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Municipal Energy Efficiency in Portugal: An Analysis of Electricity and Natural Gas Consumption

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Abstract

Analysing energy consumption efficiency is essential for understanding energy resource consumption patterns, identifying the economic consequences, and developing effective public policies. The study investigates energy consumption efficiency levels in Portuguese municipalities in order to analyse disparities in energy consumption efficiency. The aim is to observe the possible relationship between population density and the energy consumed by residents. The study uses the DEA model to detect benchmarking patterns, inefficiencies, and opportunities for improvement in energy consumption practices. The results suggest that there are serious disparities in energy consumption efficiency between Portuguese municipalities and a significant positive correlation between population density and the amount of energy consumed. The disparities can be attributed to the different levels of adoption of efficient energy consumption practices. The results point to the need to define public policies aimed at promoting more efficient energy consumption practices. The research emphasises the importance of implementing more effective public policies that encourage the adoption of sustainable energy consumption practices by residents. The conclusions have important practical implications for the formulation of public policies aimed at local energy efficiency and the development of sustainable energy consumption.

Keywords: *Energy Consumption, Energy Efficiency, Population Density, Sustainable Development, Public Policies, Local Economies.*

INTRODUCTION

The efficiency of electricity and natural gas consumption in municipalities is a relevant topic for research, since reducing the use of fossil fuels can help reduce greenhouse gas emissions and contribute to climate change mitigation. On the other hand, it allows for the development of resource savings by allocating available financial resources to other priority areas and the creation of more competitive, energy-efficient local economies, making it possible to attract companies and citizens who are more aware of the benefits of green economies.

The research problem stems from the need to increase the efficiency of electricity and natural gas consumption in municipalities. Defining a balance between energy efficiency and the quality of life of residents is fundamental to promoting sustainable local development and adopting more effective public policies and new technologies. The research aims to address the relationship between energy consumption and population levels. By explaining this relationship, the research seeks to contribute to the perception of energy consumption efficiency levels and assist in the process of drawing up public policies that can promote the adoption of more sustainable environmental practices.

The topic is pertinent because municipalities face notable challenges in terms of promoting and increasing environmental sustainability, fulfilling the objectives of the SDGs, adopting innovative technologies, and improving citizens' quality of life.

LITERATURE REVIEW AND HYPOTHESES

Energy efficiency is currently one of the most relevant areas of analysis in the theoretical field of public and territorial administration (Rezessy et al., 2006.

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For the doctrine, efficiency involves analysing the methods, practices, and processes adopted by municipalities (Phillips & Thorne, 2013) and, above all, the relationship between the development of the economy and energy consumption levels (Topolewski, 2021) in order to identify possible sustainable energy consumption benchmarking practices (Roth et al., 2020). In terms of theory, the DEA model makes it possible to identify the most efficient municipalities (Bruno & Erbetta, 2013).

According to sustainable development goals and financial theory, one of the main metrics for assessing energy efficiency is the relationship between energy consumption and the population density of municipalities (Zarco-Periñán et al., 2021), analysing energy markets (Dolšak et al., 2020), and the efficiency of energy distribution chains (Marchi & Zanoni, 2017).

Analysing the efficiency of local energy consumption stems from the need for actors to reduce the effects of greenhouse gas emissions by making public investments in new energy sources capable of increasing the efficiency levels of local energy consumption (Sotnyk et al., 2023). On the other hand, the adoption of sustainable energy consumption practices by residents enables economic growth in the industrial sector (Agrawal et al., 2023), stimulates energy innovation (Bossink, 2017), and increases the competitiveness of local authorities (Janikowska & Jebreel, 2022).

The theory defends energy as a high-value economic good capable of affecting the socio-economic development levels of regions (Ziolo et al., 2020). Therefore, one of the aims of public policy is to increase energy efficiency by changing energy consumption patterns and by defining and implementing legislative instruments (Nadimi & Tokimatsu, 2019).

More recent research seeks to analyse energy efficiency levels in order to identify benchmarking practices (Tan et al., 2015) and ways to reduce electricity and gas consumption (Vaisi et al., 2023). To this end, the theory advocates analysing energy efficiency from the consumer's perspective, i.e., by defining the number of resources needed to be extracted to meet the needs of the inhabitants (Nørgard, 2006) and using data envelopment analysis (Koilo et al., 2022).

In the view of Lozynsky et al. (2021), rather than adopting and implementing smart management models for municipalities, it is essential to develop more active government instruments, complemented by public measures to increase energy efficiency.

With regard to energy consumption efficiency, Michailidis et al. (2024) suggest adopting neural network approaches to solve energy efficiency management problems in order to achieve an approximate expected value of the energy required for consumption. However, just defining algorithms to solve municipalities' energy efficiency problems is not, at least hypothetically, an ideal solution. According to Streimikiene et al. (2023), it is necessary to define and implement policies that promote local awareness of energy efficiency. On the other hand, consumers' adherence to the efficient consumption of available energy resources depends above all on population density and their particular energy needs. It is in this sense that the definition of regional strategies for involving consumers in energy efficiency is essential.

Another important study for analysing and perceiving the energy efficiency of municipalities was carried out by Tsurkan et al. (2017). For the authors, in Russia, funding sources are a key component for increasing the energy efficiency of local economies. The authors concluded that one of Russia's energy problems stems from high consumption, which hinders the sustainable growth of municipalities and exacerbates inequalities in local energy efficiency. In the Ukrainian context, Pimonenko et al. (2017) point out that civil society's lack of awareness leads to a slow adoption of more efficient energy consumption practices. To this end, the authors propose the creation and implementation of economic benefits related to the purchase of solar equipment.

