Studies in Energy, Resource and Environmental Economics

Rossella Bardazzi
Maria Grazia Pazienza *Editors*

Vulnerable Households in the Energy Transition

Energy Poverty, Demographics and Policies

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Preface

Household energy poverty has received unprecedented attention from policymakers and the general public in recent months in the context of the sudden rise in energy prices. However, energy and transport poverty is widespread even in non-exceptional times, limiting the well-being and growth potential of non-negligible parts of the world's population. Moreover, the transition from fossil fuels to renewable energy sources promoted by the European Green Deal not only requires new supply systems but also necessitates that the consumers be motivated to change their consumption habits and supported to adopt new technologies requiring private capital investments. Energy poverty alleviation should be placed within the EU 'just and fair' energy transition process aimed to 'leave no one behind'. This collection of essays is a part of the results of the HOPPER project (*HOuseholds' energy Poverty in the EU: PERspectives for research and policies*), a Jean Monnet Chair funded by the Erasmus+ Programme of the European Union, aimed to examine and disseminate the results of studies on the significance and the causes of this phenomenon in Europe. In particular, studies and policy assessments in France, Germany, Greece, Italy and Spain are presented, based on the seminars and research activities that took place within the project. Therefore, the case studies discussed in the volume do not cover the full extent of the phenomenon in Europe, which is also significant in Eastern European countries and the UK, but are the result of an exchange of research and knowledge within the HOPPER network. The book chapters as a whole offer an advance in the current knowledge on household energy vulnerability in the context of the energy transition process using different methodological and empirical approaches, and various complementary perspectives.

All chapters have been peer-reviewed by the book editors and selected external reviewers.

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HOuseholds' energy **P**overty in the EU:
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HOPPER

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Vulnerable Households in the Energy Transition

Rossella Bardazzi and Maria Grazia Pazienza

Energy transitions are multi-dimensional and multi-actor processes involving technical systems, social networks and societal institutions and regimes (Sovacool and Geels 2016). Interactions between firms, households, policymakers and social bodies are at the core of the shift from one energy system to another. This nexus of interactions is even more important to be analysed when considering the current energy transition towards decarbonization, which is mainly policy-driven rather than social- or technology-driven. Policies, regulations and incentives have been widely used to shape energy markets and consumer energy use according to different goals, ranging between energy saving, environmental protection and energy independence. Since the European Green Deal plan, low-carbon transition has become the main goal in the EU and the related policy packages—among which the 'Fit for 55' legislation is the most important pillar—make use of all policy levers: regulation and standardization, investment, national reforms and international cooperation (EC 2019; Paleari 2022). Market-based policies—such as environmental taxes, tradable permit systems or targeted subsidies— represent central tools in the transition to a climate-neutral society by 2050. Indeed, they provide incentives to firms and consumers to opt for less polluting energy sources and products. Fundamentally, the EU policy package stresses that decarbonization can be reached by putting a price on a resource either with taxation or through regulation to make environmentally harmful energy sources and products more expensive. These policies should generate a long-term upward trend in fossil fuel prices and consequently they should provide the right signal to reduce the energy consumption (through higher energy efficiency) and/or to redirect

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the energy use towards those sources with the lowest carbon footprint. As argued by Pisani-Ferry (2021), the new long-term growth strategy implemented with the EU ambitious climate package has economic transition costs as any other macroeconomic policy. These costs will be unevenly distributed, creating winners and losers and should not be overlooked. Focusing on households, consumers will be better off in the long run because of the avoided costs of climate change but in the short run they will suffer significant transition costs due to sizeable relative price changes. There is a general agreement in the literature that climate policies have distributional implications that are larger among the lowest deciles of income distribution (see Fullerton and Muehlegger 2019 for a review of several studies) although the overall final impact is affected, among others, by the revenue recycling schemes adopted to address these effects (Ohlendorf et al. 2021). These social transition costs are acknowledged also by the European Commission which stresses that energy and climate transitions should be 'just and fair' and 'leave no one behind'. Indeed, the Impact Assessment accompanying the European plan (EC 2020) expresses concern about the increasing risk of energy poverty for vulnerable households if not addressed by appropriate policies. Energy vulnerability may arise for reasons not necessarily related to income levels but to other characteristics (Bouzarovski and Petrova 2015): specific socio-demographic factors (age, household type), critical dependence on energy-intensive equipment due to health reasons or limited energy literacy, such as difficulty to understand complex contracts and to react to aggressive commercial practices. In general, vulnerable households are more affected by climate policies because they have constraints in their consumption baskets and they have less information to make informed choices, including about making investments in energy efficiency and energy saving.

At the time of writing, the transition costs are being exacerbated by the high volatility in energy prices—and the resulting inflation—due to the uneven emergence of different economies from the pandemic and the geopolitical situation. The EU and member state energy transition policy—which, with the 'Fit for 55' package, has placed great emphasis on market instruments—has been thus overlaid by an unexpected effect of great intensity, which, precisely because of the geopolitical component, increased the level of uncertainty about future trends. The pressure on consumers has therefore been considerable and sudden. Households need to be able to absorb rising costs and, at the same time, have the flexibility to innovate and change technology and, above all, habits (Ari et al. 2022).

