration. Achieving the EU's 10 Mt renewable hydrogen target requires up to 180 GW of solar and wind capacity (ACER, 2024), meaning significant investments in electricity networks. In Portugal, where hydrogen consumption is currently negligible, up to 67 TWh of electricity may be required solely for renewable hydrogen production, powering electrolysers with capacities that may reach 14,5 GW (DGEG, 2025). Despite its critical role in decarbonization and grid investment (EuropeanParliament, 2024), hydrogen remains outside the scope of this paper due to limited historical data, financial and regulatory uncertainties, and divergent national strategies.

the rest of the world, as it will be necessary to electrify the equivalent of almost all the energy Portugal current imports, a tough challenge given the need to decarbonize energy generation. Furthermore, to replace oil consumption, (Martins et al., 2022) recommends the promotion of electric mobility (also argued by (Ribeiro et al., 2024)) and at the same time, incentives to phase-out the number of internal combustion vehicles in circulation, as transport is the largest sector of oil consumption. As for natural gas, (Martins et al., 2022) suggested the use of thermal solar energy in the buildings sector as well as tailored measures to electrify industry, taking into account the type of industry. These authors concluded that the contribution of electricity to decarbonization depends on renewable capacity deployment, uptake of electrification and the replacement of other fossil fuels with natural gas.

Regarding the influence of energy policies on the electrification process, (Felício et al., 2024) stated that they were successful in promoting electrification within the primary energy mix, in order to enhance energy independence and reduce carbon emissions.

(Fortes et al., 2019) identified transport and industry as the most sensitive sectors in terms of increasing the share of electricity in final energy consumption, and found that additional investment required for the deployment of new technologies in end-use sectors were moderate, even under the most stringent mitigation emission caps.

Regarding broader geographical research, (Liddle et al., 2023) found that the income elasticity for electricity is declining and could be as low as 0.2. The authors suggest that the most likely explanation for time-varying/declining electricity demand elasticities is demand saturation due to a stagnation in the rate of electrification of energy services.

While (Tamba et al., 2022) believes that a higher level of road transport electrification can help reduce the cost of climate change policies, (Nam and Jin, 2021) points out that electrification policies should be implemented after energy transition policies in the generation sector. In the same lines, (Stringer et al., 2021) reported that an increase in investment in electrification required by net-zero scenarios will represent an economic burden until 2050, but from 2050 onwards the savings will exceed the costs incurred.(Lin and Li, 2020) showed evidence that the level of electricity use has a significant negative effect on carbon emissions. Thus, investments in renewable energy generation and improvements in the efficiency of generating plants, transmission and distribution networks and storage leads to lower growth in carbon emissions.

Nevertheless, electrification of transport comes with major challenges: there is socio-economic implications of EV deployment, that include high upfront costs, inadequate charging infrastructure, uneven regional impacts and disproportionate distribution of network tariffs.

2.2 Energy Efficiency

Energy efficiency measures have been implemented, at national and European level, in order to relatively reduce the electricity consumption and provide economic savings.

The Energy Efficiency Directive (EED (EP, 2012)) is at the heart of the European Union's strategy to reduce energy consumption and mitigate climate change. Since its inception in December 2012, the EED has driven significant progress towards achieving the EU's energy efficiency targets. The Directive required Member States to set national energy efficiency targets, aiming for a 20% improvement by 2020, and introduced binding measures to ensure compliance. These efforts have evolved with each revision, notably increasing the target to a 32.5% improvement by 2030. Subsequent revisions in 2018 (EP, 2018) and 2023 (EP, 2023) placed further emphasis on reducing annual energy consumption and alignment with broader climate goals. The latest revision in 2023 set an 11.7% reduction target for final energy consumption by 2030, reflecting the EU's commitment to energy efficiency, fighting energy poverty and increasing energy savings in the public sector.

Based on the general concept behind the EU directives that energy efficiency policies will lead to savings in energy consumption, many authors have researched the topic in diverse contexts, which can be categorized as follows:

- Decoupling Economic Growth and Energy consumption: even though some studies point to the decoupling of income and energy demand ((Kan et al., 2019), (Wu et al., 2018), (Mulder and de Groot, 2004) and (Liddle et al., 2020), conclusive evidence has been lacking ((Moreau and Vuille, 2018) and (Liddle, 2023)). Most of these studies report weak decoupling between economic growth and energy consumption, which means that economic growth has somewhat become more efficient in terms of energy use, but it has been accompanied with significant rebound effect.

- Rebound effects: refers to the increased use of energy services given energy savings (Sorrell et al., 2007). (Berner et al., 2022a) estimated a rebound effect between 78% and 101% within two years in France, Germany, Italy, the UK, and the US. (Berner et al., 2022b) found that while energy efficiency improvements reduce firm-level energy consumption if output remains constant, these improvements also drive output expansion, counteracting potential savings. On a residential level, (Baležentis et al., 2021) noted a decrease in the rebound effect from 2000 to 2015, with significant spatial variations. Smaller effects were found for Portugal. (Brockway et al., 2021) reviewed economy-wide rebound effects, indicating these may reduce more than half of the expected energy savings from improved efficiency. (Bongers, 2024) found that the rebound effect, at the household level, disappears in recessions but is reinforced in expansions. Finally, (Rajabi, 2022) and (Özsoy, 2024) concluded that there is no consensus on the magnitude of the energy rebound effect or its consideration in new environmental policies, though (Özsoy, 2024) admits that it can be high (between 70% and 100% in the long-run).

- Digitalization: According to (Lange et al., 2020) and (Tao et al., 2024) Information and Communication Techonologies (ICT) activities allow for more efficient production, but sometimes also leads to new behaviors that are more energy intensive (Ehigiamusoe et al., 2024). Thus, there is evidence that rebound effects are significantly high for ICT. Additional studies remain skeptical of the long term effects of the use of ICT on energy efficiency and have limited evidence on the relationship ((Usman et al., 2021) and (Zhao et al., 2022)).

- Institutional quality: many governments and institutions have, in recent years, strategically incorporate energy efficiency policies and targets into their national agendas. Thus, quality of government institutions and the level and direction of scientific and technological development can influence energy efficiency ((Tao et al., 2024) and (Sun et al., 2019)).

2.3 Self-consumption

The EU's "Clean Energy for all Europeans" (EC, 2019) package aimed to empower end consumers within the energy market, emphasizing the involvement of "active consumers" and promoting both individual and collective renewable energy self-consumption. However, self-consumption also presents socio-economic challenges. There are concerns across some EU countries that energy communities could exacerbate economic disparities, potentially leading to unfair imbalances and higher system charges for vulnerable groups and non-participating consumers ((Frieden et al., 2021) and (Roberts et al., 2022)). (Bielig et al., 2022) conducted a comprehensive literature review on the social impact of energy communities, revealing that while there are benefits (for example more resilience to price shocks, like the 2022 European energy crisis (Pelka et al., 2023)), these communities face significant social and economic hurdles (ensuring equal access, fair infrastructure siting and acknowledgment of marginalized groups) that must be addressed to maximize the positive impact of energy communities while mitigating potential drawbacks.

The most significant initial milestone for renewable self-consumption in Portugal was the publication of Decree-Law No. 153/2014 (PortugueseRepublic, 2014), that established the first clear rules for the installation of self-consumption production units (UPAC), allowing individual consumers and companies to produce their own electricity and sell the surplus injected to the grid.

In October 2019, Decree-Law no. 162/2019 (PortugueseRepublic, 2019) was published, replacing the previous decree and bringing significant changes. Among the innovations, it allowed the aggregation of several production units and collective self-consumption, facilitating the creation of renewable energy communities (REC). Since the implementation of Decree-Law No. 162/2019, self-consumption has grown rapidly in Portugal. Ease of installation, lower costs for photovoltaic systems and tax and financial incentives have contributed to a substantial increase in the number of self-consumption installations, both in homes and in companies and public institutions.

Further authors (Frieden et al., 2021) (Rocha et al., 2021) have identified regulation barriers to the adoption of european law regarding self-consumption and energy communities that may lead to heterogeneous technologies within the EU. Further guidance is needed for definitions, types of legal entities, data access and ownership, spatial limitation, financing tools and relationship with external DSOs.

At national level (Algarvio, 2021) proved that REC have the potential to be a more carbon-neutral framework in relation to electricity consumption via power grid. Additionally, it also pointed evidence towards a reduction in costs, in particular in the variable term (energy). In the flexibility context (Rocha et al., 2023) defended the re-dispatching of the flexible resources and the curtailment of local generation or consumption to tackle local distribution grid constraints. According to (Rocha et al., 2023) this would minimize prosumer's energy bill. For (Lage et al., 2024), energy communities are more economically viable in Portugal and Italy than individual consumption, as individual households continue to prioritize self-consumption and personal savings while selling their excess energy at a more favourable price than what they would receive from the grid.

Summing up, it is regarded that self-consumption reduces the electricity consumption supplied over the power grid (Garrido-Herrero et al., 2024) and help to mitigate energy poverty (Campagna et al., 2024).

2.4 Share of Services Sector in the Economy

Structural shifts are changes in the economy's energy intensity due to the changing composition of activities within the economy (Huntington, 2010). Portugal is an example of an almost stylized fact: energy intensity is lower in the services sector compared to industry (Amador, 2022). Therefore, as economies develop and shift from manufacturing to services, their overall energy intensity should tend to decrease (EEA, 2020) and for which (Huntington, 2010) and (Weber, 2009) provide empirical evidence. Counterbalancing this view, (Csereklyei et al., 2016) provided evidence that technological change within industries have more impact on the decline in energy intensity than structural changes towards services. As for informal economy (Canh et al., 2021) showed that a higher shadow economy would induce a higher level and intensity of energy consumption, including a higher renewable energy use. Therefore, mixed signals can be expected from the impact of the share of services in the GDP on electricity demand.

