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Research article

It starts at home: Space heating and cooling efficiency for energy poverty and carbon emissions reduction in Portugal

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Abstract

Climate change mitigation, the economy's decarbonisation, and energy poverty reduction are major challenges globally and for the European Union. However, competing agendas might create trade-off situations that hinder the achievement of these goals. Energy efficiency promotion in the residential sector, through the replacement of space heating and cooling equipment, can be an important solution to simultaneously contribute to reducing energy poverty and carbon emissions whilst improving households' comfort and wellbeing. This paper analyses the regional impact of replacing space heating and cooling equipment on energy poverty levels in the population using the Energy Poverty Vulnerability Index. Moreover, the impact on carbon emissions is also investigated. Results show that increasing equipment efficiency to regulation levels is only effective in reducing winter energy poverty, with a decrease in municipal vulnerability levels of about 18 per cent. Implementing a "deep change" in the heating and cooling equipment stock is significantly effective for reducing winter and summer energy poverty, respectively, 47.8 per cent and 26.3 per cent in average municipal levels, while significantly decreasing potential carbon dioxide emissions by 3554 kilotons. This transformation should be coupled with the improvement of buildings' energy performance and presents various significant challenges regarding financial investment and social justice that should be addressed by authorities at different scales. This study demonstrates the relevance of exploring the impact of space heating and cooling equipment replacement measures on energy poverty, efficiency and carbon emissions at the regional level while providing a replicable method for investigating this subject and producing valuable insights into other geographical contexts.

Keywords: Regional analysis; energy efficiency; residential sector; fuel poverty; Portugal.

Introduction

Energy poverty is a severe social issue affecting populations across the globe in distinct ways. It is deeply linked to the sustainable development of society, particularly United Nations' Sustainable Development Goal 7, which underlines the need for ensuring "affordable, reliable, sustainable and modern energy for all" (United Nations, 2022). Energy poverty can be defined as the inability of households to meet adequate energy needs, taking different forms depending on context. In developing countries, it is mainly reflected by the lack of access to modern energy services such as electricity (Li et al., 2014). In 2019, 770 million people still lived without access to electricity, mostly in Africa and Asia (IEA, 2022). These people must rely on harmful fossil fuels and inefficient rudimentary equipment for space heating and cooking. The use of such fuels increases carbon dioxide emissions and deteriorates indoor air quality, with serious ill effects on the health and safety of the population (WHO, 2021). In developed countries, the term energy poverty is more frequently used to describe the inability to afford the necessary level of energy services to maintain an adequate indoor temperature (Li et al., 2014). Despite affecting populations globally, this form of energy poverty looms large in the European Union (EU), affecting over 34 million people, with severe impacts on the population's wellbeing, contributing to health problems such as cardiovascular and respiratory diseases, as well as being a cause of stigma and social exclusion (EPAH, 2022). Alleviating energy poverty, together with energy efficiency improvement and decarbonisation of the economy, are primary policy goals for the EU (European Commission, 2019), as highlighted in the 2030 energy and climate framework and further reinforced by the European Green Deal and the Fit for 55's legislative package. The main root causes of this social issue are the energy inefficiency of homes, low incomes, and high energy prices (Dobbins et al., 2019). The global energy crisis of 2021 and, more recently, the Ukraine invasion and the sanctions imposed on Russia, have caused a significant recent spike in energy prices, especially natural gas, with increased negative impacts for households and particularly for the energy poor. The European Commission has recently approved the REPowerEU plan, aiming to assure European independence from Russian fossil fuels before 2030, by mitigating the impact of rising energy prices, diversifying gas sources, and boosting a clean energy transition (European Commission, 2022a).

Simultaneously, the building stock is also a major target for decarbonising the economy and reducing energy demand, representing about 40 per cent of the EU's energy consumption and 36 per cent of its greenhouse-gas emissions, considering the whole life cycle (European Commission, 2020a). The residential sector accounts for two-thirds of the final energy consumption (Build Up, 2017). Increasing the energy efficiency of buildings can be achieved through passive measures, such as improving the building envelope energy performance for reducing energy needs. Alternatively, active energy consumption measures can be applied such as the use of more efficient electric appliances and Heating, Ventilation, and Air-Conditioning (HVAC) equipment for reducing energy consumption. Both types of measures are highlighted and prioritised by the European Commission in the Energy Performance of Buildings Directive (EPBD) 2010/31/EU. The REPowerEU plan underlines the importance of energy efficiency for the EU's energy transition and independence, encouraging the roll-out of heat pumps for increasing energy savings and reducing gas consumption in buildings (European Commission, 2022b). Active measures in homes have been shown to be effective in ameliorating energy poverty (Boardman, 2013).

Research shows there is potential for synergies between climate change and energy poverty mitigation policies, especially when the focus is energy efficiency promotion

(Ürge-Vorsatz and Tirado-Herrero, 2012). The authors state that the integration of the two policy goals is paramount for mobilising large-scale energy efficiency measures that could lead to the resolution of both issues, with positive effects on energy security and employment. Chakravarty and Tavoni (2013) report that reducing global energy poverty may increase consumption. Still, this increase would not hinder the attainment of climate targets. It could be mitigated with efficiency improvement, thus achieving both goals would not result in a bottleneck. Bouzarovski (2013) highlights that systemic energy efficiency policies can help address both objectives of fighting climate change and addressing energy poverty.