The household sector is therefore a key player in this process: individuals must be engaged in the deep behavioural changes required in this transformation to avoid the risk of a mismatch between implemented policies and social acceptance. In this challenging framework, particular care should be devoted to the distributional impact, in particular to the 'left behind', since in the European Union a significant share of households is already experiencing energy vulnerability (Bouzarovski et al. 2020; Koukoufikis and Uihlein 2022). The current phase of high energy prices is showing that every household may become vulnerable to energy costs because of economic factors (low income, unemployment or poor jobs) and also of some other characteristics such as being a woman, having disabilities, having poor health, being single-parent, with low education or belonging to a minority group. Energy poverty is a complex phenomenon that needs to be addressed within the energy transition agenda, not only to avoid exacerbating the problem, but mainly to implement a win–win strategy achieving a solution while following a decarbonization path. Unfortunately, an effective knowledge of the real vulnerabilities on which to base policies is still lacking, especially in a world where innovation is widening the gap between different types of consumers. As the recent period of high volatility in energy prices is exacerbated by the impact of European policies—as shown by the record price of ETS allowances—, the change in relative prices is driving behavioural changes in favour of energy efficiency and towards less carbon-intensive energy sources across the economy and the household sector. However, the speed of reaction may not be homogeneous: vulnerable households lack the knowledge, the financial resources, the time and the information to seize the opportunities of a shift in the energy system (Eurofound 2021). Moreover, vulnerable households suffer the most from carbon pricing not only because they have a higher share of energy costs in their total expenditure but also because they are estimated to experience a larger fall in income as they tend to work in sectors more sensitive to changes in demand (Ari et al. 2022; Faiella et al. 2022; Kanzig 2022). Therefore, the vulnerable households segment needs to be supported with appropriate policies to access the benefits of the transition and to limit the inequality in energy use and energy expenses. These needs are even more important if we consider the projection of a fast ageing society in almost all EU member countries. Indeed, ageing may worsen all of these vulnerabilities, including the increasing demand for energy services from those who spend progressively more time at home. Although this higher residential energy consumption of the elderly may be compensated by lower consumption of energy for transport services and production activities, some empirical studies show that a change in generational preferences should also be considered as younger cohorts will get older with practices and lifestyles that are different from the current elderly cohorts (Bardazzi and Pazienza 2020; Han et al. 2022). Therefore, future patterns of energy consumption and emissions will be affected not only by changes in population size but also by the fact that younger generations will substitute older cohorts in the population.

For the aforementioned reasons, the study of energy poverty and household energy demand is of utmost importance, not only with a focus on the present but also in view of the future societal transformations and the planned energy and environmental policy of the European Union.

This volume is a collection of essays dealing with the nexus between energy transition and energy poverty in some countries of the European Union, considering the effects on the household sector of energy transition and related policies. The book is divided into three sections, corresponding to the premises, the identification of the problem and the policies to address it. In the first section, the European energy context and the long-term scenario are discussed in more detail, with particular reference to the impact of ageing, one of the most influential elements in the long term. The second section looks at the multi-faceted issue of energy poverty, including a gender perspective, transport poverty and the health consequences of lack of access to adequate energy services. The last section discusses the impact of some policies on energy transition—mainly carbon price—and on energy poverty. As for the geographical analysis, we consider five countries, most with a connection with the Mediterranean area (France, Greece, Italy and Spain) and Germany, where the debate on energy transition started long ago, but where major reforms are still needed. Several chapters are dedicated to Italy, where the project on energy poverty—the HOPPER Jean Monnet Chair—that inspired this collection of essays originated.

Drawing connections and scenarios in the energy field is a really difficult task in this time of great turbulence. However, the work of Lutz and Becker does an excellent job of clarifying the underlying relationships and thus signalling the significance of the projections being made. As an overall assessment of the macroeconomic impact of the energy transition scenarios, Lutz and Becker's contribution uses a multisectoral model to consider the new framework of increasing energy prices to estimate the effects on the economy in general and on the household sector in particular, taking Germany as a case study. The results quantify the expected negative macroeconomic effects on GDP and the labour market, induced by the sharp increase in energy prices. The findings also show the key importance of the consumption structure and income position in evaluating how the price shock propagates in private households. The regressive effects of the shock may be lightened by effective public policies and the authors support the idea of a per capita bonus, firstly because the savings incentive of high prices must be maintained and secondly because low-income consumers are relatively more relieved. However, Lutz and Becker stress that an accelerated policy of fossil fuel independence and decarbonization remains the only effective long-term policy to address climate change, exposure to international price volatility and, ultimately, budget protection.

In the second chapter, Bardazzi and Pazienza analyse how another important transition, the demographic change in the structure of the population, interacts with future trends in household consumption behaviour. After providing an overview of population trends at the EU level—both in terms of size and composition—the authors emphasize that the age effect is not linear and depends not only on the life cycle but also on energy cultures and the relative wealth position of different contingent age groups. By estimating price and income elasticities by age group, Bardazzi and Pazienza find a lower responsiveness in the residential energy consumption of the elderly compared to the younger population. The authors interpret this result in terms of the relatively better income and wealth position and the persistent energy-saving behaviour of the oldest part of the Italian population, which will, however, come under greater pressure in the future due to changes in the welfare system and the progressive effects of the energy transition policies.

The second section of the volume collects several contributions exploring some determinants and consequences of energy poverty and overlapping vulnerabilities that play a part in shaping this phenomenon. Charlier and Legendre investigate the relationship between energy poverty and health using an original survey on French households designed specifically for this empirical study. By using econometric models, Charlier and Legendre investigate the two-sided relationship between energy poverty and health clarifying that falling into energy poverty significantly degrades objective and subjective health scores, such as those used by WHO both at physical and mental health levels. These findings highlight the positive spill-over effects that can be expected from effectively tackling energy poverty, both in terms of individual well-being and potential savings for public budgets. The authors therefore call for a holistic approach to these policies, considering the environmental, social and health aspects of tackling energy poverty as inextricably linked.

Then, the spatial dimension of a specific type of energy poverty, related to the use of fuels for private transport, is investigated by Mattioli, Dugato and Philips. The authors focus on Italy, an interesting case study due to the combination of one of the highest motorization rate in EU and high fuel prices. They define a composite indicator of vulnerability, considering the role of high exposure (high car use), high sensitivity (low income) and low adaptive capacity (high car dependence). As a general finding, the long-standing economic divide between Italian regions also reflects in a higher vulnerability in the South of Italy, largely driven by economic deprivation. However, areas of great concern are also in the Centre of the country and within the centre/periphery divide. This finding should also be considered in the context of electrification of the energy system and of the vehicle fleet in particular, which can widen the gap between Italy—characterized by a very low transport-related electrification rate—and other EU countries in terms of vulnerability to fuel price increases, by reducing other countries' exposure more rapidly than Italy's.

Finally, in the last chapter in this section, Toro, Fernández-Vázquez and Serrano examine the link between gender and energy poverty through a longitudinal analysis of Spanish households. The authors show that the gender gap in energy poverty is mainly due to women's greater exposure to energy-related activities. The results show that female householders spend a significantly higher proportion of their income on residential energy than their male counterparts, regardless of the income level, although these differences decrease as the expenditure quintile increases. The opposite is true for transport fuels for male breadwinners. As there are few substitutes for household energy, while there are substitutes for transport fuels in public transport, female breadwinners are relatively more affected. This gender inequality in energy consumption is exacerbated in the case of the most disadvantaged households, where women should limit their expenditure on energy products, especially those related to private transport.