3. Data

On this chapter it is displayed the summary statistics as well as the charts that illustrate the evolution of the main variables of interest. Data was collected either in DGEG, National Statistics Institute (INE) or EUROSTAT databases, between 1995 and 2023 for all regions in Portugal mainland according to Nomenclature of territorial units for statistics III (NUTS III). Data is available at 10.5281/zenodo.15161098. Regions are defined as in table 1

Table 1: Regions (NUTS III - 2013) and corresponding abbreviations

Abbreviation	**Region**
AC	Alentejo Central
AL	Alentejo Litoral
Al	Algarve
AA	Alto Alentejo
AM	Alto Minho
AT	Alto Tâmega
AML	Área Metropolitana de Lisboa
AMP	Área Metropolitana do Porto
A	Ave
BA	Beira Alta
BB	Beira Baixa
BSE	Beiras e Serra da Estrela
C	Cavado
D	Douro
LT	Lezíria do Tejo
MT	Médio Tejo
O	Oeste
RA	Região de Aveiro
RC	Região de Coimbra
RL	Região de Leiria
TS	Tâmega e Sousa
TTM	Terras de Trás-os-Montes
VDL	Viseu Dão Lafões

Sources: INE

In the model: Dependent Variable: Electricity consumption per capita (EC_Pc) - Electricity consumption supplied by the network, at all voltage levels, per capita. Source: DGEG, INE

Independent Variables:

1. GVA per capita (GVA_Pc) - Value created by any unit involved in any productive activity. Source: INE.

2. Cooling Degree Days (CDD) - a weather-based technical index designed to describe the need for the cooling energy requirements of buildings. Source: Eurostat

3. Heating Degree Days (HDD) - a weather-based technical index designed to describe the need for the heating energy requirements of buildings. Source: Eurostat.

4. Electricity prices (DC and IC)- it was considered the final prices reported by DGEG and published by Eurostat. These are divided into household and non-household (different voltage levels) and then by band of annual consumption. For residential/services prices it was considered the band of consumption DC (between 2,5MWh and 5MWh of annual consumption). For industrial prices it was considered the band of consumption IC (between 500 MWh and 2000 MWh of annual consumption). Source:DGEG and Eurostat.

5. Oil Prices (OIL) - Average of monthly crude oil prices (Brent). Source: DGEG.

6. Selfconsumption (SC): Use of decentralized production which comes from generation schemes carried out close to the production sites. It can be either reneweable or non-reneweable generation. Source:DGEG

7. GVA Services (GVA_S): Value created by any unit involved in a services productive activity. Used to determine the share of the services in total economy. Source: INE

8. Energy Consumption: It includes the consumption of electricity and natural gas and sales of oil derivatives. It is excluded the energy that is used to generate electricity. It excludes coal, as its consumption is related mainly with electricity production. These exclusions helps to isolate the effect of energy efficiency policies on end-use electricity consumption, which is beneficial because the primary interest is to understand how policies directly affect electricity use by consumers and businesses, rather than improvements in power generation efficiency. It is used to form the energy intensity and the electrification indicators.

Table 2 and 3 show the summary statistics of dependent, independent and auxiliary variables used.

Table 2: Statistics for Energy and Economic Indicators (Part 1)

	EC (GWh)	**GVA (10^6 EUR)**	**HDD (Days)**	**CDD (Days)**	**OIL (EUR/bbl)**	**POP (10^3 People)**	**SC (GWh)**
Minimum	129	689	444	2	10	81	-
Mean	1 759	6 729	1 190	154	46	429	84
Maximum	13 286	72 243	2 304	585	107	2 922	864
Standard Deviation	2 501	12 371	405	120	26	593	152

Sources: DGEG, Eurostat and INE

Table 3: Statistics for Energy and Economic Indicators (Part 2)

	DC (EUR/KWh)	**IC (EUR/KWh)**	**GVA_S (%)**	**EC_S (%)**	**EI (Toe/10^3 EUR)**
Minimum	165	104	0,39	0,08	35,21
Mean	196	131	0,64	0,28	117,02
Maximum	232	178	0,88	0,71	740,79
Standard Deviation	21	18	0,09	0,12	75,61

Sources: DGEG, Eurostat and INE.

Furthermore, it is provided in table 4 a characterization of the regional data. By comparing minimum and maximum values it is possible to conjecture that there is a positive trend in the income, cooling degree days, share of services and population.

Table 4: Minimum and Maximum Years and Regions for Various Indicators

		EC	GVA	HDD	CDD	OIL	DC	IC	GVA_S	POP	SC	EC_S	EI
Minimum	Year	1995	1995	1997	2008	1998	2007	2008	1996	2023	2009	1998	1995
	Region	AT	AT	Al	O	-	-	-	A	BB	AC	TTM	TS
Maximum	Year	2010	2023	2004	2022	2022	2016	1995	2023	2023	2003	2020	2020
	Region	AML	AML	AT	BB	-	-	-	AML	AML	RC	AA	AL

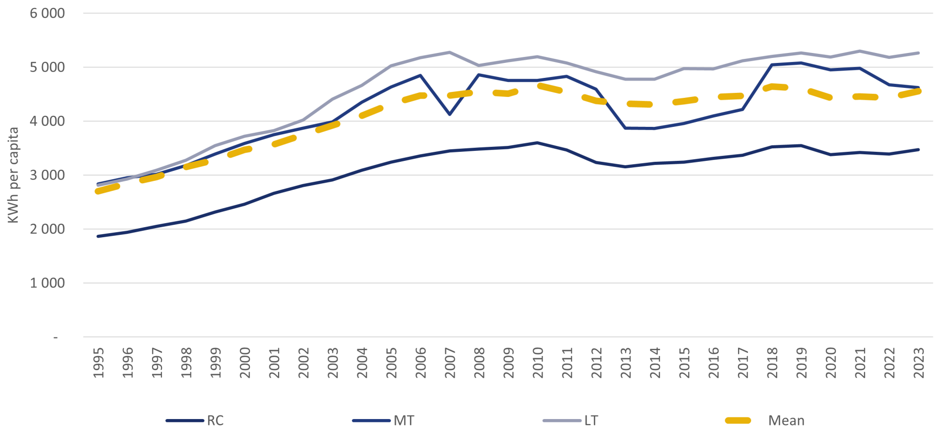
Sources: DGEG, Eurostat and INE. Note: For OIL, DC and IC the values don't vary with the region.

On the next subsection it is presented, with further detail, the variables of interest used in the model.

3.1 Electricity consumption per capita

Figure 1 shows the evolution of electricity consumption per capita supplied via power grid for portuguese NUTS III regions and nationwide. It is possible to identify two different stages: i) between late 90's and late 00's there was a strong increase in the electricity consumption per capita, which coincides with the robust economic growth in the 90's and early 00's. The annual growth rate between 1995 and 2010 was 3.7%. ii) During the debt crisis (between 2011-2016 the national GDP decreased or had low growth) electricity consumption per capita stalled. Despite the robust economic growth since 2016 (with the exception of the first year of the COVID-19 pandemic crisis), the electricity consumption has not been able to retake the positive trend. Thus, the annual growth rate between 2010 and 2023 was -0.2%.

Figure 1: Electricity consumption per capita by regions and nationwide



Sources: Own elaboration based on DGEG and INE data. Notes: Regions depicted in the chart correspond to first, second and third quartile in 2023. During this period some regulatory milestones stand out: 1996 and 2003 first steps on EU electricity market focused on unbundling the industry and on a gradual opening of national markets; 2007 - creation of the Iberian wholesale (spot) electricity market (MIBEL); 2012 - Major Energy Efficiency Directive; 2014 - Takeoff of electric vehicles subsidies; 2018 - Strengthening of European legislation on the promotion of renewable energy; 2019 - Major national legal framework for self-consumption (and energy communities) and "Clean Energy Packages";2022 - "RepowerEU plan".

Over the years, the electricity sector has undergone several changes: In the late 90's, independent regulation was established with the reprivatisation of electricity companies and the liberalisation of the electricity market. In 2007, it was created the Iberian wholesale market -MIBEL- that implied investment in the interconnections and regulatory harmonization between Portugal and Spain. This was a cornerstone of the promotion of market competition along with the unbundling (between generation, network and supply activities) and the introduction of the right for the consumers to choose their supplier (ERSE, 2018). Recently, the national electric system has been focused on decarbonization (over 70% clean energy in 2024 (APREN, 2023)), promotion of competitive markets, accessible prices and adequate security of supply (Marques, 2021).