In China, studies on the energy sector have neglected the importance of consumption efficiency. In this context, Hu and Wang (2006) analysed the energy efficiency of 29 administrative regions between 1995 and 2002 using the DEA methodology in order to find the most efficient consumption in each region for each year. According to the results, the centre of China has the worst energy efficiency levels compared to the rest of the country. The authors conclude that the regions with the highest levels of energy efficiency are those that contribute most to improving economic growth. Another study on the Chinese context was carried out by Bian and Yang (2010).

The authors applied the DEA model to assess energy efficiency. The results suggest that there are different levels of efficiency between the provinces.

In Japan, Honma and Hu (2008) studied the energy efficiency levels of 47 municipalities using the DEA model, based on 11 energy sources. According to the data, the most inefficient municipalities are Niigata, Wakayama, Hyogo, Chiba, and Yamaguchi. In contrast, municipalities inland and along the Sea of Japan are the most efficient in terms of energy consumption. The authors also conclude that there is a direct relationship between energy efficiency and the per capita income of Japan's municipalities.

For Shang et al. (2020), there is currently a notable imbalance between regional development and energy consumption among municipalities, which is why the authors highlight the importance of analysing and measuring energy efficiency. For this purpose, 30 municipalities were selected. The data suggests an average energy consumption efficiency of 45.59 percent and that investments in technology could increase efficiency by 50 percent. On the other hand, they also indicate the existence of a significant positive correlation between consumption and territories, i.e., a given more efficient municipality can promote the development of the efficiency levels of the surrounding municipalities.

In addition to analysing the efficiency of energy consumption, the doctrine also analyses the efficiency levels of distribution channels. Using the DEA model, Wei et al. (2021) sought to estimate the efficiency levels in energy production, transmission, and distribution of 30 municipalities in China between 1998 and 2019. The study concludes that average efficiency is low and the disparities between municipalities are considerable. In most municipalities, the results suggest that efficiency in electricity production is higher than efficiency in transmission and distribution.

In terms of gas, studies have centred on the efficiency of natural gas production and the relationship between gas and economic growth. Currently, there are few studies on the efficiency of natural gas consumption. In order to fill this gap, Li et al. (2020) and Zeng et al. (2018) analysed the efficiency of municipalities' natural gas consumption. To this end, they applied the DEA model and concluded that efficiency levels tend to decrease over time. On the other hand, the results also suggest that in order to improve efficiency, it is necessary to invest in new technologies. Another similar study was carried out by Bai et al. (2012) and concluded that the efficiency levels of municipalities are low and tend to improve slowly.

In Brazil, Mello et al. (2008) analysed the levels of efficiency in converting energy consumption into income in the municipalities of Rio de Janeiro. The classic DEA models (CCR and BCC) were used, and the results indicate that municipalities with higher GDP values have lower levels of efficiency.

The research analyses the efficiency of electricity and natural gas consumption in Portuguese municipalities between 2018 and 2022, looking at the level of correlation between the number of resident inhabitants and the amount of electricity and natural gas consumed.

The aim of the research is to analyse the efficiency of municipalities' energy consumption in order to assess the effectiveness of energy policies and the relationship between local population density and consumption.

To this end, the following hypotheses were established:

H1: Electricity and natural gas consumption are not related to municipal population density with an efficiency equal to 1 ($e\lambda=0$);

H2: Electricity and natural gas consumption have a certain level of relationship with municipal population density, with an efficiency equal to 1 ($0>e\lambda<1$);

H3: Electricity and natural gas consumption have a perfect relationship with municipal population density, with an efficiency equal to 1 ($e\lambda=1$).

METHODS

This research is based on a case study and examines the official statistical data of 308 Portuguese municipalities regarding population densities, electricity, and natural gas consumption for the period from 2018 to 2022. The databases for population levels and energy consumption were obtained from the official websites of the National Statistics Institute (INE) and the Francisco Manuel dos Santos Foundation (PORDATA).

The statistical data for Portuguese municipalities was broken down into a matrix and organised into decision centres (municipalities), inputs (population densities), and outputs (electricity and natural gas consumption).

For each type of energy consumption, the weights of population levels (inputs) and their relationship with electricity and natural gas consumption (outputs) were assessed.

The study adopts the classic, non-parametric DEA model, in which a direct relationship between inputs and outputs is not defined in advance. The efficiency of population distribution (inputs) in relation to levels of electricity and natural gas consumption is assessed using a weight index (Aparício et al., 2016). According to the model adopted, municipalities are more efficient the higher the population density and the lower the level of energy consumption (Morikawa, 2012).

In this research, the efficiency of energy consumption per inhabitant alternates between 0 (inefficient) and 1 (efficient) and is measured by the distance between the inefficient municipality and the most efficient one (Jahanshahloo & Afzalinejad, 2006).

The analysis model selected to analyse efficiency was the input-oriented DEA model, in which efficiency is described as follows (Soares et al., 2024):

$$Efficiency=\frac{\sum_{r=1}^{s} U_r Y_r}{\sum_{i=1}^{m} V_i X_i} \quad (1)$$

In which U_r = weights of kWh (kilowatt-hour) and Nm3 (standard cubic metre) consumption per municipality; Y_r = level of kWh and Nm3 consumed per municipality; V_i = weight of population density of municipalities; X_i = level of population density of the municipalities; s = number of sectors related to the energy consumption of the municipalities; e m = number of sectors related to the municipal inhabitants.