The third section of the book deals with the distributional impacts of decarbonization policies and the possible role of compensatory measures for vulnerable households. Specifically, Dobbins and Fahl use an energy system optimization model to estimate the distributional impacts of the carbon tax in Germany so as to consider how to compensate lower-income households. Redistribution mechanisms per person and per household are considered. The authors stress that by linking redistribution to energy efficiency investments in buildings, low-income households would be more able to absorb the long-term impact of energy and carbon price increases. Social acceptance of CO_2 pricing and redistribution schemes can better be guaranteed when resources are channelled into investments that will reduce carbon emissions in the future.

In the chapter by Faiella and Lavecchia, demand elasticities for different energy sources are estimated and then used to calculate the distributional effects of a carbon tax on households in Italy. The authors use these estimates to assess the impact of different levels of carbon taxation on energy demand and the revenue that can be raised from these different tax levels. In all cases, the price increase induced by the carbon tax is regressive: poorer households' expenditure increases more, while their energy consumption decreases more. To increase the political acceptability of carbon pricing policies, the authors suggest compensating vulnerable households, for example, through lump-sum transfers or by financing low-carbon energy solutions.

Martini provides a different glimpse on the energy poverty phenomenon and analyses the different distributional effects of specific policies designed to mitigate energy poverty in European countries. In particular, she focuses on the Ecobonus instrument, which has been introduced in Italy since 2016 with the aim of incentivizing investments in energy efficiency, especially by low-income households. The author stresses that, in addition to the allocation of resources, it would be necessary to strengthen training, information, dissemination and awareness-raising activities in order to facilitate access to this incentive for energy-poor households.

Finally, Fragkos and colleagues examine the impact of the just transition on Greece using a general equilibrium model that disaggregates income by class and source. The authors quantify the distributional impact of Greece's ambitious emission reduction targets and find that the country's transition to climate neutrality is regressive, but only modestly increases income inequality. They suggest using carbon revenues to finance a lump-sum transfer to support household income. According to the authors, this compensatory measure has the potential to boost employment and reduce income inequality in Greece.

The challenges posed by the EU's decarbonization ambitions, coupled with the particularly volatile period for prices, and energy prices in particular, put a particular strain on the situation of the most vulnerable, which certainly includes the elderly and low-income households. After describing the general context, a number of contributions in this volume stress that vulnerability is a complex phenomenon and that energy poverty in particular has many facets and interrelationships, at least with mobility, health status and gender well-being gap. These vulnerabilities certainly need to be addressed by public policies, and it has been shown that there are many ways in different countries to turn the burden of carbon pricing policies into an opportunity, especially if the funds, in addition to alleviating the current situation, act as an incentive for investments that help decarbonise and make the energy consumption of vulnerable households more efficient and therefore less expensive.

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Households in the Energy Transition: Some General Issues

Effects of Energy Price Shocks on Germany's Economy and Private Households

Christian Lutz and Lisa Becker

1 Introduction

The current sharp rise in energy prices has far-reaching consequences not only for the economy, but also for private end consumers. In addition to the overall high inflation, households are hit by high prices for energy for which they often have no possibility to substitute, e.g., tenants with regard to the heating system as landlords decide on the heating system and insulation measures. Furthermore, the energy costs per household do not increase proportionally with income, as energy is a basic good, but account for a higher share for lower income households, so that they are more burdened with energy expenses.

There are different approaches to measuring energy poverty (Halkos and Gkampoura 2021). In the expenditure approach, a household's spending on energy is put in relation to its income. Generally, a household is considered energy poor if this proportion is 10% or more. In Germany, the energy poverty rate had fallen by 2020 due to lower energy prices: while it was 18.3% in 2016, only 13.6% were affected by energy poverty in 2020. In 2021, energy prices increased more than incomes, partly because Germany introduced a national CO_2 price of 25 €/t CO_2 for transport and heating that year, which corresponds to a premium of about 7–8 €-cents at the petrol stations. Fueled by Russia's war against Ukraine, energy prices increased dramatically in 2022, so that in May 2022 the share of the population at risk of energy poverty had jumped to 25.2% (Henger and Stockhausen 2022). However, households are not equally burdened by income deciles: Bach and Knautz (2022) estimate that the burden of higher prices for electricity, heating, and fuels will increase by 6.7%

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of their net income for the lowest-income 10 percent of households in 2022, while the highest-income decile will only be burdened by an additional 2% of net income.

Across Europe, energy poverty decreased between 2013 and 2017 with lower energy import prices, but has been rising again since then (Rodriguez-Alvarez et al. 2021). Here, drastic differences can be seen between the 30 countries examined in the study: While Bulgaria or Greece, for example, have a relatively high energy poverty index that fluctuates strongly over the period analysed from 2005 to 2018, a low proportion of population suffers from energy poverty in the Scandinavian countries in particular. Energy poverty and the specific vulnerability of low-income groups are not new findings. Basic goods are known to have a regressive effect. A 2015 study by the European Commission (Pye et al. 2015) also shows comparable differences between countries. The effect of COVID-19 pandemic on energy poverty is estimated in a paper by Carfora et al. (2022) for EU member states. Data on demographic and social conditions, energy and environmental factors, and living conditions are used as explanatory variables for this. The results show that Bulgaria, Greece, Latvia, and Italy in particular are expected to suffer a strong increase in energy poverty as a result only of the pandemic. Steckel et al. (2022) analyse the effect of energy poverty on European households by expenditure deciles in the current price crisis. In the baseline scenario, price increases of 340% for gas, 83% for oil, and 150% for hard coal are assumed. For the gas price increase, the result is an uneven distribution, whereby the additional burden of higher costs is regressively distributed across expenditure deciles. This results in additional costs of about 13% of expenditure in the poorest 10%, compared to "only" 8% for the richest decile. In contrast, the additional cost burden for oil and hard coal is at a similar level across the deciles, between 2 and 4%.