However, these two highly interlinked agendas can compete and create trade-off situations (Großmann, 2019) if policy frameworks do not evenly integrate both goals. Ürge-Vorsatz and Tirado-Herrero (2012) found that the most relevant trade-off identified is the possible worsening of energy poverty resulting from climate policy increasing energy prices through carbon pricing. Sunderland and Croft (2011) state that energy poverty significantly contributes to making the distribution of social impacts a key factor in climate change policy analysis.

Massera (2020) identifies potential redistributive consequences of the green transition and decarbonisation policies, with vulnerable layers of society being more exposed to energy poverty. The "yellow vests" case in France in 2021 is an example of this instance, where the increase in diesel prices and fuel tax aimed at protecting the environment and fighting climate change resulted in large protests and turmoil. Previously in 2018, in Bulgaria, citizens also protested the rise of fuel prices and taxes for more polluting cars, accusing the government of injustice and negligence due to the policy's regressive nature. As the author clearly states, they should not deter decarbonisation efforts but should highlight the need to consider the different parties and interests. Who will pay for the energy transition is an important debate, particularly regarding decarbonising the building stock, placing energy poverty at the centre of discussion, and not leaving any groups behind.

Carley and Konisky (2020) point out the existence of winners and losers of the energy transition. Energy justice arises in this conversation, defined as the access to affordable, sustainable, and safe energy to sustain a decent life and participate in society. There are three central tenets to consider: distributional, i.e., the just distribution of burdens and benefits; procedural justice, regarding the inclusion of people in the energy decision-making process, to guarantee processes are equitable, fair, and inclusive; and finally, recognition justice, referring to the recognition of historical and ongoing inequalities. Other types of energy justice have also been identified. Cosmopolitan justice is the acknowledgment of different ethnic groups as part of a community based on collective morality (Sovacool et al., 2016). Restorative justice focuses on reparations of past harm rather than just punishing the offender (Heffron and McCauley, 2017). Corrective justice implies that those who have committed environmental harm in processes related to energy should be responsible for the correction of this harm. Finally, intergenerational justice refers to the management of not only present-day energy decision impacts but impacts on future generations (McHarg, 2020).

Existing problems of energy justice can hinder the adoption of energy efficiency measures. These interventions are often seen as a one-size-fits-all solution, hiding structural injustices regarding urban planning, territorial development, access to housing, agency, and social inclusion, and discrimination, which affect its distributional impact (ENGAGER, 2021). For example, injustices can occur in the process of identifying the vulnerable population. The energy-poor are often identified by analysing income and energy burdens. This is not a straightforward task because the energy-poor can have lower or higher than average energy burdens. Roberts et al. (2020) highlight increased energy needs among the most vulnerable; conversely, Tirado-Herrero (2017) identifies that spending on energy among the energy-poor is insufficient to meet health and wellbeing needs. It is paramount to focus on an adequate level of energy services rather than solely on energy consumption or energy bills when identifying the population to support and when evaluating and monitoring the impact of measures. Households' varying purchasing power also plays an important role in the roll-out of domestic energy efficiency measures, as interventions often require the ability to invest in new equipment. It is an important factor to consider in the design of support schemes, to assure a just distribution of benefits. Preston et al. (2010) state the importance of linking households' expenditure on energy efficiency measures to accessible grants and subsidies.

It is necessary to fully grasp the benefits of energy efficiency measures and policies for reducing energy poverty and achieving decarbonisation goals whilst considering the implications for energy justice associated with the implementation of these solutions. This paper aims to explore the impact of energy efficiency measures in the complex context of energy poverty and carbon emissions in the Portuguese residential sector, considering the differences in territorial settings and vulnerability configurations. The country was selected due to the high estimated levels of energy poverty and low energy efficiency indicators of the building stock.

Literature Review

There is a lack of studies bringing together quantitative analyses of energy poverty vulnerability and carbon emissions reduction connected to the implementation of energy efficiency improvement measures in the residential sector. On the other hand, there are several studies and methods that focus on these two tasks separately. Measuring energy poverty has been a challenge undertaken by several researchers over the last few years. It is crucial to understand the depth and extent of this issue, aiming to produce effective policy for its reduction. Energy poverty metrics can be divided into four different types: consensual-based approaches, based on the self-reported experiences of occupants such as the EU-SILC indicators developed in studies such as the Thomson and Snell (2013) and OpenEXP (2019); Expenditure-based, in which energy expenditure is contrasted with income (e.g. Boardman, 1991; Moore, 2012; EPAH, 2021); Direct measurement of domestic energy services compared to a required set value, used in studies such as Calì et al. (2016); Kampelis et al. (2017); and Gouveia et al., (2019). Other supporting indicators of demographic, energy, health outcomes, physical infrastructure, and policy nature (Rademaekers et al., 2016) are also used in energy poverty studies. Although not directly describing the issue per se, they provide information on factors that influence energy poverty vulnerability. Most studies dedicated to assessing energy poverty, defined as the inability to attain thermal comfort, focus on European contexts, as seen in Siksnelyte-Butkiene et al. (2021), but increasing attention is being paid to this form of energy poverty in other continents, in countries like Chile (Pérez-Fargallo et al., 2020), Australia (Churchill et al., 2020) and Japan (Okushima, 2019).