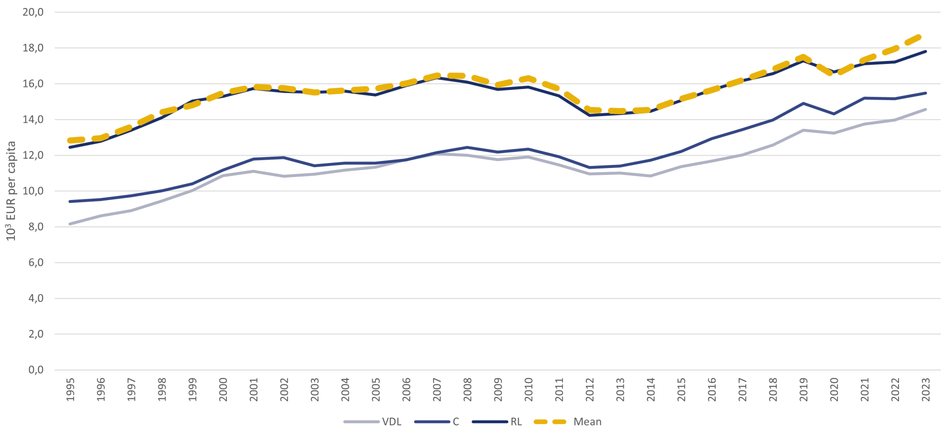
3.2 Gross value added per capita

For the GVA per capita, the sample can be divided into three main periods:

1. Between 1995 and 2008, there was a robust increase in per capita real GVA of around 1.9% per year.
2. Following the debt crisis, the GVA per capita decreased and only reached pre-crisis levels in 2018.
3. The post-2018 trend has been characterized by a robust retake of the economy. Between 2018 and 2023 the annual growth rate of the GVA was of around 2.3%.

The first use of macroeconomic analysis, by ERSE, to ensure adequate coverage of specific investment needs, the promotion of competition, as well as the coherence of the European Union-wide network, can be traced back to 2014 (ERSE, 2013)(to both distribution and transmission networks) and it is still currently applied.

Figure 2: Gross value added per capita by regions and nationwise



Sources: Own elaboration based on INE data. Note: Regions depicted in the chart correspond to first, second and third quartile in 2023.

The figures indicate that electricity consumption and income have exhibited similar trends over time, suggesting a close relationship between these variables. However, this relationship appears to have been stronger prior to 2010. This seemingly increase in electricity efficiency must be analyzed considering the context of natural gas demand growth in Portugal in the 2000's , when the regional gas networks started to develop[2] (ERSE, 2003).

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[2] Nevertheless, the consumer's transition was from bottled liquified petroleum gas to natural gas

3.3 Self-consumption

Figure 3 illustrates the evolution of self-consumption between 1994 and 2022. After the saturation of the additional number of co-generators able to comply with Administrative Rule No. 399/2002 (PortugueseRepublic, 2002) (which established guidelines for the tariff options for cogeneration installations with regard to the sale of energy to the Public Electricity Service (SEP)), self-consumption shows a decrease and a stabilization from 2010 onwards.

With the Decree-Law No. 153/2014 (PortugueseRepublic, 2014) it was established the legal framework for the production of renewable or non-renewable energy for self-consumption, with or without connection to the public grid and without prejudice to the surplus energy produced being injected into the national power grid.

This was the initial step for the deployment of self-consumption technologies that, as shown in figure 3, would later foster the increase of renewable self-consumption after 2014.

More recently, Decree-Law No. 162/2019 (PortugueseRepublic, 2019) established a new legal regime applicable to the self-consumption of renewable energy. Whereas previously only individual self-consumption was allowed, this new legal regime introduces the concept of collective self-consumption which allows consumers and other participants in renewable energy projects to form energy communities for the production, consumption, sharing, storage and sale of renewable energy.

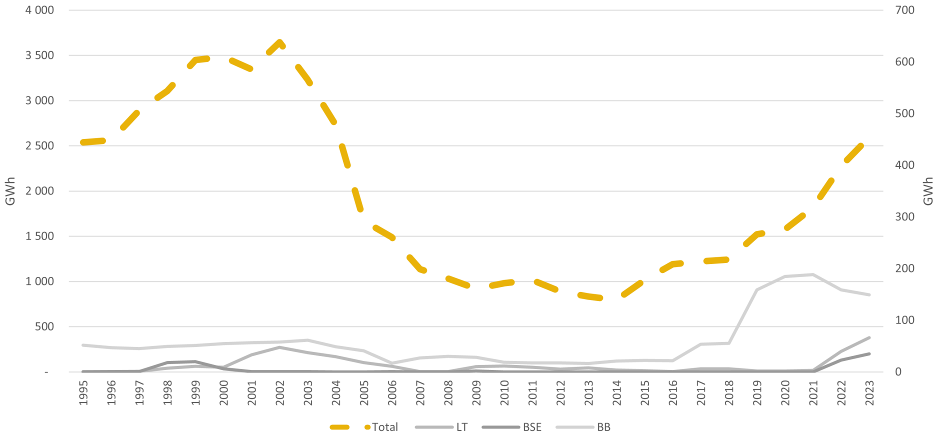
Decree-Law No. 15/2022 (PortugueseRepublic, 2022) (which transposed Directive No. 2018/2001 and No 2019/944) built upon the regulatory foundation laid by (PortugueseRepublic, 2019) by introducing more specific provisions for self-consumption and Renewable Energy Communities (It established a legal framework for the creation, governance, and operation of RECs). Furthermore, it included additional economic incentives and support mechanisms for both self-consumers and energy communities to encourage investment in renewable energy technologies and community-based energy projects. The goal is to achieve the national targets set out in the 2021-2030 Energy-Climate Plan, namely a 47 per cent share of energy from renewable sources by 2030 (DGEG, 2023).

Although self-consumption has increased in recent years, it is still below the levels observed in 2002. The various legislative changes implemented by the government over the last few years have boosted the implementation of new renewable energy production facilities for self-consumption. It is estimated that the weight of self-consumption in relation to the distributed energy will be at 20.5 per cent in 2031 (E-Redes, 2024).

3.4 Share of services in GVA

As Portugal developed its economy, the share of the services sector increased (as shown in Figure 4). This effect was particularly strong in the 1990s and early 2000s and it is a widely stylized phenomenom in global developed economies. Since 2009, the rate of growth of the share of services has fallen slightly, but is still positive: between 2009 and

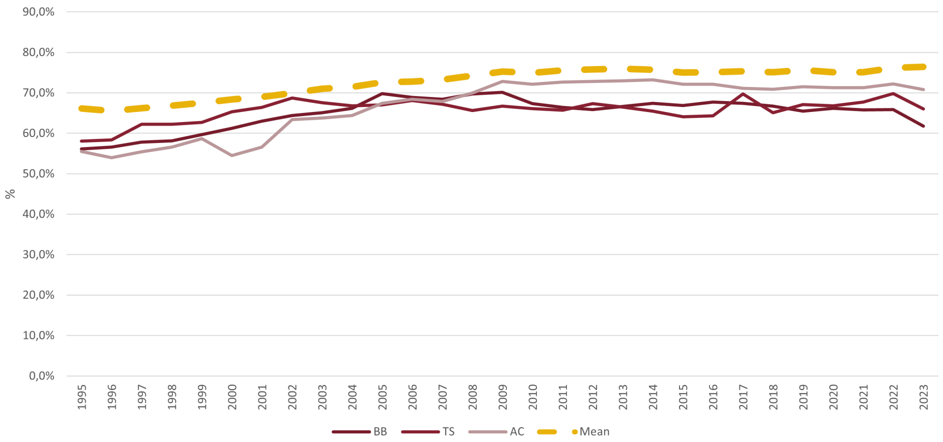
Figure 3: Electricity Selfconsumption



Sources: Own elaboration based on DGEG data. Notes: Regions depicted in the chart correspond to first, second and third quartile in 2023. The Regions self-consumption should be read in the secondary axis; During this period some regulatory milestones stand out: Late 90's - new cogeneration plants were able to inject (and sell) their surplus to the grid. 2014 - First legal framework for renewable self-consumption; 2019 - Improvement of renewable sef-consumption framework and legal establishment of RECs; 2022 - Further legal guidance to foster self-consumption, reducing complexity and improving coordination between EU nations.

2023 the growth rate was 0.1%.

Figure 4: Share of services sector in the Gross Value Added



Sources: Own elaboration based on INE data. Note: Regions depicted in the chart correspond to first, second and third quartile in 2023.

Even though the shift could lead to the expectation of electricity consumption reduction, Portugal has invested heavily in energy-intensive services activities, like tourism that has an impact on the consumption and use of energy, as well as on the CO2 emissions (Brida et al., 2023).

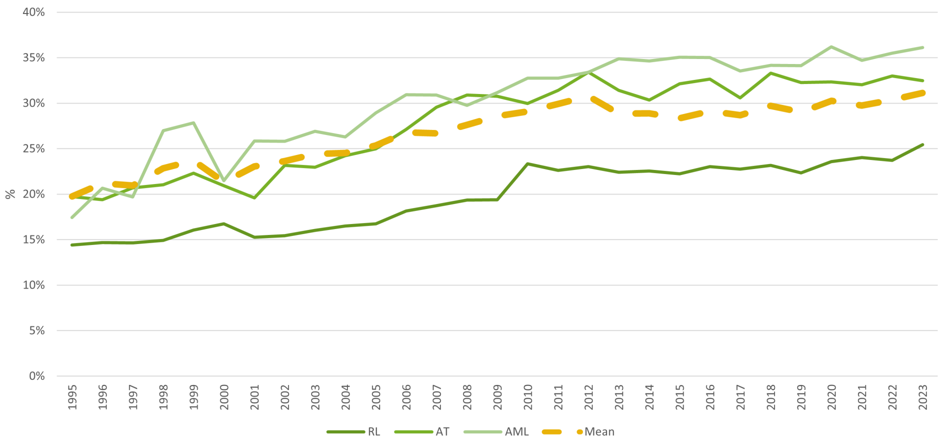
3.5 Share of electricity consumption on energy

In 2022, the share of electricity was 31%, which represented an increase from the 20% observed in 1995. At European level, electricity as a share of the energy mix has been fairly stable (EC, 2025) due, partly, to the small price differential between gas and electricity, which is not providing sufficient price signals to switch to electricity.