A literature review shows that the change in demand for energy sources due to higher energy taxes and other changes in energy prices has been investigated in many studies—both in Germany and internationally. At the macroeconomic level, the price and income elasticities of energy demand are often estimated internationally. Gao et al. (2021) calculate income elasticities of energy demand in the range of 0.6 to 0.8 and price elasticities in the range of −0.1 to −0.3 based on extensive international panel data for the period 1960–2016. Held (2017) calculates German price elasticities of −0.19 to −0.44 for electricity, −0.35 to −0.94 for heating, and −0.08 to −0.67 for private transport. According to a meta-analysis by Bach et al. (2019) price elasticities in Germany range from −0.025 to −0.8. Held (2017) and Bach et al. (2019) also show that the demand for fossil heating fuels is more price elastic than that for electricity, and long-term price elasticities are larger than short-term ones. Most short-term price elasticity estimates are below −0.3. Edenhofer et al. (2019) assume higher price elasticities for the transport and heat sectors in Germany in the order of −0.5 to −1.1, in the base case of mostly −0.7. Pothen and Tovar Reaños (2018) empirically estimate energy price elasticities in a range of −0.34 to −0.67. Estimations for Austria from Köppl and Sommer (2016) for short-term elasticities are significantly lower in a range of −0.02 to −0.24.

This chapter analyses how the expected price shocks in 2022 and the following years will affect the overall economy, consumer prices for private households, and their burden of energy costs. Therefore, the model PANTA RHEI used for the calculation is first described and the assumptions in the development of import prices for fossil energies are described (Sect. 2). The resulting effects are presented as differences between a reference development and a scenario in which the higher import prices apply (Sect. 3). Finally, the results are discussed and evaluated against the background of the current developments and compared to climate mitigation efforts (Sect. 4).

2 Material and Methods

2.1 Model Description

For the analysis of the effects resulting from a strong price increase for energy imports, the macroeconometric model PANTA RHEI is applied (Lutz et al. 2021b). It is the environmentally extended version of the INFORUM type simulation and forecasting model INFORGE (Almon 1991; Becker et al. 2022; Maier et al. 2015). In addition to the comprehensive economic core, energy and emissions are covered in detail. All model sections are consistently linked with each other.

The most important equations regarding private energy demand are presented below. For details of the complete model see Lutz et al. (2021b). Among others, it has been used for economic evaluation of different energy scenarios that have been the basis for the German energy concept in 2010 (Lindenberger et al. 2010). Applications include an evaluation of employment impacts of renewable energy promotion (Lehr et al. 2012), socio-economic impacts of the German energy transition (Lehr et al. 2019; Lutz et al. 2018, 2021b; Lutz and Lehr 2019) as well as of different energy system transformation pathways (Naegler et al. 2021; Ulrich et al. 2022), impacts of the transition to a green economy (Lutz et al. 2017), and economic effects of an e-mobility scenario (Ulrich and Lehr 2019). Rebound effects and policies to counter them have been explored by Ahmann et al. (2022) and Kern et al. (2022).

The entire model is solved simultaneously, i.e., the mutual impact of model variables is considered simultaneously. The model contains a large number of macroeconomic variables from national accounts and input–output tables and provides sectoral information according to 63 economic branches. The energy balances are fully integrated into the model.

The behavioural parameters are estimated econometrically using time series data, mainly from 2000 onwards. This basically assumes that behavioural patterns or reactions to price or quantity changes in the past will also prevail in the future. The use of econometrically estimated equations means that agents have only myopic expectations. They follow routines developed in the past. This implies, in contrast to optimization models, that markets will not necessarily be in an optimum and non-market (energy) policy interventions can have positive economic impacts. Adjustments can be implemented through exogenous specifications. For example, import prices are

Table 1 Elasticities for energy consumption purposes, own estimates

Consumption purpose	Income elasticity	Price elasticity	HDD elasticity	Trend
Electricity	0.52	−0.13	0.18	
Heating	0.12	−0.12	0.68	
Fuels	0.92	−0.07		

exogenously set in the model, based on scenarios from the World Energy Outlook (IEA 2021).

Private consumption patterns by 47 purposes of use[1] c_k are estimated as a function of real disposable income $\frac{YH}{PC}$ and relative prices $\frac{pc_k}{PC}$. PC denotes the consumer prices index. The consumption modelling is not a system estimation, but a single equation model, which explains total consumption bottom-up. Substitution between different consumption purposes is not directly modelled but can take place due to price changes and different income and price elasticities. This means that annual consumption and savings rates are variable, which is compatible with the drastic fluctuations in the German savings rate since 2019. Obviously, there is longer-term flexibility in consumption decisions through asset adjustments and debt.

For some consumption purposes, time trend t as a proxy for long-term change in consumption behaviour or the number of private households HH is used as an explanatory variable. Heating degree days (HDD) are important for energy consumption:

$$c_k = f\left(\frac{YH}{PC}, \frac{pc_k}{PC}, HDD, HH, t\right)$$

The following Table 1 shows the short-term elasticities of energy demand by private households. For electricity consumption the income elasticity is quite high. An increase in disposable of 1% income leads ceteris paribus to an increase in electricity consumption by 0.52%. The price elasticity is quite low. If the electricity price increases by 1%, consumption will fall by 0.13%. Heating degree days also have some influence on electricity consumption. Consumption for heating is dominated by temperatures in winter, i.e., the heating degree days. About 50% of private households use natural gas (AGEB 2022a). Changes in income, partly via larger living space and energy prices only have smaller impacts. Fuel demand is dominated by disposable income. The income elasticity is close to one, i.e., every increase in income translates into higher consumption, partly by buying higher-motorised cars (SUVs).

In the long term, investments in other technologies can reduce energy consumption. In the case of heat, heat pumps but also renewable energy sources such as solar thermal energy, biomass, and geothermal energy are currently ways to save

[1] The classification for purposes of use is based on the lowest level of the classification in Destatis (2021b), sheet 3.3.3.

fossil fuels. Building insulation measures also significantly reduce energy consumption per square metre of living space, which is increasing with household income. However, it will take a very long time before a larger proportion of the more than 43 million dwellings in Germany can consume less or other forms of energy. The refurbishment rate is well below 1% and craftsmen for refurbishment are scarce. The potential for additional measures is currently limited. As far as fuels are concerned, electric vehicles are currently an alternative that is subsidised by the state with a premium of up to 9.000 € plus tax reductions. Here, too, the additional potential is limited in the short term. Delivery times for new appliances and electric vehicles are currently many months. Heat pumps and electric vehicles will increase electricity consumption in Germany in the future, so overall energy consumption is not expected to change that much. Since these technical options are predominantly available to higher income households, we deliberately do not consider them in the following analysis. An analysis of the associated longer-term effects is provided by, e.g., Lutz et al. (2021b).