Computing carbon and other greenhouse gas emissions in buildings has been a relatively common enterprise in research, together with energy indicators, with the application of different modelling techniques. The Life Cycle Assessment approach has become the reference methodology for analysing the environmental performance of buildings (Piccardo and Gustavsson, 2021). Modelling choices of system boundaries, materials and energy technologies, and supply can significantly influence the model's outcomes (Dixit et al., 2012). When it comes to energy consumption inside the buildings, carbon emissions are generally calculated using emissions factors associated with each energy carrier or fuel. These emissions factors result from the conversion of each fuel or energy carrier's primary energy units, using the respective carbon intensities (Dixit et al., 2014).

There are several case studies assessing the impact of energy efficiency measures, both building fabric renovation and HVAC equipment replacement, on energy demand and energy consumption and carbon emissions reduction, spanning different spatial scales, building stock, and types of measures (Domingo-Irigoyen et al., 2015; Niemelä et al., 2017; Streicher et al., 2020, Gouveia, et al., 2021).

Nevertheless, there are very few studies analysing the impact of this kind of measure on the energy poverty levels of a population, also considering the effect on carbon emissions in the residential sector. Zhao et al. (2021) researched these topics in conjunction, estimating energy poverty levels in 30 Chinese provinces and the impact of energy poverty on CO_2 emissions. The authors found that energy poverty can increase CO_2 emissions, but the effect is heterogeneous across regions. There is a bidirectional causal connection between the two issues in regions with high levels of energy poverty, whereas, in regions with less vulnerability, energy poverty increases emissions. Subsequently, Dong et al. (2021) investigated whether a low-carbon energy transition could support energy poverty mitigation, using panel data from 30 Chinese provinces. The study focused mainly on the impact of natural gas consumption, finding that the use of natural gas was correlated with lower energy poverty levels, although with variations across regions.

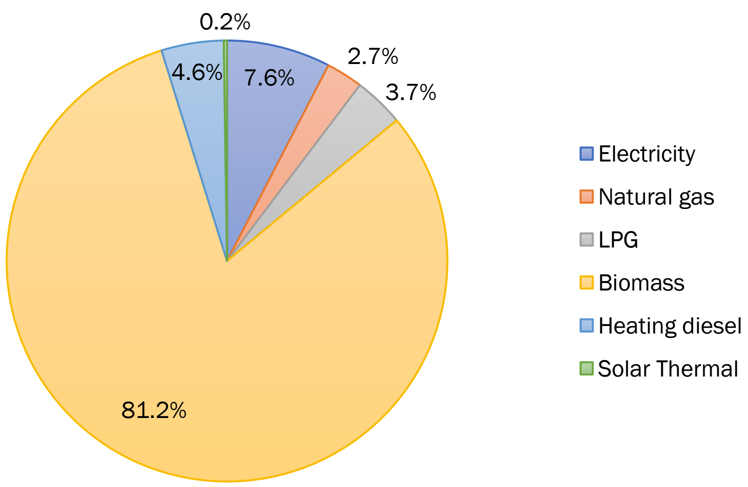
Taking into consideration the current European policy landscape, it becomes increasingly relevant to focus on the energy poverty-CO_2 nexus, developing European case studies to investigate the connection between these two energy policy cornerstones, and potentially disclose opportunities for measures or policies that could create a positive dual effect for achieving the proposed goals of reduced emissions and energy poverty eradication. Acting upon this thought and aiming to bridge the identified lack, this study proposes an approach to assess the effect of large-scale HVAC equipment replacement on regional energy poverty levels, as well as the potential variation in CO_2 emissions. It uses a previously developed index for estimating regional energy poverty vulnerability – the EPVI (Gouveia et al., 2019), to analyse all 308 Portuguese municipalities, considering the entire occupied dwelling stock. This research aims to produce valuable insights for policymaking at different scales, namely identifying the most effective technologies for energy poverty and greenhouse-gas emission reduction and pinpointing the regions that should be priority targets due to higher vulnerability and/or higher potential for improvement.

Case-study

Portugal was selected as a case study because of its severe energy poverty levels and the low energy efficiency of the building stock and its HVAC equipment. Currently, according to EU SILC indicators, which are usually used as proxies of energy poverty, Portugal has the 4th highest rate of citizens reporting their inability to maintain dwellings adequately warm during the winter (17.5 per cent) and the 2nd highest percentage of the population living in homes with a leaking roof, damp walls, floors or foundation, or rot in window frames or floor in the EU (25.2 per cent) of all 27 European member-states in 2020 (Eurostat, 2022a; Eurostat, 2022b). One of the main root causes of these energy poverty levels is the ageing and low energy-performing Portuguese residential building stock. Approximately 68 per cent of all the energy certified residential buildings from 2014 to 2021 (about 1.43 million) have an energy performance rating equal to or lower than C (below B- level, which is the standard for new buildings) (ADENE, 2022), whereas only 13.5 per cent present the highest rate A. This is a consequence of the fact that approximately 70 per cent of residential buildings were built before 1990 (INE, 2011), before the establishment of the first Portuguese energy performance regulation. The average deep renovation rate was approximately 0.01 per cent/year for the five years prior to 2019 (INE, 2019), considerably below the EU average renovation rate of one per cent (European Commission, 2020b) and target of three per cent (BPIE, 2020). Inefficient heating and cooling equipment also contribute significantly to the low EPC rates. According to DGEG (2021), about 26.4 per cent of improvement measures proposed in EPCs pertain to HVAC systems replacement.