The transport sector is considered to be the most important sector to be electrified by 2050 as it is highly dependent on fossil fuels (Martins et al., 2022). Therefore policies regarding the promotion of technology substitution of road transportation to electric cars should increase electrification (Felício et al., 2024). However, it will be difficult to achieve full electrification of the transport sector by 2050, especially if the associated costs do not fall drastically, either in terms of vehicle acquisition or in terms of installation and access to electric vehicle charging and the price of electricity.

In Portugal, the price for using each charging point and the price for selling electricity for electric mobility are set on a market framework. In 2010, it was established that the activity of electric mobility network operations management (EGME) would be regulated by ERSE (ERSE, 2021). 2021 was the first year that ERSE set the process to calculate the allowed revenue and tariffs applicable to electric mobility, applicable to all suppliers.

Figure 5: Share of electricity consumption on energy



Sources: Own elaboration. Notes: Regions depicted in the chart correspond to first, second and third quartile in 2023; During this period some regulatory milestones stand out: 2010 - First regulated electric mobility activity (MOBIE); 2014 - First subsidies to the acquisition of electric vehicles; 2019 - First european guidance for the promotion on the promotion of clean and energy-efficient road transport vehicles (Directive 2019/1161); 2021 - first year of allowed revenues of MOBIE.

In this context, it is expected that heavier carbon pricing, revised energy taxation rules, incentives to the use of heat pumps for heating and acceleration of the stock of electric vehicles, can increase the electricity share on energy consumption.

3.6 Energy Intensity

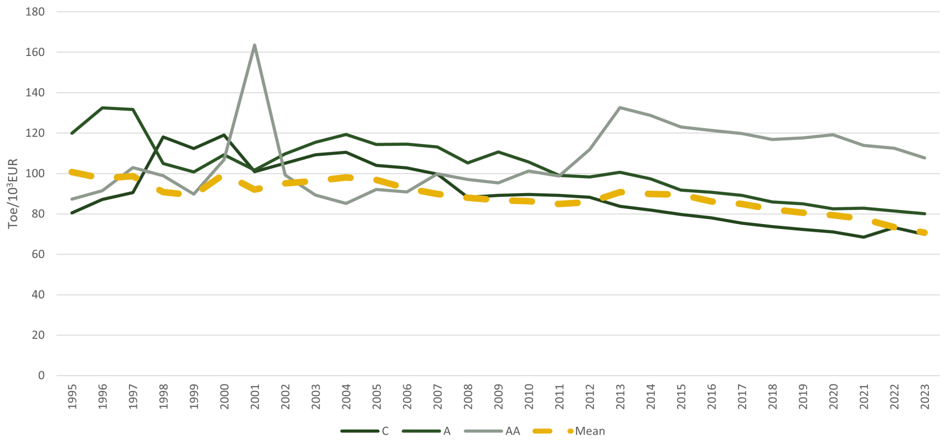
In order to fully assess the impact of energy efficiency measures, it is used an energy intensity as a proxy for the impact of energy savings. Using a broader energy indicator than electricity intensity has the advantage of allowing for substitution effects between other energy sources and electricity.

National energy intensity is on a slight downward trend: In 1995, 101 toe (tonnes of oil equivalent) were needed to generate 1 million euro of GVA. By 2023, only 71 toe were needed to generate the same amount of income, a decrease of 29.7% (note again that we are excluding fuels used for electricity generation and coal. If they were to be included, the energy efficiency gains would be higher).

In this context, ERSE has been promoting, since 2006, the Energy Consumption Efficiency Promotion Plan (PPEC), that supports financially initiatives that promote efficiency and reduce consumption in different consumer segments (ERSE, 2022). For instance the 7th edition of the PPEC supported 48 measures, with a total investment of 23 million EUR, which 15.1 million EUR were financed by PPEC programme. Measures include energy efficiency promotion campaigns, training courses, equipment acquisition and replacement (for example batteries) and online platforms. ERSE reported accumulated savings (for the 7 editions), 10 TWh and 3.7 million tons of CO2 emissions avoided.

Other public policies that have been implemented since 2020, include public lighting LED replacement, incentives for energy-efficient appliances and the building energy efficiency program (DGEG, 2023).

Figure 6: Energy Intensity in Portugal



Sources: Own elaboration. Notes: Regions depicted in the chart correspond to first, second and third quartile in 2023. During this period some regulatory milestones stand out: 2012 - Directive on Energy Efficiency 2012/27/EU; 2018 - amending Directive on Energy Efficiency (EU/2018/2002) to update the policy framework to 2030 and beyond; 2020 - NECP 2021-2030 - that aims to reduce the primary energy consumption by 35% to improve energy efficiency; 2023 - revised Energy Efficiency Directive (EU/2023/1791) that significantly raises the EU's ambition on energy efficiency.

The figure 6 only shows the data for a given regions regarding their quartile. Nevertheless, there is regional heterogeneity as well as some time-variance volatility in some regions, mainly in heavy-industry regions where energy intensity can be influenced by industry activity.

For example, in the sample, Alentejo Central (AC) region stands out. This is because AC has a large installed capacity for the production of refined petroleum products and fuel pellets, as well as for the manufacture of chemical products and synthetic fibres. Since 2013, the production of refined petroleum products and fuel agglomerates in Sines has increased significantly for various reasons related to strategic investments and industrial adjustments. The main reason was that the Sines refinery, operated by Galp Energia, underwent significant investments to modernize and increase its production capacity aimed at improving energy efficiency, increasing refining capacity and producing products with higher added value.

3.7 Data flaws, assumptions and robustness checks

Some data assumptions were taken to complete the dataset due to some flaws in the regional structure of the data, in the fuels considered or because of energy not attributed to any municipality/nuts III. Preliminary robustness checks did not yield qualitatively changes to the the results, so the analysis presented in this paper respects to the main treatment that is described below. Further, we present the identified deficiencies and the corresponding treatment.

- Self-consumption: There is a certain amount of electricity produced for self consumption that is not attributed to any geographical location. This demand is usually divided into two categories: i) unknown municipality(ies) in mainland Portugal and ii) unknown region(s). Usually, the weight of this unknown electricity consumption is low in relation to the total own consumption. Nevertheless, for the models presented ahead we decide to divide this energy according to the share of the self-consumption identified in the toal of the continent or region (NUTS II). For robustness check, it was considered an equal probability of the electricity being produced at a certain region nuts III at a continental level or at a NUTS II level.

- Sales of oil derivatives: Between 1998 and 2007, data used to eliminate fuel demand used to generate electricity, is only available per district. Therefore, it is used the closest structure of energy demand that would link districts to regions NUTS III. The same procedure was applied between 1995 and 1997, when data is available for each municipality, but there is no information about the energy used to generate electricity. The robustness check regarding oil consumption consists of a hybrid application of an average of the annual growth rate between 2008 and 2022 and a scalar to keep the total constant.

- Natural gas: The data on natural gas demand starts in 2001, but the first domestic gas networks were developed in the late 1990s, which could mean that ignoring consumption before 2000 could be an oversight. Therefore, between 1995 and 2000, the average annual growth rate between 2000 and 2006 (the period when the network was developed nationwide) was used. As a robustness check, we only consider data available after 2000.

4. Methods

This research mainly consists of testing test main hypotheses regarding the relationship between rising decarbonization factors and their relationship with electricity consumption supplied through the grid. These hypothesis are presented in table 5.

Table 5: Hypotheses regarding the influence of decarbonization on electricity consumption.

Hypothesis	**Description**
H1	A shift towards services in the economy leads to a decrease in electricity consumption.
H2	The replacement of technologies that use fossil fuels with electrical powered techonologies leads to an increase in electricity consumption.
H3	Increasing self-consumption deployment satisfies electricity needs off the grid, with no significant rebound effect.
H4	Energy efficiency policies have the ability to reduce the electricity consumption to produce the same output.
H5	Income elasticity varies when models incorporate decarbonization-driven variables.
H6	There are spatial lag spillovers that influence electricity consumption between regions.
H7	During economic contractions income elasticity is lower (or higher).
H8	Extreme weather conditions have an impact on income elasticity.
H9	There are differences on the regression coefficients between low voltage and high voltage demand models
H10	Recent data provides deeper insights into the impact of the energy transition on electricity consumption by reflecting the latest trends, policy changes, and technological advancements.

In this paper it is used the Structural Change Theory, also known as the Conservation Theory. This theory posits that income is the primary macroeconomic driver of electricity consumption (Costa-Campi et al., 2018). According to this theory, an increase in real GDP leads to an increase in energy consumption. This hypothesis implies that energy conservation policies, including initiatives to reduce greenhouse gas emissions, improve efficiency or implement management strategies to curb energy use, would not have a negative impact on real GDP. Changes in the structure of the economy, such as transitions from industrial to service-oriented sectors, may also affect the relationship between GDP and energy consumption, as service-based economies may require less energy-intensive activities compared to manufacturing. This approach is quite common in order to assess the income elasticity of energy/electricity demand.

Network operators use income data in their investment plans to justify proposed investments to meet decarbonization, flexibility procurement, security of supply and interconnection with other energy sectors (E-Redes, 2024). In addition, national institutions such as ERSE or DGEG also adopt an approach rooted in the conservation theory.