Consumer prices for private households $TJPHH_e$ per fossil energy source e are modelled in PANTA RHEI as a function of the respective import prices of coal, oil, or gas IP_f:

$$TJPHH_e = f\left(IP_f\right)$$

Here, only the price component excluding taxes is estimated. For gas, the elasticity is 0.476, for coal products it is even lower between 0.237 and 0.241. Thus, the influence of import prices is well below 1, since long-term supply contracts with binding prices for end consumers buffer the price fluctuations on the international market. In the case of oil products, the import price has a stronger impact, with an elasticity of between 0.753 and 0.779: Both at petrol stations and in the supply of heating oil, changes in the oil price on the world market are passed on to end consumers.

For electricity, the price is first divided into its components, then only the price component for procurement and distribution is estimated, the other electricity price components are modelled separately of—if no change is foreseeable, as in the case of the electricity tax—left constant. As gas power plants currently dominate the price formation on the electricity market due to the merit order principle, the gas import price of both the current and the previous year is included as an explanatory variable in the regression. The reason for this is the merit order principle, according to which the most expensive power plants set the price, in this case the gas-fired power plants. Here it can be seen that the gas price of the previous year, with an elasticity of 0.691, has a greater influence on the electricity price than that of the current year, with an elasticity of 0.133. Subsequently, end-use price indices are estimated. These are set as a function of consumer prices, to which the energy tax and value-added tax (VAT) have previously been added. Here, the elasticities are close to 1.

Looking at the current development of the electricity price in Germany (Fig. 1), it can be seen that there is a strong change in the composition between 2021 and July 2022. Procurement and distribution costs have risen from just under 8 cents/

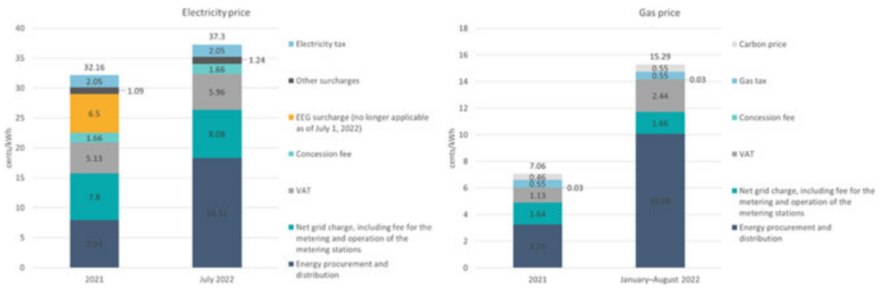

Fig. 1 Composition of prices for electricity and gas for German private households (reproduced from BDEW [2022a, 2022b])

kWh to over 18 cents/kWh. In contrast, the EEG[2] surcharge was initially halved at the end of 2021 and completely abolished on 1 July 2022. Since then, the renewable energy plants have been financed entirely through the federal budget, whereby due to the very high procurement prices, a high surplus has actually accumulated in 2022 (around €17 billion [50 Hz et al. 2022]) in autumn 2022, which is to be used to reduce grid costs in 2023. The gas price composition has also changed significantly in the period. Procurement costs have roughly tripled. As a result, the value-added tax that final consumers have to pay has also more than doubled. On 1 October 2022, the federal government temporarily reduced the VAT rate for gas from 19 to 7%. As the CO_2 price has risen to 30 €/t CO_2 as of 1 January 2022, the corresponding price component has also increased.

2.2 *Assumptions on Import Prices for Germany*

The assumptions for import prices are set against the background of current developments. Import prices for fossil fuels have already started to climb in the second half of 2021. As a consequence of Russia's invasion of Ukraine and Western sanctions, the import and domestic supply of natural gas in particular has become critical. According to the latest energy data for 2021 (AGEB 2022b), Germany produces only about 5% of its natural gas consumption domestically. Short-term production increases are not possible, even if an additional natural gas field in the North Sea close to the Dutch border is put into operation in the winter. There has been a high import dependency on Russia as one of the three supplier countries here (along with the Netherlands and Norway) (BMWK 2022). However, crude oil with 32% (2019) and hard coal with 45% (2020) import share of Russia have also become politically problematic energy sources given the current situation.

The monthly data for natural gas in Fig. 2 show that the import price has increased sharply during 2022, but it already rebounded to 2019 levels after the lockdowns due

[2] EEG = Renewable Energy Sources Act ("Erneuerbare-Energien-Gesetz").

to the pandemic in 2021: A first rise happened with the start of the Russian war in February 2022. Deliveries from Russia through the Nord Stream 1 and Jamal pipelines were sharply reduced in July and then suspended altogether, causing a further sharp rise in prices. It should also be borne in mind that Germany at the same time increased the requirements for the storage of natural gas to 85% by 1 September and around 95% by 1 November, which made additional imports necessary. In the meantime, natural gas is flowing into Germany from Norway, the Netherlands, and Belgium, with increasing flows of liquefied natural gas (LNG). From winter 2022/2023, Germany is planning four LNG ports in the North and Baltic Sea of its own, which will significantly increase import opportunities. In July 2022, the gas import price was 103.72 euros/MWh, a 387% price increase compared to July 2021 (BAFA 2022).

Looking at end-user prices also shows a sharp increase in 2022. The gas price analysis by components (BDEW 2022a) (see Fig. 1) reveals that the higher import prices are reflected in the procurement and distribution component which accounts for 66% of the total price in 2022 (considered up to August). In the previous year, procurement and distribution made up only 46% of the price. In absolute terms, the component has roughly tripled from 3.25 cents/kWh to 10.06 cents/kWh (for single-family houses).