Moreover, the ownership and use of decentralised, low-efficiency heating systems such as fireplaces and electric oil heaters are widespread (INE/DGEG, 2021). Biomass is the most commonly used energy carrier for indoor space heating (INE/DGEG, 2021), as evidenced in Figure 1. District heating is virtually inexistent in the country. Space cooling equipment ownership is still low, at around 32.7 per cent nationally (INE/DGEG, 2021) when compared to countries with a similar climate (Castaño-Rosa et al., 2021). Space cooling is provided only through electricity, and cooling fans are more commonly used equipment, providing ventilation rather than cold air. Furthermore, there is considerable geographic variation in the ownership and type of heating and cooling equipment across Portugal, particularly between rural and urban settlements (Gouveia et al., 2019). This variation is related to cultural factors, energy infrastructure, and fuel availability (Horta et al., 2019), resulting in distinct consumption patterns and instances of underconsumption.

Figure 1: Energy consumption per energy carrier for space heating in Portugal (data from INE/DGEG, 2021)



Portugal is among one of the warmest countries in the EU with high temperatures in the summer, with the fifth-highest number of CDD cooling degree days (i.e., 269) and the third with lower HDD (i.e., 1008) in 2020 (Eurostat, 2022c). Furthermore, the country is located in one of the most climate change-impacted regions of Europe (Ducrocq, 2016), with predicted increases in total CDD, frequency and intensity of heatwaves, and a decrease in HDD (Sanchez-Guevara et al., 2019; Meteonorm, 2020).

In the policy arena, building renovation and increased energy efficiency are considered a priority in the national strategy instruments such as the National Energy and Climate Plan 2030 (Portuguese Republic, 2019a), the Long-term National Strategy for the Renovation of the Building Stock (Portuguese Republic, 2021), and the Roadmap for Carbon Neutrality for 2050 (Portuguese Republic, 2019b). Recently, a national Plan for Recovery and Resilience, stemming from a European debt issuance mechanism to face the crisis, will unlock €620M for buildings' energy efficiency, €300M of which for the residential sector, and a total of €774M to invest in new public housing (Portuguese Republic, 2020).

Methodology

The energy poverty levels for both winter and summer were estimated using the Energy Poverty Vulnerability Index (EPVI) developed by Gouveia et al. (2019), composed of two sub-indexes. The first is the sub-index energy gap, representing the difference between the theoretical final energy consumption for thermal comfort conditions and the actual final energy consumption, as in Palma et al. (2019). The theoretical consumption is calculated through a bottom-up dwelling typology approach based on a set of buildings' characteristics (e.g., area, walls, roof, bearing structure), where a total of 264 representative typologies are defined using regional data harvested from approximately 525 thousand energy performance certificates. The energy needs of every typology are calculated according to a steady-state method based on the requirements and methodology defined in the current National Energy Performance Regulation, implemented in 2013 (DRE, 2013), which derives from the EN ISO 13790 approach. It considers the maintenance of an optimal inside temperature of 18°C in the heating season and 25°C during the cooling season for the whole useful area of the dwelling and during the total duration of the respective season. The theoretical consumption is then computed using data on the occupied dwelling stock per typology and the ownership percentages and efficiencies of the different space heating and cooling systems. The actual final energy consumption for space heating and cooling is estimated using municipal statistics (DGEG, 2022a) on total final energy consumption per energy carrier and representative municipal energy matrixes for each country's climatic zones.

The second sub-index portrays the adaptive capacity of the population to implement measures to cope with thermal discomfort. It is calculated using socioeconomic indicators such as unemployment rate, income, dwelling ownership rate, population share with a university degree, population's age, and building conservation state. The sub-index is the weighted sum of these indicators, and the weights were selected according to feedback from national experts in this field. The median income after income tax was used instead of the gross average monthly income included in the original study. Income inequality in Portugal is high, evidenced by a GINI index of 31.2 per cent, the 9th highest in the EU in 2020 (Eurostat, 2022d) and the median income is less distorted by outliers, representing more adequately the financial means of the population to heat or cool their homes.

The EPVI ranges from 1 (less vulnerability) to 20 (highest vulnerability). It is a linear, equal average of the energy gap sub-index and the symmetrical value of the adaptive capacity sub-index. More information and detail on the index development can be consulted in Gouveia et al. (2019).

The effect of the improvement in the efficiency of HVAC systems in the theoretical final energy consumption and subsequently on the EPVI values was assessed for two different scenarios: Current Situation; Scenario A, where heating and cooling equipment ownership rates were maintained, but the efficiencies were improved to the level required by the residential buildings' energy performance regulation (DRE, 2013); and Scenario B, based on the pathways to 2050 of the "Yellow Jersey" scenario set in the Portuguese Carbon Neutrality Roadmap (Portuguese Republic, 2019b), which considers a socioeconomic evolution compatible with carbon neutrality, supported on structural change in the production chains, integration of circular economy models and growth of medium cities. Following an optimisation modelling of the entire energy system, this scenario considered the necessary national split of HVAC equipment ownership for achieving carbon neutrality objectives. The regional ownerships needed in this study were altered proportionally from the current situation scenario to reach the established national ownerships for 2050. Current climate indicators provided in the regulation for the current situation were considered for both scenarios.