The high probability of existing endogeneity between electricity consumption (and demand), gross value added, energy intensity, electricity consumption share, services share on GVA, self-consumption, and prices, led to the implementation of a two step first differences generalized method of moments (FD-GMM) developed by (Arellano and Bond, 1991), but also to the implementation of the System-GMM estimator (Blundell and Bond, 1998) to include exogenous variables in levels, both with robust standard errors (Windmeijer, 2005). Additionally, as robustness check, the results of the one step estimator are also presented.

Due to multicolinearity issues between Energy Intensity, Electricity Consumption Share on Energy and Gross Value Added given by the VIF values of the Ordinary Least Square (OLS) regression that included all the variables, the analysis was separated into two different final specifications:

One evolving around electricity consumption share:

$$\begin{aligned}\Delta \ln\left(\mathrm{EC\_Pc}_{i,t}\right) = \hat{\alpha}_i &+ \hat{\beta}_1 \Delta \ln\left(\mathrm{GVA\_Pc}_{i,t}\right) + \hat{\beta}_2 \Delta \ln\left(\mathrm{HDD}_{i,t}\right)\\ &+ \hat{\beta}_3 \Delta \ln\left(\mathrm{DC}_{i,t}\right) + \hat{\beta}_4 \Delta \ln\left(\mathrm{GVA\_S}_{i,t}\right)\\ &+ \hat{\beta}_5 \Delta \ln\left(\mathrm{AC\_Pc}_{i,t}\right) + \hat{\beta}_6 \Delta \ln\left(\mathrm{EC\_S}_{i,t}\right) + u_{i,t}\end{aligned} \tag{1}$$

Another revolving around energy intensity:

$$\begin{aligned}\Delta \ln\left(\mathrm{EC\_Pc}_{i,t}\right) = \hat{\alpha}_i &+ \hat{\beta}_1 \Delta \ln\left(\mathrm{GVA\_Pc}_{i,t}\right) + \hat{\beta}_2 \Delta \ln\left(\mathrm{HDD}_{i,t}\right)\\ &+ \hat{\beta}_3 \Delta \ln\left(\mathrm{DC}_{i,t}\right) + \hat{\beta}_4 \Delta \ln\left(\mathrm{GVA\_S}_{i,t}\right)\\ &+ \hat{\beta}_5 \Delta \ln\left(\mathrm{AC\_Pc}_{i,t}\right) + \hat{\beta}_6 \Delta \ln\left(\mathrm{EI}_{i,t}\right) + u_{i,t}\end{aligned} \tag{2}$$

For exogenous variables it was considered the lags of dependent and independent variables. Variables that were not included in the final models, and their lags, were also tested in the combination set of instruments. The use of exogenous variables in levels were did not improve or qualitatively change the results. The model and instruments specification must be validated by the Wald, Hansen and AR tests. We follow (Roodman, 2009) and do not let the number of instruments to be higher than the number of regions (in order to avoid instruments proliferation the command "collapse" in Stata is used).

5. Results

5.1 Main Results

Table 6 provides the results from the regressions performed as well as the results of AR(1), AR(2) and Hansen tests. All variables are first log differentiated.

Table 6: Regression Results on Electricity Consumption

	(1) d_EC_Pc	(2) d_EC_Pc	(3) d_EC_Pc	(4) d_EC_Pc
d_GVA_Pc	0.422^{***}	0.426^{***}	0.404^{***}	0.367^{***}
	(5.64)	(5.35)	(6.77)	(4.23)
d_HDD	0.111^{***}	-0.009	-0.086^{**}	-0.027
	(3.66)	(-0.30)	(2.95)	(-0.95)
d_DC	0.086	0.017	0.041^{*}	0.059
	(1.19)	(0.08)	(2.01)	(0.22)
d_GVA_S	0.345^{***}	$0.301^{\prime}$	0.345^{***}	0.270
	(3.59)	(1.87)	(3.40)	(1.52)
d_AC	-0.002^{*}	-0.003	$-0.002^{\prime}$	$-0.003^{\prime}$
	(-2.16)	(-1.45)	(-1.68)	(-1.89)
d_EC_S	0.082		0.100	
	(0.95)		(1.03)	
d_IE		0.109^{**}		0.110^{***}
		(2.74)		(3.65)
_cons	0.016^{***}	0.018^{***}	0.018^{***}	0.021^{***}
	(4.12)	(5.97)	(5.72)	(8.45)
N	644	644	644	644
Wald chi2	345.43 (0.000)	233.30 (0.000)	366.77 (0.000)	294.54 (0.000)
AR(1) p-value	0.002	0.001	0.005	0.001
AR(2) p-value	0.249	0.208	0.098	0.104
Hansen p-value	0.156	0.116	0.156	0.116
Number of instruments	16	16	16	16

t statistics in parentheses

$^{\prime}p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

The results show that:

H1: 3 out of the 4 models performed concluded that an increase in share of services on the GVA leads to an increase of electricity demand to the network (with a p-value of, at least, 10%). This result may seem counter intuitive, but is aligned with the portion of the literature that finds that factors like the development of the information and communication technologies (Lange et al., 2020) and the increasing of services subsegments that are energy intensive, like tourism (Pablo-Romero et al., 2023), can lead to an increase of electricity consumption. It should be noted that, for example, the transportation sector is considered to be within the services sector. Investment in tourism (AICEP, 2024) leads to an increase in demand of transportation (higher traffic on roads, railways, airports and ports) that may imply a shift into new investment in electric transportation (electric buses or trams). Additionally, further tourist infrastructure, like hotels, restaurants, museums, parks, shops, may adopt technologies that rely on electric powered appliances. Another example that supports the impact of services on electricity demand would be data centers. Portugal has been investing data centers ((Covas et al., 2013) and (ECO News, 2025)), facilities that process and store data, that are known for their high electricity needs to power IT equipment and support cooling systems (Covas et al., 2013). In spite of these effects, as economies may reach a cap on the % of services, the impact of the share of services on electricity consumption may lose impact.

H2: Evidence shows a positive relationship between electrification and electricity consumption supplied over the power grid. Nevertheless, this is a weak nexus since coefficients are not significant. As electric vehicles stock rise and the replacement of other fuels technologies with electrically-powered equivalents takes place, a closer monitoring of this indicator is recommended. In this context, it is important to note the potential confounding effects between the variable 'electricity share in energy consumption' and 'the growth rate of electricity consumption per capita,' which could render the variable insignificant. For instance, (Liddle et al., 2023) uses the growth rate of electricity demand as a proxy for electrification. The results are also aligned with the weak electrification process in Europe that should start to pick up when technologies like electric vehicles and heat pumps get a relevant share of their market (EC, 2025). Furthermore, data that may serve as proxies for electrification could serve as complement to deepen this analysis. Number (or consumption) of electric vehicles per nuts III and investment or incentives to switching into electric technologies (domestic and industrial) would be suitable candidates for these proxies.

H3: Increasing self-consumption deployment satisfies electricity needs off the grid. Self-consumption has the expected sign in all four models, meaning that an increase in self-consumption leads to a decrease in the electricity consumption provided by the power grid. In 3 out of the 4 models the regression coefficient is significant at a 10% level (nevertheless, coefficients are rather small). This may indicate that the effect of renewable self-consumption and energy and communities is still new, and thus, the development of these technologies should be closely monitored. Another hypothesis for the low significance may be related to a rebound effect that may be present in self-consumption, where the investment in these technologies does not necessarily means a decrease of the electricity supplied over the network (though the existence of this effect and its extent have not yet been assessed in the literature).

H4: Energy efficiency policies seems to be efficient in reducing the electricity consumption necessary to produce the same output, ceteris paribus. The low coefficient (slightly above 0.1) may be due to the fact that energy efficiency policies usually target more prominently on fossil fuels consumption, as seen in the RepowerEU plan (EC, 2022), while electricity generation relies further more on renewable capacity.

H5: Income Elasticity varies with regards to the model specification used. Income elasticity varies between 0.367% and 0.426%. These results are well within the intervals presented by (Zhu et al., 2018), (Mubiinzi et al., 2024), or (Csereklyei, 2020) and corroborate the view that income remains a valid driver of electricity demand on the power grid.

Furthermore, two robustness checks are conducted in Annex A and B. In Annex A, various lag specifications are tested to validate the results. In Annex B it is presented the results for the System-GMM estimator. Qualitatively, the main findings remain consistent.

5.2 Is there evidence of spatial spillovers?

Due to potential spatial lag spillovers that may arise between nuts III regions, the two first models were extended to include a spatial lag dependencies using a binary rook contiguity matrix [3].