The percentage gas price surcharges for German industry are much more severe. For large customers, distribution costs (network fees) and taxes have so far been significantly lower than for private households (Bundesnetzagentur and Bundeskartellamt 2022). This is because large customers also incur lower transmission costs. In terms of gas tax, very energy-intensive companies are largely exempt, and VAT does not apply to any company. The higher costs for companies mean that

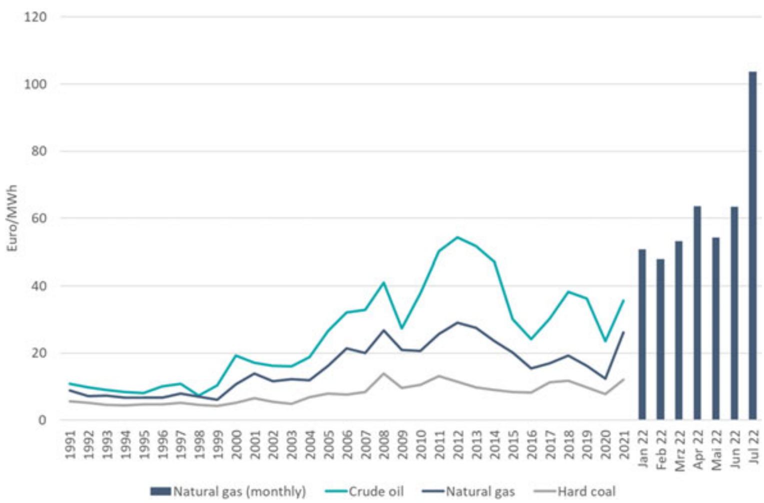

Fig. 2 Development of import prices for crude oil, gas, and hard coal since 1991 (reproduced from BMWK [2022] and BAFA [2022])

they have to pass on a large part of the cost increase to prices. Their substitution and energy efficiency opportunities are small in the short term, without investment in improved facilities. Studies have so far assumed short-term price elasticities of demand in the range of −0.1 to −0.4 (Köppl and Schratzenstaller 2021; Li et al. 2022; Lutz et al. 2021a; Prognos 2013; Zarnikau et al. 2021). Only low cross-price elasticities are also reported (Stern 2012). Reducing production is another possible reaction in this context. The cost increases then also lead to price increases at further production stages downstream. In the macroeconomic outcome, the German inflation rate has risen to 10% in September 2022 (Destatis 2022), the highest value in 70 years. However, this is also due to the sharp rise in food prices, internationally increased transport costs, and general problems in the international supply chains, which are not considered in this chapter. So, the energy price increase alone is likely to have a much smaller effect on inflation.

The reference scenario already includes an accelerated energy transition, based on the German government's "Easter Package" and aims for faster expansion of renewable electricity generation capacity although the targets for PV and offshore wind energy cannot be achieved due to bottlenecks in the construction sector (see also Zika et al. 2022). In addition, the consequences of Russia's war against Ukraine are partly considered, through increased import prices, especially for food, sanctions against Russia, as well as an increase in defence spending and in net immigration. Due to the current political situation and the pandemic, supply chains are interrupted, negatively affecting the economic activity in most sectors. Import prices for fossil energies develop as in the Announced Pledges Scenario from IEA (2021) which assumes an increase of between 32% (coal) and 60% (crude oil) by 2030 compared to 2020. In contrast, for the price shock scenario, the import price in 2022 is assumed to be four times as high for natural gas as in the reference scenario and twice as high for oil and coal. After 2022, it is assumed that prices will return linearly to the level of the reference case by 2030 (see Fig. 3). This assumption may seem too low in view of the extreme increase in European gas price futures in the summer and autumn of 2022. On the other hand, these are annual averages that also include significantly lower prices at the beginning of the year. Furthermore, price increases for other commodities are not taken into account.

3 Results

3.1 Effects on Consumer Prices

The rise in import prices for energy means that consumer prices also increase. As a result, the price for gas is almost 6 cents/kWh higher than in the reference in 2022, and heating oil rise by almost 35 cents/litre (see Fig. 4). In the following years, the difference is assumed to decrease again. Electricity is also becoming more expensive compared to the reference in 2022, although there is a time lag before

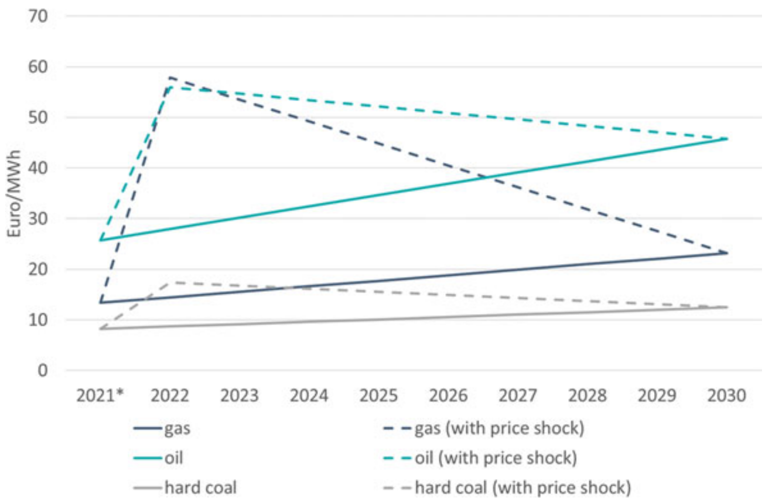

Fig. 3 Assumed development of import prices in the reference (solid lines) and price shock scenario (dotted lines). *The data for 2021 are calculated model figures and not historical ones, so the values differ from those in Fig. 2.

the cost increases reach final customers. In many cases, the suppliers have already bought the electricity months and years in advance. In 2022, the increase is still very small at 2 cents/kWh (comment: but then it is much lower than in reality). In 2023, the electricity price then rises by 20 cents from 37.3 cents/kWh in 2022 to 57.7 cents/kWh.