The methodology adopted looks at the level of efficiency of the population's energy consumption (electricity and gas), by municipality. While the numerator $\sum_{r=1}^{s} U_r Y_r$ represents the total consumption of electricity and natural gas weighted by the consumption weights per municipality, the denominator $\sum_{i=1}^{m} V_i X_i$ represents the total population density of the municipalities, weighted by the population density weights. This ratio makes it possible to assess the efficiency of the municipalities' electricity and natural gas consumption per inhabitant, taking into account both energy consumption and population density.

The efficiency of electricity and natural gas consumption is statistically obtained by dividing the quantities consumed locally by the total efficiency weighted by population density. The results obtained provide a practical overview of the efficiency levels of energy consumption per inhabitant of municipal territories, taking into account the appropriate delimitations and theoretical reservations of the classic DEA methodology (Kang, 2021).

Municipal efficiency levels in terms of electricity and natural gas consumption were measured using Excel software. The choice of the classic DEA model stems from its remarkable ability to measure efficiency levels, its high level of flexibility in constructing input-output matrices, as well as allowing the selection of the model's orientation to inputs or outputs since the research preference is to maintain population densities (inputs) and reduce energy consumption levels (outputs).

RESULTS

After applying the methodology adopted, we can see that the results offer a new perspective on the efficiency levels of the 308 municipalities in terms of electricity and natural gas consumption per inhabitant. Table 1 highlights the municipalities, organised by district and autonomous regions, where energy consumption per inhabitant is most and least efficient, in order to analyse which municipalities are the most energy sustainable.

According to the results obtained in 2018, the most efficient municipalities in terms of electricity and natural gas consumption were Estarreja (Aveiro), Castro Verde (Beja), Terras de Bouro (Braga), Freixo Espada à Cinta (Bragança), Vila Velha de Ródão (Castelo Branco), Pampilhosa da Serra (Coimbra), Portel (Évora), Vila do

Bispo (Faro), Manteigas (Guarda), Pedrógão Grande (Leiria), Azambuja (Lisboa), Avis (Portalegre), Trofa (Porto), Constância (Santarém), Sines (Setúbal), Viana do Castelo (Viana do Castelo), Boticas (Vila Real) and Nelas (Viseu).

With regard to the autonomous regions in 2018, the results suggest that the most energy-efficient municipalities were Porto Moniz (Madeira) and Corvo (Açores).

Conversely, the results suggest that the least energy-efficient municipalities were Santa Maria da Feira with a total efficiency level of 3.104% (Aveiro), Moura with a total of 4.502% (Beja), Braga with an efficiency level of 11, 491% (Braga), Vinhais with 39.489% (Bragança), Castelo Branco with a total of 0.244% (Castelo Branco), Coimbra with an efficiency per inhabitant of 6.854% (Coimbra), Évora with 5.127% (Évora), Faro with a total of 7.383% (Faro), Gouveia with an efficiency level per inhabitant of 21.010% (Guarda), Leiria with 6.449% (Leiria), Sintra with a total of 1.972% (Sintra), Elvas with 11.060% (Portalegre), Vila Nova de Gaia with a total consumption efficiency level of 9, 925% (Porto), Ourém with 1.140% (Santarém), Almada with a result of 0.292% (Setúbal), Ponte de Lima with an energy efficiency level of 7.827% (Viana do Castelo), Valpaços with 25.405% (Vila Real) and Viseu with a level of 3.381% (Viseu).

In terms of the autonomous regions, the results show that the least efficient municipalities in terms of electricity and natural gas consumption per inhabitant were Câmara de Lobos with an estimated efficiency level of 3.546% (Madeira) and Ponta Delgada with a total of 0.851% (Açores).

As for 2019, the results show that the most energy-efficient municipalities were Estarreja (Aveiro), Castro Verde (Beja), Terras de Bouro (Braga), Torre de Moncorvo (Bragança), Vila Velha de Ródão (Castelo Branco), Pampilhosa da Serra (Coimbra), Portel (Évora), Alcoutim (Faro), Manteigas (Guarda), Pedrógão Grande (Leiria), Azambuja (Lisboa), Avis (Portalegre), Trofa (Porto), Constância (Santarém), Sines (Setúbal), Vila Nova de Cerveira (Viana do Castelo), Boticas (Vila Real) and Nelas (Viseu).

As for the autonomous regions in 2019, the estimated results suggest that the most efficient municipalities in terms of energy consumption per inhabitant were Porto Moniz (Madeira) and Corvo (Açores).

In contrast, for the same period of analysis, the results indicate that the least efficient municipalities in terms of energy consumption were Santa Maria da Feira with an average efficiency level of 3.040% (Aveiro), Moura with a total of 4.680% (Beja), Braga with a level of 8.014% (Braga), Vinhais with an estimated total efficiency of 34.495% (Bragança), Castelo Branco with an average total of 0.271% (Castelo Branco), Coimbra with 6.269% (Coimbra), Évora with an estimated average efficiency of 4.546% (Évora), Faro with 7.333% (Faro), Gouveia with an energy efficiency level of 21.309% (Guarda), Leiria with 3.505% (Leiria), Sintra with an estimated total efficiency of 1.951% (Lisboa), Elvas with 10.864% (Portalegre), Vila Nova de Gaia with a total of 9.772% (Porto), Ourém with an estimated total of 1.259% (Santarém), Almada with 0.266% (Setúbal), Ponte de Lima with an efficiency of 7.896% (Viana do Castelo), Valpaços with 26.972% (Vila Real) and Viseu with an average estimated energy efficiency of 4.296% (Viseu).