Extended spatial model revolving around electricity consumption share (where W represents the spatial weight matrix.):

$$\begin{aligned}\Delta \ln \left(\mathrm{EC\_Pc}_{i,t}\right) = \hat{\alpha}_i + \hat{\rho}_1 \sum_j W_{ij} \Delta \ln \left(\mathrm{EC\_Pc}_{j,t}\right) + \hat{\rho}_2 \sum_j W_{ij} \Delta \ln \left(\mathrm{GVA\_Pc}_{j,t}\right) \\ + \hat{\beta}_1 \Delta \ln \left(\mathrm{GVA\_Pc}_{i,t}\right) + \hat{\beta}_2 \Delta \ln \left(\mathrm{HDD}_{i,t}\right) \\ + \hat{\beta}_3 \Delta \ln \left(\mathrm{DC}_{i,t}\right) + \hat{\beta}_4 \Delta \ln \left(\mathrm{GVA\_S}_{i,t}\right) \\ + \hat{\beta}_5 \Delta \ln \left(\mathrm{AC\_Pc}_{i,t}\right) + \hat{\beta}_6 \Delta \ln \left(\mathrm{EC\_S}_{i,t}\right) + u_{i,t}.\end{aligned} \tag{3}$$

Extended spatial model revolving around energy intensity:

$$\begin{aligned}\Delta \ln \left(\mathrm{EC\_Pc}_{i,t}\right) = \hat{\alpha}_i + \hat{\rho}_1 \sum_j W_{ij} \Delta \ln \left(\mathrm{EC\_Pc}_{j,t}\right) + \hat{\rho}_2 \sum_j W_{ij} \Delta \ln \left(\mathrm{GVA\_Pc}_{j,t}\right) \\ + \hat{\beta}_1 \Delta \ln \left(\mathrm{GVA\_Pc}_{i,t}\right) + \hat{\beta}_2 \Delta \ln \left(\mathrm{HDD}_{i,t}\right) \\ + \hat{\beta}_3 \Delta \ln \left(\mathrm{D\text{-}C}_{i,t}\right) + \hat{\beta}_4 \Delta \ln \left(\mathrm{GVA\_S}_{i,t}\right) \\ + \hat{\beta}_5 \Delta \ln \left(\mathrm{AC\_Pc}_{i,t}\right) + \hat{\beta}_6 \Delta \ln \left(\mathrm{EI}_{i,t}\right) + u_{i,t}.\end{aligned} \tag{4}$$

According to (Elhorst, 2022) the GMM estimators can be used to estimate spatial econometric models by extending the spatial autoregressive (SAR)((Kelejian and Prucha, 1999), (Kukenova and Monteiro, 2008) and (Bouayad-Agha and Vedrine, 2010)) with spatial lags in the explanatory variables. According to (Elhorst, 2022) the inclusion of independent spatial lags does not cause severe supplementary econometric issues.

Results are presented in table 7

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[3] For this hypothesis, the models presented include the spatial lag of the dependent variable and the independent spatial lag for the best performing variable (GVA) in terms of significance, which also has the greatest theoretical impact.

Table 7: Regression Results on Electricity Consumption considering Spatial Spillovers

	(5) d_EC_Pc	(6) d_EC_Pc
d_GVA_Pc	0.321**	0.380*
	(2.70)	(2.10)
d_HDD	0.124*	0.004
	(2.02)	(0.28)
d_DC	0.042	0.041
	(0.43)	(0.26)
d_GVA_S	0.261*	0.264
	(2.01)	(1.47)
d_AC	-0.002$'$	-0.002$'$
	(-1.80)	(-1.76)
d_EC_S	0.162	
	(1.34)	
d_IE		0.105***
		(3.19)
w_EC	-0.139	0.092
	(-0.59)	(0.54)
w_GVA	0.215*	0.011
	(2.24)	(0.09)
_cons	0.017**	0.016***
	(2.38)	(3.73)
N	644	644
Wald chi2	467.26 (0.000)	356.27 (0.000)
AR(1) p-value	0.005	0.001
AR(2) p-value	0.137	0.452
Hansen p-value	0.171	0.322
Number of instruments	20	22

t statistics in parentheses

$' p < 0.1$, $^{*} p < 0.05$, $^{**} p < 0.01$, $^{***} p < 0.001$

H6: There is scarce evidence for the existence spatial lags. This can be attributed to a key characteristic of electricity: it cannot be easily stored, or at least, current storage capacity remains far from covering a substantial share of total consumption. The only significant effect may be that an increase in the GVA can lead to an increase of electricity consumption on neighbor region. A possible explanation is that an income increase in a given region may stimulate the economic activity of other regions due to economic spillovers and infrastructure dependency. This relationship between income and spatial electricity consumption has been observed in the studies conducted by (Duan et al., 2021) and (Blázquez Gomez et al., 2013).

5.3 How does income elasticity of electricity demand vary during periods of economic contraction and under extreme weather conditions?

On this subsection the previous models are extended with dummies and interactive terms in order to answer two questions: 1) does income elasticity varies with business cycles, in particular, does economic contractions lead to changes in the economic elasticity? 2) does unusual weather conditions influence the income elasticity?

For the contraction hypothesis it was used an interactive dummy variable that captures falls in the GVA for each region. For the weather conditions analysis it was used an interactive dummy variable regarding the z-scores for CDD and HDD variable in models 7 and 8. Models 9 and 10 include a dummy variable for CDD and HDD without interaction with GVA. A z-value threshold of 1.96 ($P(Z) > Z = 0.05$) is considered in order to indicate unusual weather conditions. This approach can provide a more nuanced understanding of how weather extremes affect the variables of interest.

The results are reported on the table 8.

Table 8: Regression Results for Economic Downturns and Unusual Weather Conditions

	(7) d_EC_Pc	(8) d_EC_Pc	(9) d_EC_Pc	(10) d_EC_Pc
d_GVA_Pc	0.489^{***}	0.533^{***}	0.408^{**}	0.578^{***}
	(4.31)	(6.66)	(3.03)	(6.11)
d_HDD	0.096^{*}	-0.053		
	(2.36)	(-0.81)		
d_DC	0.298	0.195	-0.085	0.059
	(1.52)	(1.22)	(-0.40)	(0.41)
d_GVA_S	0.322^{**}	0.175	0.191^{**}	0.206^{*}
	(3.05)	(1.29)	(2.94)	(1.99)
d_AC	-0.002	-0.001	-0.001	-0.016^{*}
	(-0.82)	(-0.63)	(-0.95)	(-2.01)
d_EC_S	(0.044)		$0.198'$	
	(0.62)		(1.93)	
d_IE	(0.044)	0.140^{***}	0.001	0.134^{***}
	(0.62)	(5.08)	(0.70)	(3.53)
D_GVA_Contraction	0.002	0.004	-0.103	0.003^{**}
	(1.25)	1.55	(-1.33)	(2.64)
D_GVA_CDD	0.000	-0.009		
	(0.07)	-1.04		
D_GVA_HDD	0.019	$0.028'$		
	(0.74)	1.64		
D_CDD	0.000	-0.009	-0.103	-0.064
	(0.07)	-1.04	(-1.33)	(-1.22)
D_HDD			0.315^{*}	$0.163'$
			2.40	(1.67)
_cons	0.016^{***}	0.020^{***}	0.004	0.018^{***}
	(4.40)	(6.23)	(0.56)	(4.29)
N	644	644	644	644
Wald chi2	386.72 (0.000)	1358.07 (0.000)	126.56(0.000)	278.54 (0.000)
AR(1) p-value	0.121	0.016	0.000	0.002
AR(2) p-value	0.899	0.144	0.395	0.056
Hansen p-value	0.139	0.137	0.382	0.493
Number of instruments	16	17	16	17

t statistics in parentheses

$' p < 0.1$, $^{*} p < 0.05$, $^{**} p < 0.01$, $^{***} p < 0.001$

In this paper, income elasticity refers to the impact of a 1% increase in income on electricity demand. Despite this definition, this subsection introduces other variables: `d_GVA_Pc` represents income elasticity, `D_GVA_Contraction` captures income elasticity during contractions (1 if the region is in recession), `D_GVA_CDD` and `D_GVA_HDD` are interaction terms between income and weather variables, while `D_CDD` and `D_HDD` are dummy variables that take the value 1 if extreme degree days are observed.

The results show that:

H7: There is not evidence that during economic contractions periods there is changes in the income elasticity. The interactive dummy variable was insignificant in all models tested. For example, in 2020, during the pandemics crisis, the Portuguese Gross Domestic Product (GDP) fell 8.2% while electricity consumption decrease only 3.2%. This would mean an income elasticity around 0.4 which is totally within the interval given by this paper's estimates.

H8: The models don't provide clear evidence that weather has the potential to create an impact on electricity consumption via increases on the income elasticity. Regarding dummies withou interactions (models 9 and 10) it is possible to observe that when unusual heating needs occur, they have significant impact on electricity demand (and with greater impact than cooling needs).

5.4 Does results change among voltage levels?

Next, it is separated the electricity demand by two voltage levels, according to data reported by DGEG: i) Low-voltage level (consumption associated with connection voltages less than 1000V, usually by residential sector as well as small agriculture and services consumers); ii) High-voltage level (consumption associated with connection voltages equal to or greater than 1000V , usually demanded by industrial sector as well as big agriculture and services consumers).

Tables 9 and 10 show the results for low voltage and high voltage regressions.

Table 9: Regression Results - Low voltage consumption

	(11) d_EC_Pc	(12) d_EC_Pc	(13) d_EC_Pc	(14) d_EC_Pc
d_GVA_Pc	0.480^{*}	0.552^{***}	0.571^{**}	0.371^{**}
	(2.54)	(3.46)	(2.83)	(2.79)
d_HDD	$0.023^{\prime}$	0.022	$0.158^{\prime}$	$0.081^{\prime}$
	(1.95)	(1.14)	(1.86)	(1.76)
d_DC	0.162	0.307	0.379	0.270
	(1.50)	(1.14)	(1.27)	(0.80)
d_GVA_S	0.514^{***}	0.506^{*}	0.557^{***}	0.302
	(3.10)	(2.46)	(3.69)	(1.52)
d_AC	-0.004	$-0.003^{\prime}$	-0.003	$-0.030^{\prime}$
	(-1.30)	(-1.28)	(-1.48)	(-1.66)
d_EC_S	0.039		0.181^{*}	
	(0.43)		(2.03)	
d_EI		0.184^{***}		0.019
		(3.50)		(0.44)
w_EC			$-0.597^{\prime}$	-0.030
			(-1.78)	(-0.329)
w_GVA			0.379^{**}	0.026
			(2.96)	(0.40)
_cons	0.025^{***}	0.026^{***}	0.031^{***}	0.016
	(3.75)	(4.86)	(3.57)	(1.34)
N	644	644	644	644
Wald chi2	204.78 (0.000)	160.77 (0.000)	277.75 (0.000)	152.09(0.000)
AR(1) p-value	0.002	0.001	0.002	0.002
AR(2) p-value	0.293	0.795	0.115	0.144
Hansen p-value	0.126	0.160	0.146	0.177
Number of instruments	22	22	21	18

t statistics in parentheses

$^{\prime}p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

The income elasticity varies between 0.371% and 0.571%, slightly higher coefficients than the ones obtained by the models (1) to (6). Heating Degree Days surges as significant variable at 10% in models (11), (13) and (14), which aligns with the expected behavior that the residential sector is sensible to extreme cold temperatures and make use of electric heating to heat homes. Additionally, self-consumption remains significant (at 10% level) in models (12) and (14) and on the edge of significance in model (13).