The increases in HVAC efficiency are explored as a proxy of a deep energy efficiency program for replacing the old and inefficient HVAC equipment currently being used. The HVAC efficiencies before the increase of energy efficiency and in the two tested scenarios are shown in Table 1. The split of equipment ownership rates for the current situation and the two scenarios is displayed in Table 2. The data for the ownership rates split is from the 2011 Census, as it is still the only data available at regional level.

Table 1: HVAC equipment efficiencies in % and Coefficient of Performance (for air conditioner and heat pumps) (Palma et al., 2019; DRE, 2013; Portuguese Republic, 2019b)

HVAC system for space heating	Current situation	Scenario A	Scenario B
Open fireplace	35	75	75
Fireplace with heat recovery	60	75	75
Closed biomass stove	55	75	75
Biomass boiler for central heating	70	75	75
Solar Thermal	-	-	100
Diesel boiler for central heating	75	89	-
Natural gas boiler for central heating	75	0.89	-
Electric heater	99	100	100
LPG heater	85	85	-
Heat pump	2.20	4.30	4.30
HVAC system for space cooling	**Efficiency before HVAC substitution**	**Energy Efficiency scenario 1**	**Energy Efficiency scenario 2**
Air conditioner	2.38	3.00	3.00
Fan	100	100	-
Heat pump	2.30	3.00	3.00

Table 2: National space heating and cooling equipment ownership (%) (INE, 2011; INE/DGEG, 2011; Portuguese Republic, 2019b)

Heating System	Current Situation/ Scenario A	Scenario B
Open fireplace	21.7	2.2
Fireplace with heat recovery	8.4	
Closed biomass stove	4.5	
Biomass boiler for central heating	1.3	
Solar Thermal	-	1.1
Diesel boiler for central heating	3.2	0.0
Natural gas boiler for central heating	6.0	0.4
Electric heater	54.5	10.8
Liquified Petroleum Gas (LPG) heater	0.4	0.0
Air conditioning (Heat pump)	2.2	85.6
Cooling system		
Air conditioner	7.0	2.0
Fan	68.0	0.0
Heat pump	25.0	98.0

The carbon dioxide emissions resulting from the real final energy consumption and the theoretical final energy consumption before and after the energy efficiency measures were computed using default emissions factors from the IPCC's Guidelines for National Greenhouse Gas Inventories for Stationary combustion in the residential and agriculture/forestry/fishing/fishing farm categories (IPCC, 2006), for LPG (butane and propane), natural gas, and diesel, and the Portuguese energy supplier Energias de Portugal S.A: (EDP, 2021) for electricity. The electricity emission factor is derived from an energy mix of 72 per cent non-renewable energy (10 per cent of coal, 49 per cent of natural gas, 12 per cent of fossil cogeneration and one per cent of solid waste) and 28 per cent of renewable energy (one per cent of wind energy, eight per cent of hydric energy, 11 per cent of other renewable energy and eight per cent of renewable cogeneration) (EDP, 2021). The methodology follows a similar approach to the one of Gouveia and Palma (2019). The difference in the total carbon emissions was estimated and analysed for the different scenarios in light of the variation in energy poverty levels.

Results and Discussion

The results show unequivocally that the increase in energy efficiency in residential homes in Portugal positively affects energy poverty levels when assessing vulnerability with the multidimensional approach for regional assessment advanced by Gouveia et al. (2019). Average municipal EPVI values for space heating and cooling seasons decreased from 10.0 and 11.4, respectively, to 8.2 and 11.2 in Scenario A, with 17.8 per cent and

1.0 per cent decreases. In Scenario B, percentage decreases are even higher, respectively, 47.8 per cent and 26.3 per cent, with EPVI average values of 5.2 and 8.4. These findings indicate a more significant effect of equipment replacement and efficiency increases in the winter energy poverty season as the equipment currently in use has lower efficiency. Inefficient equipment includes fireplaces, biomass stoves, and diesel boilers. On the other hand, although real consumption is considerably lower in the summer season, the equipment stock composed of fans and air conditioners is more efficient. The maps displaying EPVI values for the current situation, Scenario A and Scenario B, are shown respectively in Figure 1, Figure 2, and Figure 3. Both in the heating and cooling season, higher EPVI values can be found in the interior of the Portuguese mainland and the islands in the current situation. In Scenario B, higher average municipality reductions in winter EPVI are observed in the centre littoral regions of Leiria, Aveiro, and Coimbra (29 per cent, 27 per cent, and 27 per cent, respectively) and the centre inland region of Beira Baixa (28 per cent). This is explained by higher ownership rates of biomass systems in house and apartment typologies, which have lower energy efficiency. In Beira Baixa, open fireplaces are particularly common.

In contrast, in the central coastal regions, all types of biomass equipment can be frequently found, as well as natural gas boilers in apartment buildings. In the summer, as the equipment ownership split was considered the same for every municipality, the highest decreases are found in Lisbon and Porto regions (minus two per cent and minus three per cent) due to the greater size of the dwelling stock, magnifying the effect. Reductions of EPVI levels are considerably lower than for space heating because the cooling systems' stock already has an efficiency very close to regulation requirements. Only replacing less efficient systems for new and substantially more efficient systems can result in a substantial change at a larger scale, as observed in Scenario B. In this scenario, summer EPVI reductions are considerably higher, especially in the urban centres of Lisbon and Porto, where actual consumption levels are more significant, and together with a decrease in theoretical consumption, result in lower energy gaps and vulnerability. Additionally, municipalities in northern regions like Alto Minho and Ave would benefit significantly from an energy efficiency upgrade given that energy demand for space cooling due to climate conditions is low; hence efficiency upgrades could reduce energy needs and the energy gaps and vulnerability in a tangible form. Regarding space heating in Scenario B, the change of equipment stock is transversally impactful across the country, with significant reductions in energy needs and ultimately vulnerability levels to a value lower than five in about 59 per cent (182) of all 308 municipalities, which is a considerable achievement.