With regard to the autonomous regions of Madeira and the Açores, the results indicate an estimated average efficiency level of 3.838% (Câmara de Lobos) and 0.836% (Ponta Delgada), respectively.

The results for 2020 show that the most efficient municipalities in terms of electricity and natural gas consumption were Estarreja (Aveiro), Castro Verde (Beja), Terras de Bouro (Braga), Torre de Moncorvo (Bragança), Vila Velha de Ródão (Castelo Branco), Pampilhosa da Serra (Coimbra), Portel (Évora), Alcoutim (Faro), Manteigas (Guarda), Pedrógão Grande (Leiria), Azambuja (Lisboa), Avis (Portalegre), Trofa (Porto), Constância (Santarém), Sines (Setúbal), Vila Nova de Cerveira (Viana do Castelo), Boticas (Vila Real) and Nelas (Viseu).

In terms of the autonomous regions, in 2020, the data shows that the most energy-efficient municipalities per inhabitant were Porto Moniz (Madeira) and Corvo (Açores).

Conversely, according to the estimated results, the least energy-efficient municipalities per inhabitant were Santa Maria da Feira with an average efficiency level of 3.531% (Aveiro), Moura with 4.982% (Beja), Braga with an average total of 7.952% (Braga), Vinhais with a total technical efficiency of 33.686% (Bragança), Castelo Branco with 0.260% (Castelo Branco), Coimbra with an average energy efficiency level of 5.843% (Coimbra), Évora with 3.665% (Évora), Faro with 6.932% (Faro), Gouveia with an estimated average total of 22.293% (Guarda), Leiria with an energy efficiency of 3.916% (Leiria), Sintra with 1.924% (Lisboa), Elvas with an average of 10.950% (Portalegre), Vila Nova de Gaia with an estimated efficiency of 9.459% (Porto), Tomar with 1.444% (Santarém), Vila Nova de Gaia with an estimated efficiency of 9.459% (Porto).

In 2020, for the autonomous regions, the data shows that the least efficient municipalities in terms of electricity and natural gas consumption were Câmara de Lobos with an average efficiency of 4.052% (Madeira) and Ponta Delgada with an average total of 0.519% (Açores).

With regard to 2021, the data suggests that the most energy-efficient municipalities were Estarreja (Aveiro), Castro Verde (Beja), Terras de Bouro (Braga), Torre de Moncorvo (Bragança), Vila Velha de Ródão (Castelo Branco), Penela (Coimbra), Portel (Évora), Alcoutim (Faro), Manteigas (Guarda), Castanheira de Pêra (Leiria), Azambuja (Lisboa), Avis (Portalegre), Trofa (Porto), Constância (Santarém), Sines (Setúbal), Vila Nova de Cerveira (Viana do Castelo), Boticas (Vila Real) and Nelas (Viseu).

As for the autonomous regions, the most efficient municipalities in terms of electricity and natural gas consumption per inhabitant were Funchal (Madeira) and Corvo (Açores).

On the contrary, the results suggest that the least efficient municipalities were Santa Maria da Feira with an efficiency of 3.655% (Aveiro), Moura with a total of 4.965% (Beja), Braga with an average level of 6.694% (Braga), Mirandela with an estimated total of 5.856% (Bragança), Castelo Branco with a total of 0.289% (Castelo Branco), Coimbra with 5.614% (Coimbra), Évora with a level of 4.733% (Évora), Faro with an average efficiency of 6.918% (Faro), Gouveia with a total of 20.946% (Guarda), Leiria with a result of 4.806% (Leiria), Sintra with an energy efficiency of 1.952% (Lisboa), Elvas with 11.109% (Portalegre), Vila Nova de Gaia with an average efficiency of 9, 386% (Porto), Tomar with 1.450% (Santarém), Almada with an estimated average result of 0.265% (Setúbal), Ponte de Lima with 8.716% (Viana do Castelo), Valpaços with 25.592% (Vila Real) and Viseu with an efficiency level of 3.350% (Viseu).

With regard to the autonomous regions, in 2021, the results show that the least efficient municipalities were Câmara de Lobos with an average total energy consumption efficiency of 4.003% (Madeira) and Ponta Delgada with an efficiency of 0.518% (Açores).