Table 10: Regression Results - High voltage consumption

	(15) d_EC_Pc	(16) d_EC_Pc	(17) d_EC_Pc	(18) d_EC_Pc
d_GVA_Pc	0.516***	0.570***	0.521**	0.500**
	(4.11)	(3.25)	(2.59)	(2.62)
d_HDD	0.033**	0.130	0.211***	0.149**
	(2.79)	(1.59)	(2.92)	(2.65)
d_IC	0.042	0.118	0.136$^{\prime}$	0.086
	(1.00)	(1.46)	(1.80)	(1.25)
d_GVA_S	0.462***	0.547***	0.493***	0.483***
	(3.38)	(3.65)	(3.73)	(3.65)
d_AC	-0.004$^{\prime}$	-0.003	-0.004$^{\prime}$	-0.002$^{\prime}$
	(-1.77)	(-1.23)	(-1.94)	(-1.88)
d_EC_S	0.092		0.218	
	(0.99)		(1.33)	
d_EI		0.164***		0.165***
		(3.40)		(3.52)
w_EC			-0.611**	-0.444*
			(-3.02)	(-2.07)
w_GVA			0.435$^{\prime}$	-0.440
			(1.83)	(0.95)
_cons	0.022***	0.026***	0.031***	0.034
	(4.57)	(4.84)	(3.95)	(5.89)***
N	644	644	644	644
Wald chi2	112.74 (0.000)	139.15 (0.000)	180.98 (0.000)	289.75(0.000)
AR(1) p-value	0.002	0.000	0.002	0.001
AR(2) p-value	0.291	0.709	0.117	0.423
Hansen p-value	0.166	0.137	0.340	0.347
Number of instruments	22	20	21	22

t statistics in parentheses

$^{\prime}p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Overall, the results suggest that:

H9: High voltage levels reported by table (10) a slightly higher income elasticity than residential demand. Similar results can be found for the case of heating degree days, where an increase of 1% in the heating days leads to an incshow rease of the electricity between 0.033% and 0.211%. Self-consumption has a homogeneous impact on electricity demand independently of considering low voltage or high voltage consumption. Regarding energy efficiency, results support the idea that energy policies are more effective in reducing electricity demand on consumers that have higher connection capacities while electrification seems to have a greater impact on demand in the residential users. This indicates that policies targeting electricity savings are more efficient for the industrial consumers. Development and replacement of industrial/agriculture equipment, incentivized by public policies, helps to generate a greater amount of electricity savings. Nevertheless, it should be highlighted that energy efficiency is treated by economic theory as a limited resource, whose adoption, driven by public policies and prices, is under diminishing returns (yet with no consensus (Lovins, 2018)). Thus, rising energy saving costs per unit should be taken into consideration when assessing the implementation of energy efficiency policies.

Overall, and consistent with the findings of (Zhu et al., 2018), (Byrne et al., 2021) and (Idsø et al., 2024)), demand is inelastic to price changes. Though positive in most models, it is not significant in any model at a 5% significance level. Due to being used for essential needs, people are willing to pay a higher price for electricity rather than go without it. Additionally, there are very few (if any) substitutes for electricity.

5.5 How do the results change when considering only recent data?

Regressions presented in table 11 consider only data after 2014. This period is chosen to represent the ramp up of the decarbonization drivers where the impact on electricity consumption may be greater. In particular:

- 2014 coincides with the first legal initiatives to promote renewable self-consumption
- EU Directive No. 2012/27 on energy efficiency, was transposed to national law in 2015
- In 2014, portuguese government introduced a programme to write-off old vehicles that would grant fiscal benefits for the purchase of an electric vehicle (**?**)

Additionally, this subset, allow to keep 207 observations.

Table 11: Regression Results - After 2014

	(19) d_EC_Pc	(20) d_EC_Pc
d_GVA_Pc	0.467***	0.388***
	(3.36)	(3.43)
d_HDD	0.048$'$	0.119*
	(1.91)	(2.17)
d_DC	0.059	-0.108
	(0.68)	(-0.76)
d_GVA_S	0.084	-0.038
	(0.42)	(-0.20)
d_AC	-0.003	-0.001
	(-0.94)	(-0.17)
d_EC_S	0.326**	–
	(2.22)	–
d_EI	–	0.247***
	–	(3.83)
_cons	-0.002	0.005
	(-0.34)	(0.85)
N	207	207
Wald chi2	81.91	115.45
	(0.000)	(0.000)
AR(1) p-value	0.016	0.030
AR(2) p-value	0.964	0.217
Hansen p-value	0.222	0.334
Number of instruments	16	16

t statistics in parentheses
$'p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

H10: Recent data shows that electrification is gaining momentum on the impact of electricity demand (model 19), while energy savings policies remain effective on reducing electricity consumption. As the uptake of electrification, fostered by electric vehicles and residential appliances, occurs, the pressure of the demand on the electricity provided by the power grid is expected to increase. Changes to a more services oriented economy, does not lead to an increase in electricity consumption after 2014. One possible explanation, is that the highest growth of the services sector happened in th 90's and 00's combined with a possible saturation of digitalization and tourism investment in the late 10's and 20's.

6. Policy Implications

Achieving net zero targets is crucial for mitigating climate change and limiting global temperature rise to 1.5°C above pre-industrial levels. Reducing GHG emissions helps to prevent the worst effects of climate change, such as extreme weather events, sea-level rise, and ecosystem collapse (IPCC, 2023). It also promotes sustainable economic growth, protects public health, and ensures energy security.

Portugal has shown strong commitment to achieving net zero emissions by 2050, aligning with both the European Union's Green Deal and global climate goals. The country has made significant progress in renewable energy, with over 70% of it ts electricity consumption coming from renewable sources like wind, solar, and hydropower in 2024 (APREN, 2023). This push toward clean energy has helped Portugal reduce its carbon emissions and decrease reliance on fossil fuels.

Portugal's National Energy and Climate Plan (DGEG, 2023) emphasizes policies on decarbonization of the energy sector, sustainable transport, and energy efficiency in buildings. Key policies include phasing out coal by 2023, increasing electric vehicle adoption, and enhancing forest management to act as carbon sinks. The government also seeks to expand offshore wind projects and hydrogen production as part of its strategy to meet net zero targets.

A resilient and decarbonized electricity network is essential for achieving net zero, as it enables the integration of renewable energy sources, electrification of sectors, and reduction of carbon emissions. In order to long-term planning and forecasting be successful regarding optimal grid investment, it must take into account the ever changing decarbonization drivers.

In particular, the policy implications of this paper are as follows:

- Energy efficiency policies should continue be fostered - Even though savings on energy consumption may partially be counterbalance by increased consumption over the long-run, electricity generation has becoming more clean, as renewable capacity grows. Programs implemented in Portugal (such as Public Lighting LED Replacement Initiative, Energy-efficient Appliances Incentive and Building Energy Efficiency Program) has led to more cost effective and resilient energy services that need to continue to be promoted (Martins et al., 2022). Nevertheless, as the most efficient programs are implemented, future measures should account for diminishing returns.

- Electrification should be incentivized along with renewable deployment - in order to electrification to reach its potential for decarbonization it is essential to promote renewable generation (Felício et al., 2024) along with other policies (demand flexibility, batteries, investment in hydrogen). Incentives for the adoption of electric vehicles, public transport electrification or subsidies to appliances (for example heat pumps (Felício et al., 2024)) have been reasonable successful in shifting from fossil fuels to electricity generation (EC, 2025). Planning and investment on the electricity generation and grid should incorporate information about the evolution of the electrification.

- Energy efficiency and electrification policies should be jointly assessed - Incentivize energy savings while promoting shifts from fossil fuels to electricity can interact in confounding ways: improving efficiency may reduce electricity demand, but rapid electrification can lead to increased consumption. Nevertheless, the author view is that these two effects are complementary. Deployment of electrification projects should be accompanied by efforts to efficiency improvements in order to avoid strains in the grid and increases in the peak demand (and, therefore, investment). A coordinated approach ensures that electrification efforts do not undermine efficiency gains and that efficiency measures support a sustainable, low-carbon energy system. By aligning these policies, governments can optimize economic, environmental, and social benefits, leading to a more resilient and cost-effective energy transition.