The Açores and Madeira's islands are the regions where energy efficiency measures are less effective for space heating because there is a widespread use of portable electric heaters in both dwelling typologies, which have a higher efficiency than most of the other systems in the stock. Moreover, real consumption in the municipalities of both islands is generally meagre. Thus, efficiency increases and even equipment replacements are not so impactful in reducing winter EPVI levels and summer EPVI to a lower degree in both scenarios.

Looking at carbon dioxide emissions at the national level, displayed in Table 3, there is a large gap between current emissions and the emissions that would result from the necessary consumption to attain thermal comfort in all Portuguese dwellings, around 2565 kiloton for space heating and 1112 kiloton for cooling. The increase of efficiency in Scenario A does not significantly reduce this gap in percentage - 79.8 per cent to 78.5 per cent for heating and 84.7 to 84.1 per cent for cooling - resulting in reductions of around 195 kilotons and 43 kilotons. Considering the current energy performance of the residential building stock, consumption levels and carbon dioxide emissions would have to increase significantly to guarantee thermal comfort for the population. On the other hand, in Scenario B, emissions drop to around 779 kilotons for space heating, 16.5 per cent above the emissions with the current consumption, which means even in a scenario of carbon neutrality and a very favourable and efficient equipment stock, consumption levels and emissions would still need to rise to guarantee energy sufficiency in Portuguese homes. However, for space cooling, carbon dioxide emissions associated with the necessary thermal comfort consumption drop to 198 kilotons, below current emissions, which means an increase in cooling energy consumption and carbon dioxide emissions would not be needed.

Figure 2: EPVI in the heating season (left) and cooling season (right) in the current situation

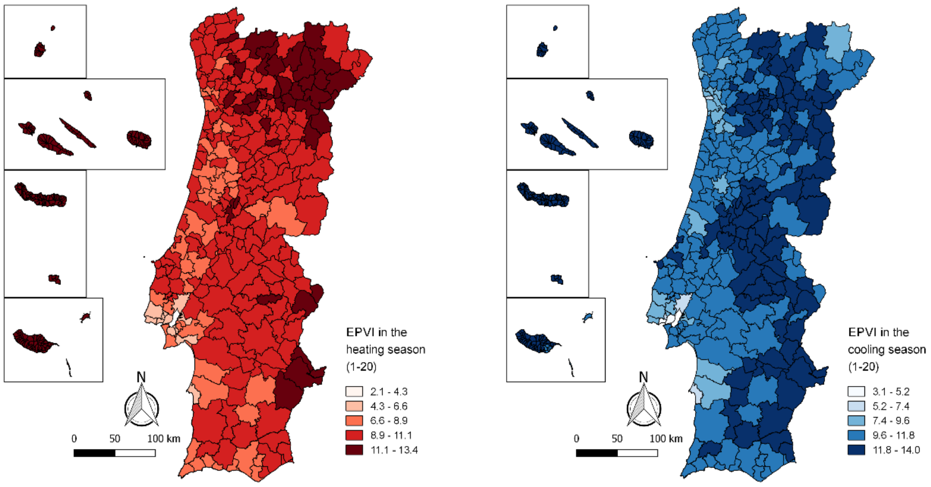


Figure 3: EPVI in the heating season (left) and cooling season (right) in Scenario A

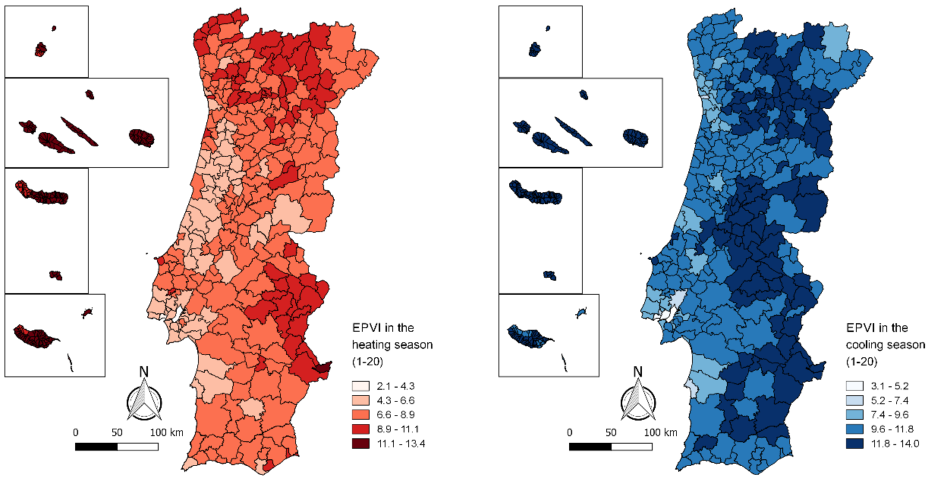


Figure 4: EPVI in the heating season (left) and cooling season (right) in Scenario B