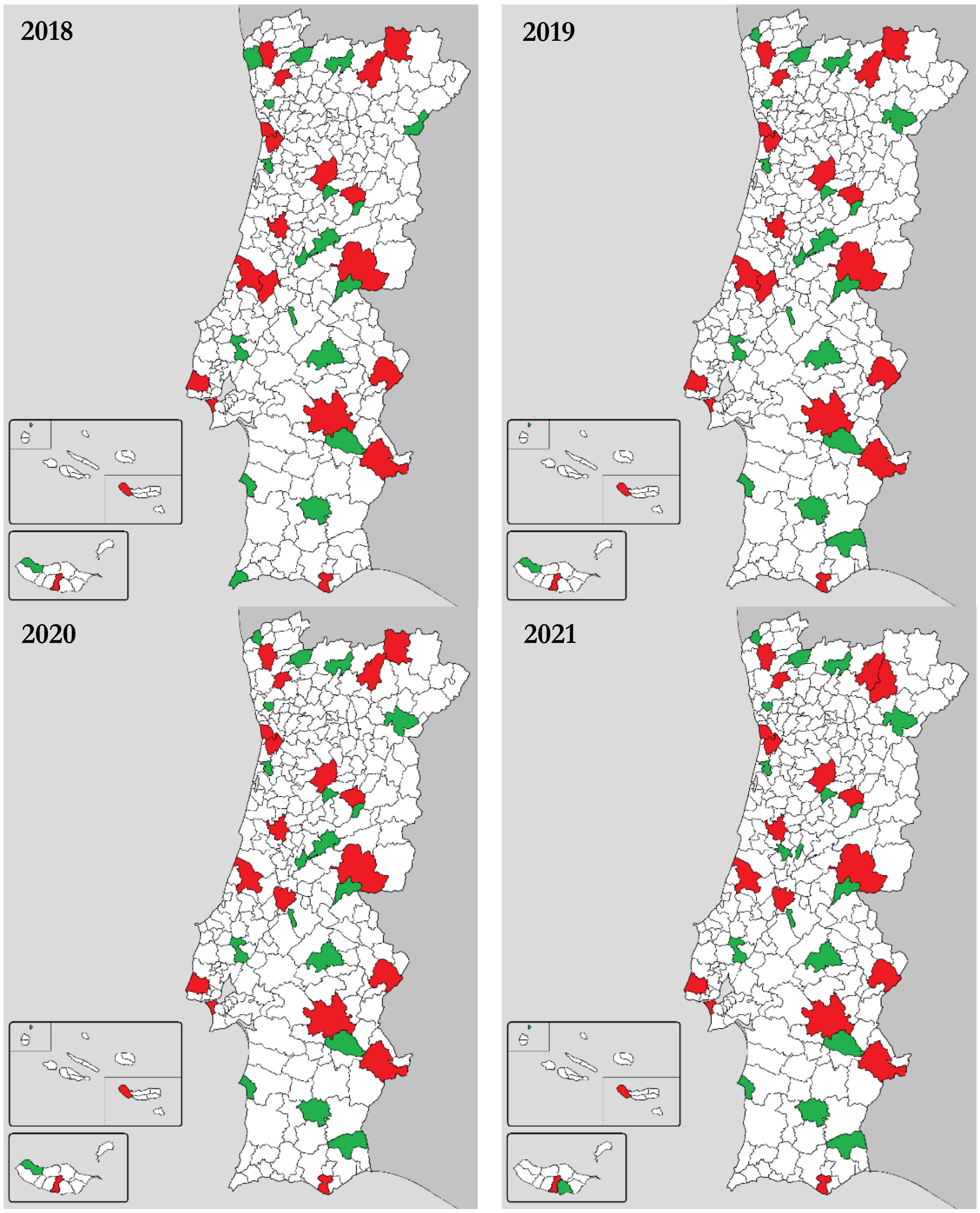
With reference to 2022, the results show that the most efficient municipalities in terms of energy consumption per inhabitant were Estarreja (Aveiro), Castro Verde (Beja), Terras de Bouro (Braga), Freixo Espada à Cinta (Bragança), Vila Velha de Ródão (Castelo Branco), Penela (Coimbra), Portel (Évora), Alcoutim (Faro), Manteigas (Guarda), Pedrógão Grande (Leiria), Azambuja (Lisboa), Avis (Portalegre), Trofa (Porto), Constância (Santarém), Sines (Setúbal), Vila Nova de Cerveira (Viana do Castelo), Boticas (Vila Real) and Nelas (Viseu).

In the autonomous regions, the most efficient municipalities in terms of electricity and natural gas consumption were Porto Moniz (Madeira) and Corvo (Açores).

With regard to the least efficient municipalities for the period in question, the results suggest that they were Santa Maria da Feira with a total average efficiency level of 3.630% (Aveiro), Moura with 4.989% (Beja), Braga with a total of 7.816% (Braga), Vinhais with 32.576% (Bragança), Castelo Branco with an energy efficiency level of 0.320% (Castelo Branco), Coimbra with a level of 5.841% (Coimbra), Évora with 3.408% (Évora), Faro with an efficiency of 7.007% (Faro), Gouveia with a total of 19, 482% (Guarda), Leiria with an estimated 3.865% (Leiria), Sintra with an estimated technical efficiency level of 2.015% (Lisboa), Elvas with 10.378% (Portalegre), Vila Nova de Gaia with an estimated average total of 10.280% (Porto), Ourém with an average efficiency of 1, 418% (Santarém), Almada with an energy level of 0.286% (Setúbal), Ponte de Lima with a total of 9.106% (Viana do Castelo), Valpaços with an average efficiency value of 25.769% (Vila Real) and Viseu with an average total efficiency of 3.503% (Viseu).

As for the autonomous regions of Madeira and the Açores, the least efficient municipalities in terms of electricity and natural gas consumption per inhabitant were Câmara de Lobos (3.874%) and Ponta Delgada (0.602%), respectively.

The data also suggests that the least efficient municipalities correspond, over the periods under observation (2018–2022), to the district capitals (Braga, Castelo Branco, Coimbra, Évora, Faro, Leiria, Viseu, and Ponta Delgada) and the largest cities.