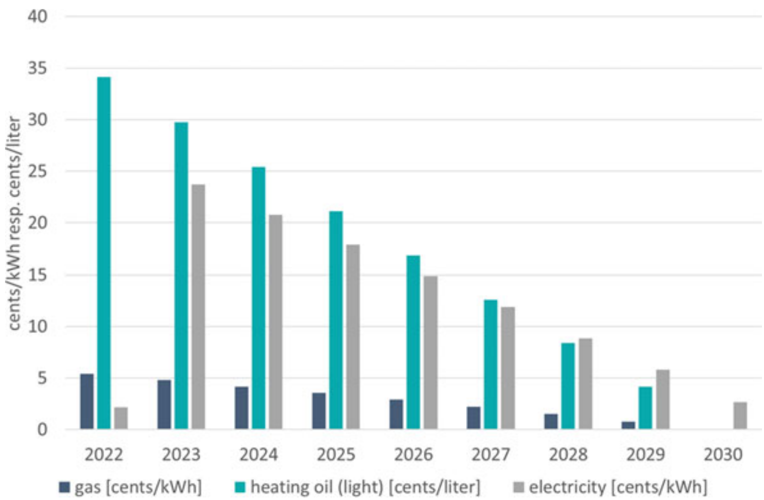

Fig. 4 Absolute deviations of private household energy prices for gas, fuel oil, and electricity in the price shock scenario compared to the reference

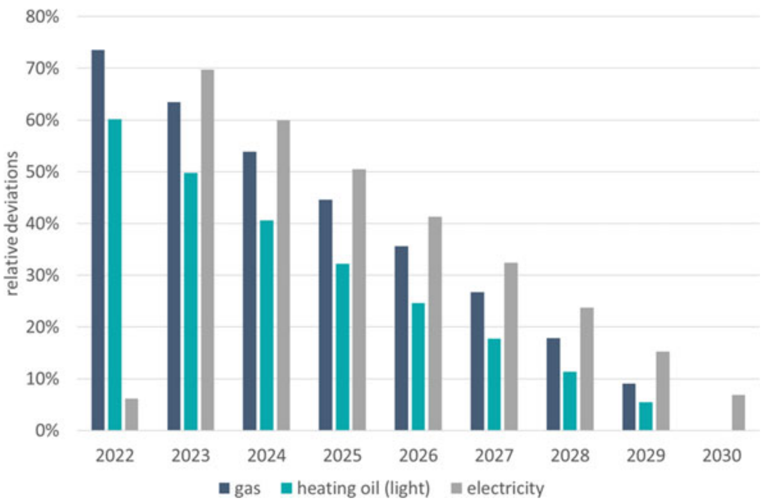

Fig. 5 Relative deviations of private household energy prices for gas, liquid fuels, and electricity in the price shock scenario compared to the reference

The following Fig. 5 shows that the percentage deviations are highest for gas at 70%, while heating oil will become more expensive by just under 45% compared to the reference development in 2022. For electricity, the increase in 2023 is particularly drastic at over 70%, after the effect in 2022 is relatively moderate at just over 6% due to the lagged impact mechanism. This is also the reason why the electricity price in 2030 is still higher in the price shock scenario, although import prices are again assumed to be the same in both scenarios.

This raises the question of how to proceed in an annual model with certain time lags in the cost pass-through during the year. Usually this is not a problem because the price changes are limited. In 2022 it is a different story, given the huge changes in procurement prices. We have assumed that the import price increases for gas will be passed on immediately, but that there will be a time lag for electricity and that the strong price increase will not occur until 2023.

3.2 Macroeconomic Effects

The strong energy price increases and the associated inflation negatively affect the gross domestic product (GDP) (see Fig. 6). As a result, the GDP in 2022 is more than 2% lower than in the reference, in which high growth was still expected at the end of the Corona pandemic. At −2.8%, private consumption is even hit worse than GDP. Exports also decline at an above-average rate due to higher prices. However, since energy imports have risen sharply in price, the overall economic import in constant

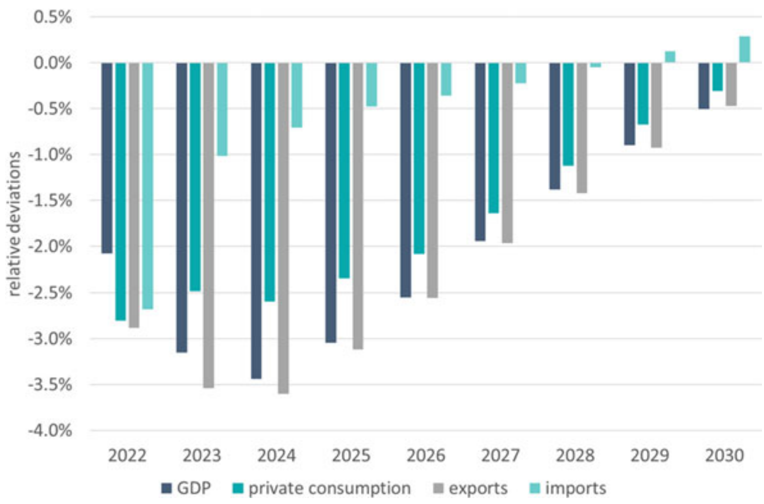

Fig. 6 Relative deviations of selected GDP components (in real terms) in the price shock scenario compared to the reference

prices reacts below average. With the assumed end of the higher prices at the end of the decade, the negative effects on the economy will also be significantly reduced.

On the German labour market (see Fig. 7), it should be noted that in previous crises such as the financial crisis or the pandemic, declines in production had only a below-average effect on employment. In 2022, a 2.5% reduction in production leads to employment losses of 0.3% against the reference, in which employment would have increased. This has to do with the delayed wage formation on the German labour market—hourly wages increase only slightly in nominal terms (0.6% in 2023), while production prices increase strongly (4.4% in 2023)—state support such as short-time working allowance and the shortage of skilled workers. Due to the strong price increase, there is a temporary significant decline in real wages in 2022, which is also partly maintained in 2023. Companies that cut back their production can continue to pay their employees through the short-time allowance. In addition, due to the shortage of labour and the low unemployment rate in Germany, they lay off as few workers and employees as possible. For private households, too, this means that wage payments only decline to a limited extent, which somewhat dampens the decline in the compensation of employees and final consumption.