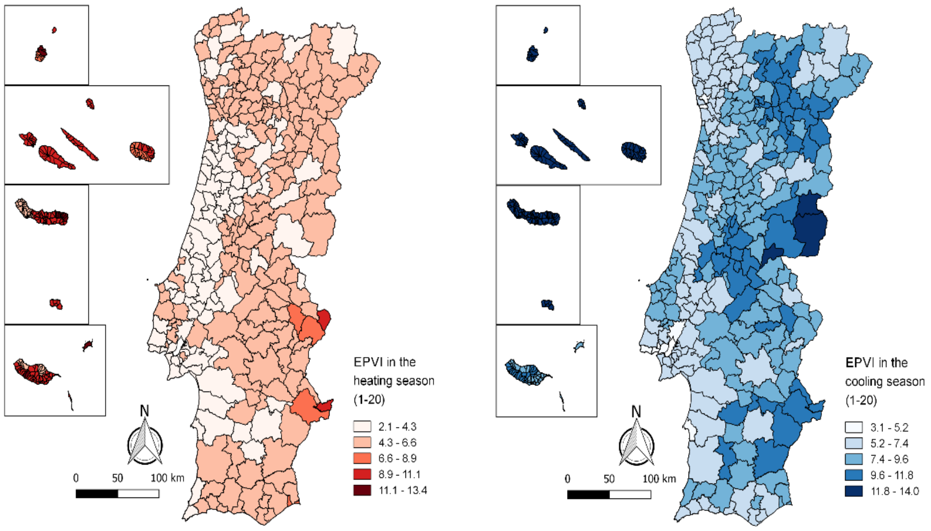


Table 3: Total carbon dioxide emissions in the current situation, Scenario A and Scenario B

CO_2 emissions (kton)	Space Heating	Space Cooling
Current Situation (Real consumption)	651	202
Current Situation (Theoretical consumption)	3217	1314
Scenario A (Theoretical consumption)	3021	1270
Scenario B (Theoretical consumption)	779	198

It should be noted that, whilst heating and cooling equipment replacement and increase of efficiency is an essential part of the solution, it should not be the only effort towards increased thermal comfort, decarbonisation, and reduction of energy consumption. The increase in the population's quality of life and economic development may lead to excessive energy consumption in the long run. Indeed, the Building Renovation Strategy raises concerns about the so-called "rebound effect" (Portuguese Republic, 2021). Moreover, the roll-out of the necessary equipment for Scenario B is of great magnitude, with heavy investment and inherent environmental impacts. Efficiency systems like heat pumps and air conditioners still pose challenges to climate change mitigation, as they use f-gases, which have a global warming effect up to 23 000 times greater than carbon dioxide (European Commission, 2022c), and avoiding them can be a major climate change solution (Project Drawdown, 2020). Therefore, it is also crucial to tackle the problem upstream, i.e., reducing building stock energy needs by increasing energy performance via renovation interventions. In Portugal, due to the very high energy gaps (Palma et al., 2019) resulting from the lower energy performance of an old building stock and historical underconsumption, this renovation might not reduce consumption in the short term. However, it will improve the thermal comfort of occupants and provide other positive externalities such as better indoor air quality, which, together with efficiency upgrades in heating and cooling systems, might result in energy consumption savings in the medium or long term.

At the policy level, efforts have derived mainly from the central administration under the recent scope of the Recovery and Resilience Plan. There are currently two programs supporting building renovation and energy efficiency measures in the residential sector. The first one is directed at the general population, providing 85 per cent of the investment (VAT excluded) after the implementation of both kinds of measures. The other program distributes vouchers of €1300 + VAT before the intervention to homeowners that benefit from the social energy tariff. The €300 million allocated for the residential sector until 2025 represent nevertheless a small percentage of the necessary investment, falling short of making a significant impact. Palma et al. (2022) reported a minimum total investment of €70 billion euros to renovate the Portuguese residential building stock to the optimal regulation standards. Conducting a small theoretical exercise, considering an average cost of €1200 for installing two regular split heat pumps in a dwelling, increasing ownership by 25 per cent would require an investment of roughly 1.25 billion euros. Also, there are over 800 thousand social energy tariff beneficiaries in Portugal (DGEG, 2022b). As the EU mandates Member-states to achieve energy savings in energy-poor homes, the energy gaps between ideal and actual consumption in the residential sector in Portugal are a substantial barrier to creating sustainable business models around energy savings. The energy-poor population does not have the financial resources to conduct interventions in their homes, thus sustained state financial support after 2025 at central level is essential to drive permanent transformation in the sector.

Regional and local governments have tax incentives in historical areas and mainly support the renovation of rundown buildings but often have problems regarding funding availability. Nevertheless, due to their closer relationship with the people, they can play an important role in increasing energy literacy, supporting the population in accessing the state programs, and collaborating with central administration to guarantee higher adoption and effectiveness of these support programs. The results of this study highlight the regions where energy efficiency support measures can have a higher impact, which can be useful for prioritizing and mobilizing efforts at both national and regional levels.