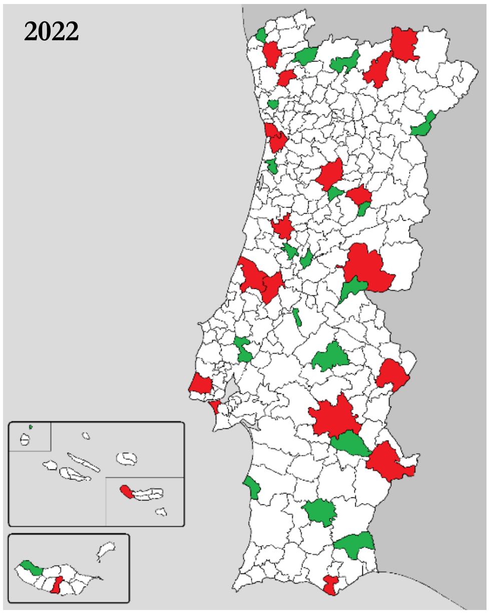


Figure 1. The most (green) and least (red) energy-efficient municipalities per inhabitant, 2018–2022

Table 1. Results of the most and least energy-efficient municipalities by district and autonomous regions (2018-2022)

Efficiency	Districts and Autonomous Regions	2018		2019		2020		2021		2022	
		Municipalities	Results	Municipalities	Results	Municipalities	Results	Municipalities	Results	Municipalities	Results
More efficient	Aveiro	Estarreja	100,000%	Estarreja	100,000%	Estarreja	100,000%	Estarreja	100,000%	Estarreja	100,000%
	Beja	Castro Verde	100,000%	Castro Verde	100,000%	Castro Verde	100,000%	Castro Verde	100,000%	Castro Verde	100,000%
	Braga	Terras de Bouro	100,000%	Terras de Bouro	100,000%	Terras de Bouro	100,000%	Terras de Bouro	100,000%	Terras de Bouro	100,000%
	Bragança	Freixo Espada à Cinta	100,000%	Torre de Moncorvo	100,000%	Torre de Moncorvo	100,000%	Torre de Moncorvo	100,000%	Freixo Espada à Cinta	100,000%
	Castelo Branco	Vila Velha de Ródão	100,000%	Vila Velha de Ródão	100,000%	Vila Velha de Ródão	100,000%	Vila Velha de Ródão	100,000%	Vila Velha de Ródão	100,000%
	Coimbra	Pampilhosa da Serra	100,000%	Pampilhosa da Serra	100,000%	Pampilhosa da Serra	100,000%	Penela	100,000%	Penela	100,000%
	Évora	Portel	100,000%	Portel	100,000%	Portel	100,000%	Portel	100,000%	Portel	100,000%
	Faro	Vila do Bispo	100,000%	Alcoutim	100,000%	Alcoutim	100,000%	Alcoutim	100,000%	Alcoutim	100,000%
	Guarda	Manteigas	100,000%	Manteigas	100,000%	Manteigas	100,000%	Manteigas	100,000%	Manteigas	100,000%
	Leiria	Pedrógão Grande	100,000%	Pedrógão Grande	100,000%	Pedrógão Grande	100,000%	Castanheira de Pêra	100,000%	Pedrógão Grande	100,000%
	Lisboa	Azambuja	100,000%	Azambuja	100,000%	Azambuja	100,000%	Azambuja	100,000%	Azambuja	100,000%
	Portalegre	Avis	100,000%	Avis	100,000%	Avis	100,000%	Avis	100,000%	Avis	100,000%
	Porto	Trofa	100,000%	Trofa	100,000%	Trofa	100,000%	Trofa	100,000%	Trofa	100,000%
	Santarém	Constância	100,000%	Constância	100,000%	Constância	100,000%	Constância	100,000%	Constância	100,000%
	Setúbal	Sines	100,000%	Sines	100,000%	Sines	100,000%	Sines	100,000%	Sines	100,000%
	Viana do Castelo	Viana do Castelo	100,000%	Vila Nova de Cerveira	100,000%	Vila Nova de Cerveira	100,000%	Vila Nova de Cerveira	100,000%	Vila Nova de Cerveira	100,000%
	Vila Real	Boticas	100,000%	Boticas	100,000%	Boticas	100,000%	Boticas	100,000%	Boticas	100,000%
	Viseu	Nelas	100,000%	Nelas	100,000%	Nelas	100,000%	Nelas	100,000%	Nelas	100,000%
	A.R. of Madeira	Porto Moniz	100,000%	Porto Moniz	100,000%	Porto Moniz	100,000%	Funchal	100,000%	Porto Moniz	100,000%