- Self-consumption flexibility and awareness - renewable self-consumption and energy communities are starting to reach a substantial amount of installed capacity. In order to reap the best benefits from these, policymakers should pay careful attention to laws, finances and social developments of self-consumption as its complexity and novelty aspect will demand an extreme learn by doing approach. On this topic, it should be noted that new European laws will set to require solar installations on buildings across the European Union (Widuto, 2022). This means that solar installations must be integrated into building works, and public bodies must retroactively install PV panels on their buildings, entering into force gradually from 2026. Fostering energy communities and self-consumption is accompanied with a number of social issues. High income consumers may have the best means (financial, siting, legal) to deploy self-consumption technologies leaving the burden of the costs with network investment and operation/maintenance to the lowest income consumers that are already penalized by being excluded from the self-consumption benefits. This is where regulatory authorities should coordinate with governments, as self-consumption can play a role in grid infrastructure investment strategies (by, for example, reducing investment needs) but that must be accompanied by social policies that are beyond the scope of regulatory authorities [4]. As these technologies are deployed, the allowed revenues and tariffs best strategy may be shifting towards a more capacity/peak demand approach rather than an approach based on electricity supply. Nevertheless, this paper advocates that the user-basis principle should not be completely eliminated.

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[4] Although, ERSE is mandated to protect the interests of consumers, particularly the most vulnerable, and create the conditions for their empowerment, the social policies are primarily conducted by governmental agencies.

- Improving services sector remains a valid strategy - even though increasing GVA share leads to an increase of electricity consumption, this sector remains the less energy intensive. Investment in segments such as tourism, transportation and digitalization (for example datacenters) must be met with efforts to address environmental concerns that comes from the increase in electricity demand. First, and as stated before, increase in electricity demand should be met with more renewable capacity rather than fossil fuel generation. Second, the services sector should expand at the "expense" of deployment of electricity-fueled technologies and with the enforcement of the required energy efficiency standards. Investment in tourism and transportation should be seen as an opportunity to deploy and develop the public electric vehicle fleet. Development of energy efficiency measures targeted to datacenters may translate to further uses in residential or industrial appliances.

- The absence of spatial lags suggests that policies, such as those aimed at improving energy efficiency, may only have an impact in electricity consumption in a given region without spillover effects in neighboring areas. Consequently, in the example presented, implementing energy efficiency measures in one region would not necessarily justify disinvestment in network capacity elsewhere. At the same time, while there is some evidence that an increase in income may lead to spatial spillovers, this may suggest that investment in the network in a given region must take into account the economic development of surrounding regions. Nevertheless, the overall results suggest that decisions on local investment in the power sector can be assessed using regional data.

- Lastly, in order to design the best policies to reduce GHG emission, recommendation is that all stakeholders should take into consideration decarbonization factors into their forecasts, in particular for decisions regarding energy (and electricity) investment, prices and demand decisions.

The energy transition will require significant investments in the energy sector, including in the electricity power grid and other regulated activities, to increase grid capacity to integrate variable renewable energy sources such as wind and solar, to upgrade ageing infrastructure, to handle increased loads and to improve reliability, to implement smart grid technologies, to invest in batteries and other storage solutions, to balance supply and demand, to develop systems to manage and reduce peak demand through consumer engagement and incentives, and to strengthen defences against cyber threats to ensure the security and resilience of the grid. For these reasons, there is a need for a framework that takes into account the evolution of electricity supplied by the grid in order to accurately assess investments.

7. Conclusions

This paper focused on determining the impact of rising decarbonization and economic drivers on the electricity consumption supplied over the power grid, in Portugal, between 1995 and 2023.

Climate change has been affecting inhabited regions of the world, with human activities contributing significantly to many of the observed changes in climate extremes. In response, various global organizations and countries have committed to achieving net-zero emissions. At the level of the European Union (EU27), the main strategies identified to achieve carbon neutrality include (1) the implementation of the "energy efficiency first" principle in energy policy formulation and investment decisions, (2) the promotion of electrification of the energy sector, supported by the generation of electricity from endogenous renewable energy sources (target of at least 40% of energy from renewable sources by 2030), (3) the financing of the green transition to provide funding for environmentally sustainable economic activities, or (4) research and innovation to develop new technologies and solutions for climate change mitigation and adaptation.

Investment in power grids is driven by increasing electrification and the need to integrate high levels of renewable capacity across Europe. Investment in power grids is expected to account between 15% to 20% of total investment(EC, 2023b), and will take place in both transmission and distribution networks to further develop smart grids, integrate decentralized energy sources and electric vehicles, and enable the energy consumers to actively participate in energy markets.

If it is considered only the consumption of electricity supplied by the network, an important implication is derived: forecasting may become more uncertain, which may lead to a less accurate assessment of the investment needs in the network proposed by the network operators. In addition, it may lead to greater deviations in the provisional allowed revenues (whether in the form of unit costs or via operational cost drivers of the network activities) which can greatly impact final consumers and financial stability of operators. It is therefore important to assess the impact of future policies on the electricity consumption (supplied over the power grid) as well as the impact on income elasticity that may also influence electricity consumption.

A regulatory framework that is capable of adapting and capturing the impact of energy transition, by allowing the right set of drivers of firm's allowed revenues and tariffs while providing the necessary signals for investment, is better prepared to deliver an efficient national electric system that empowers consumers, ensures the financial stability and the regulated firms, and deploys the necessary infrastructure to meet energy transition challenges. Thus, in order to accurately forecast long-term electricity demand, it is vital to include rising trends related to decarbonization and economic development/structures.

With further research, this study can be improved and extended to make long-term electricity forecasts. Its results should be tested against other methodologies, the data sample could be extended to cover a longer time period and recent developments on energy transition should be included. It should be noted that this study does not measure all decarbonization factors that are having an impact on electricity consumption either due to the lack of data (stock electric vehicles or their electric consumption per nuts iii) or because they are a very recent phenomenon (for example hydrogen network developments).

Annex A

Table 12: Robustness Check with Lags - Regression Results

	(1b) d_EC_Pc	(2b) d_EC_Pc	(3b) d_EC_Pc	(4b) d_EC_Pc	(5b) d_EC_Pc	(6b) d_EC_Pc
d_GVA_Pc	0.399^{***}	0.554^{***}	0.360^{***}	0.538^{***}	0.321^{**}	0.367^{**}
	(5.38)	(3.70)	(3.43)	(8.28)	(2.70)	(2.84)
d_HDD	0.100^{***}	0.223^{**}	0.013	0.124^{***}	-0.124^{*}	0.147^{**}
	(3.77)	(2.80)	(0.68)	(4.57)	(2.02)	(2.80)
d_DC	0.068	0.376	0.105	0.122	0.042	0.120
	(1.38)	(1.11)	(0.31)	(0.85)	(0.43)	(0.66)
d_GVA_S	0.353^{***}	0.528^{**}	$0.314'$	0.484^{***}	0.261^{*}	0.309^{**}
	(4.19)	(2.85)	(1.72)	(5.89)	(2.01)	(2.85)
d_AC	$-0.003'$	0.0001	$-0.003'$	-0.001	$-0.002'$	-0.001
	(-1.83)	(0.38)	(-1.89)	(-0.57)	(-1.80)	(-0.35)
d_EC_S	0.025		0.051		0.162	
	(0.95)		(0.70)		(1.34)	
d_IE		0.118^{***}		0.188^{***}		0.115^{***}
		(3.08)		(7.08)		(3.26)
w_EC					-0.139	0.009
					(-0.59)	0.06
w_GVA					0.215^{*}	0.123
					(2.24)	1.17
_cons	0.017^{***}	0.017^{***}	0.020^{***}	0.018^{***}	0.017^{*}	0.018^{***}
	(4.62)	(5.79)	(5.52)	(7.73)	(2.38)	(3.91)
N	644	644	644	644	644	644
Wald chi2	215.81 (0.000)	135.03 (0.000)	469.92 (0.000)	350.03 (0.000)	467.26 (0.000)	235.98 (0.000)
AR(1) p-value	0.001	0.005	0.002	0.001	0.005	0.001
AR(2) p-value	0.306	0.774	0.326	0.750	0.137	0.708
Hansen p-value	0.220	0.082	0.236	0.106	0.171	0.108
Number of instruments	18	17	16	18	20	22

t statistics in parentheses

$'p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Annex B

Table 13: Robustness Check with System GMM estimator - Regression Results

	(1c) d_EC_Pc	(2c) d_EC_Pc	(3c) d_EC_Pc	(4c) d_EC_Pc
d_GVA_Pc	0.473***	0.385***	0.462***	0.349***
	(5.18)	(5.26)	(5.84)	(4.10)
d_HDD	0.136***	-0.001	0.136***	-0.000
	(4.52)	(-0.04)	(5.36)	(-0.01)
d_DC	0.028	-0.282	0.048	-0.284
	(0.37)	(-1.49)	(0.62)	(-1.22)
d_GVA_S	0.344**	0.250$^{\prime}$	0.351***	0.247
	(3.05)	(1.86)	(3.33)	(1.46)
d_AC	-0.002$^{\prime}$	-0.003$^{\prime}$	-0.002$^{\prime}$	-0.003**
	(-1.71)	(-1.74)	(-1.71)	(-2.09)
d_EC_S	0.208		0.205	
	(1.38)		(1.32)	
d_IE		0.099**		0.107***
		(2.87)		(3.55)
w_EC				
w_GVA				
_cons	0.012**	0.017***	0.015***	0.019***
	(2.23)	(6.34)	(3.26)	(8.04)
N	644	644	644	644
Wald chi2	314.28 (0.000)	281.42 (0.000)	364.14 (0.000)	430.31 (0.000)
AR(1) p-value	0.009	0.001	0.003	0.001
AR(2) p-value	0.193	0.170	0.058	0.099
Hansen p-value	0.157	0.122	0.157	0.122
Number of instruments	18	19	19	19

t statistics in parentheses

$^{\prime}p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

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