The private sector, particularly energy companies, should also be accountable for this transformation through obligations, as proposed by the EU in the energy efficiency directive, as they have large revenues and households suffer from high energy prices in the country. However, these obligation schemes should not be based on energy savings but rather on renovation interventions and equipment replacement, focusing instead on energy needs reduction, energy sufficiency, and thermal comfort improvement. This approach would benefit from the collaboration with local authorities to target those most in need.

While this energy transition is of utmost importance, it should assure energy justice across the country. There are households in situations associated with different types of energy injustice. Firstly, it can be argued that there is an issue of distributional justice in energy policy, as the percentage of support for each measure does not vary according to the socioeconomic status of the recipient, and the subsidies for vulnerable consumers can be significantly lower in absolute value compared to the program targeting the general population, depending on the measures adopted. Hence, there is an imbalance in the support framework resulting in inequality of opportunity, connected to a deeper problem in adequately recognising and taking into account socioeconomic inequalities. Outside the scope of support schemes, the fact that highly efficient equipment is more costly also contributes to increasing injustice. As Europe tries to move away from gas, a significant increase in demand is ramping up heat pump prices, which also exacerbates inequality (Euroactiv, 2022). There are Portuguese people in energy poverty across the whole country (Panão et al., 2021), but there is generally higher vulnerability in rural regions (Gouveia et al., 2019), thus, geography and territory should also be considered in policy design, as these factors shape injustice. This study highlighted the varying levels of energy poverty and the potential impact of measures across regions that are not considered in support provision and funding allocation. It can also be argued that there is a systemic problem of procedural justice when it comes to policymaking, as people are rarely engaged in the decision-making processes, potentially due to considerable levels of energy illiteracy in the country (ERSE, 2020) and relatively low efforts from governments to promote citizens' participation in the discussion.

There is also a set of ongoing historical and recent inequalities that should be recognised and addressed for the needed transformation to be conducted fairly. Across the country, there is still high ownership of fireplaces and other biomass-burning equipment across regions, and a part of the population still access firewood at very low or no cost, as it might be a common resource in the countryside. Replacing these fireplaces with higher efficiency equipment could mean improved efficiency but would result in added costs to these families. In apartment buildings, some newer systems are also challenging to install and require the approval of neighbours. Various efficient technologies such as monobloc heat pumps might require a considerable amount of space in the dwellings, which prevents their implementation in smaller dwellings, creating a housing inequality. Furthermore, as elderly people frequently inhabit these homes, digital difficulties in handling these new systems could also prevent smooth utilisation. Digital illiteracy is a relatively recent problem of injustice, crossing over different areas within this domain. For instance, it is also a significant handicap for accessing support programs, as the application process can only be conducted using online platforms. Ashby et al. (2020) state that policymakers often design programs to their image, though not reflecting the needs of the vulnerable, which may be the case also for ongoing support programs in Portugal. Therefore, to address that lack, state support schemes for vulnerable households should have a nuanced approach, considering geography, context, vulnerability profiles and ongoing injustices, to deliver more effective support interlinking efforts at national and regional levels. This will help not to leave anyone behind in the efforts of tackling energy poverty, boosting energy efficiency, and achieving the set energy and climate targets for 2050.

Finally, reflecting on the contribution of this paper on a broader level, it links three critical social and political subjects at a worldwide and European scale - energy poverty, decarbonisation, and energy efficiency, by analysing the potential transversal impact of a particular solution, the replacement of domestic HVAC equipment. It underscores the need for looking at this kind of measure as part of the solution for these three societal challenges, not only in Portugal but also in other geographical contexts, with an energy justice lens. It advances a context-specific but replicable methodology, that could inspire the development of similar studies. In fact, the study of the direct causal nexus between these subjects in the residential sector is still an underexplored subject in literature. Developing knowledge in this area could ultimately benefit local and national governments in their policy design and contribute, even if contextually, to tackling these major global challenges.

Conclusions

Climate change mitigation, decarbonisation, and reduction of energy poverty are three of the most critical challenges that the world and the EU currently face. While various policies are tackling each of these issues, it is crucial to support integrative and comprehensive actions which tackle all these challenges, such as increasing energy efficiency in buildings. This study proposes a methodology to assess the impact of energy efficiency upgrades, namely the replacement of domestic space heating and cooling equipment, on regional energy poverty and carbon dioxide emissions. Results show significant reductions in energy poverty levels, especially when considering equipment replacement and profound change in the national equipment stock. Due to historical, cultural, and financial reasons, underconsumption of energy is prevalent, resulting in a substantial gap between the real consumption and the necessary consumption to achieve indoor thermal comfort in every Portuguese home. This means that thermal comfort conditions would subsequently entail higher carbon emissions. Comprehensive upgrades of heating and cooling equipment would significantly reduce the consumption and emission gaps for space heating and even reduce necessary emissions below the current levels for space cooling. Increased and consistent state support at both central and regional levels is crucial for boosting energy efficiency in the residential sector, as a considerable investment is necessary and the circumstances of energy use in the sector do not enable suitable business models. Private energy companies could be part of the solution via energy retrofit and inefficient equipment replacement obligation schemes. It is paramount that this transformation accounts for energy justice issues of the different vulnerable groups of the population to ensure a just energy transition and achievement of energy and climate targets. The outcomes of this study, although specific to Portugal, emphasise the need for investigating heating and cooling systems replacement at a wider scale, as it can have a triple positive impact in simultaneously tackling the major challenges of energy poverty alleviation, decarbonisation, and energy efficiency in other geographical contexts.

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