	A.R. of Açores	Corvo	100,000%	Corvo	100,000%	Corvo	100,000%	Corvo	100,000%	Corvo	100,000%
Less efficient	Aveiro	Santa Maria da Feira	3,104%	Santa Maria da Feira	3,040%	Santa Maria da Feira	3,531%	Santa Maria da Feira	3,655%	Santa Maria da Feira	3,630%
	Beja	Moura	4,502%	Moura	4,680%	Moura	4,982%	Moura	4,965%	Moura	4,989%
	Braga	Braga	11,491%	Braga	8,014%	Braga	7,952%	Braga	6,694%	Braga	7,816%
	Bragança	Vinhais	39,489%	Vinhais	34,495%	Vinhais	33,686%	Mirandela	15,856%	Vinhais	32,576%
	Castelo Branco	Castelo Branco	0,244%	Castelo Branco	0,271%	Castelo Branco	0,260%	Castelo Branco	0,289%	Castelo Branco	0,320%
	Coimbra	Coimbra	6,854%	Coimbra	6,269%	Coimbra	5,843%	Coimbra	5,614%	Coimbra	5,841%
	Évora	Évora	5,127%	Évora	4,546%	Évora	3,665%	Évora	4,733%	Évora	3,408%
	Faro	Faro	7,383%	Faro	7,333%	Faro	6,932%	Faro	6,918%	Faro	7,007%
	Guarda	Gouveia	21,010%	Gouveia	21,309%	Gouveia	22,293%	Gouveia	20,946%	Gouveia	19,482%
	Leiria	Leiria	6,449%	Leiria	3,505%	Leiria	3,916%	Leiria	4,806%	Leiria	3,865%
	Lisboa	Sintra	1,972%	Sintra	1,951%	Sintra	1,924%	Sintra	1,952%	Sintra	2,015%
	Portalegre	Elvas	11,060%	Elvas	10,864%	Elvas	10,950%	Elvas	11,109%	Elvas	10,378%
	Porto	Vila Nova de Gaia	9,925%	Vila Nova de Gaia	9,772%	Vila Nova de Gaia	9,459%	Vila Nova de Gaia	9,386%	Vila Nova de Gaia	10,280%
	Santarém	Ourém	1,140%	Ourém	1,259%	Tomar	1,444%	Tomar	1,450%	Ourém	1,418%
	Setúbal	Almada	0,292%	Almada	0,266%	Almada	0,259%	Almada	0,265%	Almada	0,286%
	Viana do Castelo	Ponte de Lima	7,827%	Ponte de Lima	7,896%	Ponte de Lima	8,599%	Ponte de Lima	8,716%	Ponte de Lima	9,106%
	Vila Real	Valpaços	25,405%	Valpaços	26,972%	Valpaços	26,274%	Valpaços	25,592%	Valpaços	25,769%
	Viseu	Viseu	3,381%	Viseu	4,296%	Viseu	3,757%	Viseu	3,350%	Viseu	3,503%
	A.R. of Madeira	Câmara de Lobos	3,546%	Câmara de Lobos	3,838%	Câmara de Lobos	4,052%	Câmara de Lobos	4,003%	Câmara de Lobos	3,874%
	A.R. of Açores	Ponta Delgada	0,851%	Ponta Delgada	0,836%	Ponta Delgada	0,519%	Ponta Delgada	0,518%	Ponta Delgada	0,602%

In terms of the results on the efficiency of municipalities' electricity and natural gas consumption per inhabitant, table 1 shows that the data rejects hypothesis 1 ($e\lambda=0$), but validates hypotheses 2 ($0>e\lambda<1$) e 3 ($e\lambda=1$). The data also suggests that there is some relationship between the inhabitants of the municipalities and the levels of electricity and natural gas consumption, i.e., the levels of population density contribute directly to the energy efficiency and sustainability of the municipal territories.

According to the results, the efficiency of municipalities' electricity and natural gas consumption is asymmetrical (Table 1), which makes it possible to simultaneously validate and reject the hypotheses defined throughout the series. In 2018, hypothesis 1 was rejected, hypothesis 2 was accepted in 249 municipalities, and hypothesis 3 was validated in 59 municipalities. In 2019, hypothesis 1 is rejected in all municipalities, hypothesis 2 is confirmed in 252 municipalities, and hypothesis 3 is validated in 56 municipalities. For 2020, hypothesis 1 is rejected, hypothesis 2 is accepted in 252 municipalities, and hypothesis 3 is confirmed in 56 municipalities. For 2021, hypothesis 1 is rejected, hypothesis 2 is validated in 255 municipalities, and hypothesis 3 is confirmed in 53 municipalities. Finally, in 2022, we note that hypothesis 1 is rejected in all municipalities, hypothesis 2 is validated in 250 municipalities, and hypothesis 3 is accepted in 58 municipalities.

DISCUSSION

Analysing the efficiency of energy consumption by residents is fundamental to understanding the efficiency of energy resource consumption (Dolak et al., 2022), identifying possible consumption patterns (Herring, 2000) and economic impacts (Tenente et al., 2024), and designing effective public policies (Capelo et al., 2023). Energy consumption efficiency currently plays an essential role in analysing environmental sustainability, i.e., energy efficiency reduces demand, mitigates the environmental problems caused by fossil fuels, and contributes to the preservation of natural resources, mitigating environmental effects. On the other hand, the definition of more effective energy policies makes it possible to achieve increases in air quality and in people's health and well-being. In fact, the perception of energy consumption enables local political actors to design more effective energy programmes adapted to the needs and behaviours of residents.

The results obtained point to the existence of different levels of efficiency in electricity and natural gas consumption among Portuguese municipalities, which corroborates the conclusions of Bian and Yang. In fact, in Portugal, with regard to the efficiency of energy consumption, it is possible to observe the presence of some degree of inequality between territories, as Tsurkan, Andreeva, Lyubarskaya, Chekalin, and Lapushinskaya denote in the Russian context. As we see it, the situation stems from a lack of willingness on the part of residents to actively adopt more efficient energy consumption practices. In this respect, the results obtained validate the conclusions of Pimonenko, Lyulyova, and Us.

Currently, theory has sought to analyse energy efficiency in order to identify benchmarking practices. In fact, as Tan, Tjandra, and Song argue, the results show that it is possible to identify which municipalities have the best energy consumption practices. The results reveal the importance of adopting more sustainable practices capable of reducing electricity and natural gas consumption, as indicated in the studies by Vaisi, Varmazyari, Esfandiari, and Sharbaf. In Portugal, as Nørgard argues, it is essential that decision-makers are able to assess the quantities of resources that need to be extracted in order to meet local needs. It is therefore necessary to develop more active public energy efficiency policies.

Like the research by Michailidis, Michailidis, Gkelios, and Kosmatopoulos, the results suggest the need to adopt technological approaches to solving the energy inequalities observed in Portugal, such as neural networks for solving energy efficiency management problems. However, we tend to question the effectiveness of algorithms for defining optimal energy and natural gas consumption solutions. In fact, we agree with Streimikiene, Kyriakopoulos, Ślusarczyk, and Stankuniene that political actors need to define policies that promote awareness of energy consumption in Portuguese municipalities. Regardless of the level of population density in the municipalities, it is essential to define regional strategies that involve consumers in adopting more efficient energy and natural gas consumption practices.

Contrary to the conclusions of Bai, Niu, and Hao, the estimated results suggest that the energy efficiency levels of the municipalities are remarkably disparate but validate the tendency for results to improve slowly and progressively.

In the context of Chinese municipalities, Hu and Wang estimated and analysed the energy consumption efficiency levels of 29 administrative regions and concluded that the municipalities in central China have lower efficiency levels compared to the other municipalities. In the case of Portugal, the results reject the authors' conclusions since it is possible to see the existence of technically efficient ($e\lambda=1$) and inefficient ($0>e\lambda<1$) municipalities in all districts and regions.

The data suggests that there is a notable imbalance between the level of electricity and natural gas consumption and levels of regional development, i.e., in Portugal, the more developed the municipality, the lower the energy efficiency. The results validate Honma and Hu's conclusions, since the municipalities inland and along the Sea of Japan are the most efficient in terms of energy consumption. In the case of Portugal, the municipalities inland and along the Atlantic coast are the ones with the best levels of efficiency, unlike the big cities. We therefore agree with the authors' conclusions that there is a direct relationship between energy efficiency and the per capita income of inhabitants.

The data is broadly in line with the Shang, Liu, and Lv conclusions, but the authors' results show an average energy consumption efficiency of 45.59% for Chinese municipalities. In the Portuguese case, the average energy consumption efficiency was 39.76 percent (2018), 39.88 percent (2019), 40.42 percent (2020), 38.96 percent (2021), and 39.59 percent (2022). Although the average for Portuguese municipalities is lower than the Chinese average, the estimated data validates the existence of a significant positive correlation between energy consumption and territories. In fact, the data also confirms the results and conclusions obtained by Wei, Ding, Zheng, Ma, Niu, and Li when they say, in relation to Chinese municipalities, that average efficiency is low and disparities between municipalities are high, since efficiency in electricity production is higher than efficiency in transmission and distribution.

Finally, as Li, Chiu, Cen, Wang, Lin, Zeng, Zhang, and Li argue, the results suggest the need to invest in Portuguese energy infrastructure in order to improve energy consumption efficiency levels. On the other hand, the data also validates the authors' findings, i.e., they show that municipalities' efficiency levels tend to decrease over time.

With regard to the hypotheses, the results point to the validation of hypothesis 2, since the majority of Portuguese municipalities do not have an average technical efficiency equal to 1, but rather a ratio between the number of inhabitants and the consumption of electricity and natural gas greater than 0 and less than 1.

As far as future research is concerned, the theory deems it relevant that investigations observe the effects of maintenance and efficiency on the availability of drinking water (Chang et al., 2022) and its sustainable management (Santos et al., 2023), as well as the sanitation levels of municipalities (Nirazawa & Oliveira, 2018).

CONCLUSION

The research analysed the efficiency of electricity and natural gas consumption in Portuguese municipalities between 2018 and 2022, using data envelopment analysis to assess the possible relationship between population density and energy consumption.

The estimated results suggest a clear asymmetry in energy efficiency between municipalities, i.e., some municipalities are efficient while others exhibit significantly low levels of efficiency.

The results show that population density has a significant positive relationship with energy efficiency. To this end, the hypotheses were tested. Hypothesis 1, that there is no relationship between energy consumption and population density, was rejected. Hypotheses 2 (partial relationship) and 3 (perfect relationship) were validated to varying degrees, with the majority of municipalities falling under Hypothesis 2.

The data suggests that in efficient municipalities, inhabitants resort to more sustainable energy consumption practices, while in less efficient municipalities, people face serious challenges in managing their energy consumption.

The efficiency standards highlight the need to design and implement policies aimed at improving the efficiency of energy consumption in the least efficient municipalities.

It can be concluded that the efficiency of municipal energy consumption is affected by various factors, including population density, public policies, and local consumption practices. In order to promote energy sustainability, the results recommend implementing policies that encourage the adoption of more efficient technologies, making investments in modern energy infrastructure, and conducting campaigns to raise public awareness of the importance of sustainable energy consumption.

Beyond the limitations that may be identified, the research contributes to the literature by providing an inclusive analysis of the efficiency of energy consumption in Portuguese municipalities and, at the same time, providing relevant information for the formulation of more effective public policies.

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