Energy demand is largely inelastic according to Table 1. This means that despite a strong price increase in 2022 and 2023, the effects on energy demand remain limited. Private households respond to higher energy prices with lower energy consumption of 4.1% in 2022 and 4.9% in 2023 compared to the reference development. The deviation between the scenarios is 4.6% for heating oil consumption in 2022, while it is 8.4% for gas given the higher assumed price shock. Due to the lower energy consumption, CO_2 emissions are 4.9% lower than in the reference scenario. The

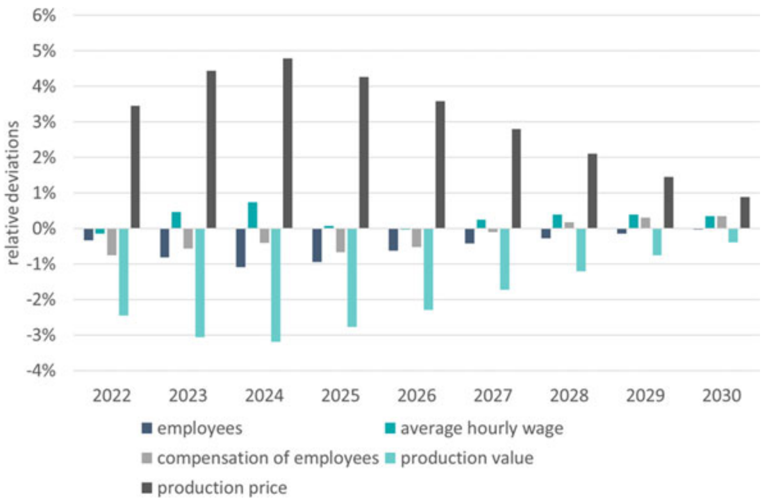

Fig. 7 Relative deviations of selected labour market variables in the price shock scenario compared to the reference

effect on emissions is stronger than the reference scenario since households also use less electricity and therefore less fossil energy is consumed in the transformation.

3.3 Distributional Effects

For the assessment of distributional effects, energy expenditures are considered by income class (see Table 2). Overall households, 4.2% of net household income was spent on energy in 2020. Across the income classes, there is a regressive development: The higher the income, the lower the share spent on energy. Thus, in the lowest income class (<1300 euros/month), 10.7% of net income is spent on energy, compared with only 2.8% in the highest (Destatis 2021a). The data source used employs a comparatively comprehensive concept of net household income,[3] so that the percentage expenditure on household energy and fuel is slightly lower than in sources referring to the socio-economic panel or the sample survey on income and consumption.

In the reference scenario, the shares for energy expenditure for the years 2022 and 2023 increase hardly or only slightly compared to the historical figure of 2020. For households with a monthly net income of less than 1300 euros, the share increases from 10.7% in 2020 to 10.9% in 2022. In the upper income classes, the share in 2023 is back at the level of 2020. Although energy prices also rise in the reference scenario, the concurrent increase in incomes evens this. In the price shock scenario, higher

[3] Net household income describes a household's disposable income minus earnings derived from the sale of goods and other earnings, which account for about 2% of disposable income.

Table 2 Share of private household consumption expenditure on energy by net income class (reproduced from Destatis [2021a] [2020] and own calculations [2022, 2023])

		2020 (%)	Reference scenario (%)		Price shock scenario (%)	
			2022 (%)	2023 (%)	2022 (%)	2023 (%)
Monthly net household income	Lower than 1300 euros	10.7	10.9	10.8	19.0	17.7
	1300 to 1700 euros	7.6	7.8	7.7	13.6	12.6
	1700 to 2600 euros	6.0	6.1	6.0	10.6	9.9
	2600 to 3600 euros	5.1	5.2	5.1	9.1	8.4
	3600 to 5000 euros	4.1	4.2	4.1	7.3	6.8
	5000 euros and higher	2.8	2.9	2.8	5.0	4.6
All households		4.2	4.3	4.3	7.5	7.0

prices lead to significantly higher shares of energy costs. Compared with 2020, the shares almost doubled in 2022. In the lowest income group, this results in almost one-fifth of net household income being spent on energy.

For transport fuels (see Table 3), expenditures in 2020 account for a similarly high share of net household income across income classes. The lowest share for fuels, at 1.6%, occurs in the group with incomes of less than 1300 euros per month, while the highest share of 2.2% is spent by households with monthly net incomes between 1700 and 2600 euros. In the reference scenario, the shares do not change in 2022 and 2023, i.e., the prices for transport fuels and incomes increase in a similar way. The higher prices for oil products in the price shock scenario lead to higher shares in fuel expenditures, but both the increase and the unequal distribution of the higher burden are less pronounced than for residential energy expenditures.

4 Discussion and Conclusions

The results show that the sharp price increases for natural gas, coal, and petroleum products due to the Russian war in Ukraine, the Western sanctions that have been adopted, and the supply stop for natural gas will lead to sharply rising prices and clearly negative macroeconomic effects, at least for Germany. German GDP is up to 3.4% lower in 2024 than in the reference development. The largest negative effects compared to the previous year occur in 2022 and 2023. In the labour market, the effects are only transferred to the number of employees to a limited extent because there is a decline in real wages and other processes also slow down the transfer. But of course, the reduced incomes of private households have a negative impact on GDP.

Table 3 Share of private household consumption expenditure on fuels by net income class (reproduced from Destatis [2021a] [2020] and own calculations [2022, 2023])

		2020 (%)	Reference scenario		Price shock scenario	
			2022 (%)	2023 (%)	2022 (%)	2023 (%)
Monthly net household income	Lower than 1300 euros	1.6	1.6	1.6	2.0	1.9
	1300 to 1700 euros	2.0	2.0	2.0	2.6	2.4
	1700 to 2600 euros	2.2	2.2	2.2	2.8	2.7
	2600 to 3600 euros	2.1	2.1	2.1	2.7	2.5
	3600 to 5000 euros	2.0	2.0	2.0	2.6	2.4
	5000 euros and higher	1.7	1.7	1.7	2.1	2.0
All households		1.9	1.9	1.9	2.4	2.3

The price shock affects private households differently according to their consumption structure. Especially in the case of heating energy, the share of disposable income that has to be spent on energy increases drastically for lower income groups, almost doubling, reaching 19% in 2022 in the lowest income group. In contrast, high-income earners are relatively much less affected. In the highest income group, the share "only" rises from 2.8% to 5%. The distribution effects are much less pronounced for fuels. Middle-income earners spend the largest percentage of their income on fuel, but the differences are limited. Low-income earners, in particular, can usually not afford car ownership, so they often do not need fuel. Moreover, the tax share for fuels is significantly higher than for gas, heating oil, and electricity, so that the relative burden remains limited. For some income groups, fuel expenses increase by 0.6 percentage points. In a study by Bach et al. (2018), a regressive distribution of the higher burden across income classes is, however, also found for the increase in fuel prices.

When interpreting the results, it must be taken into account that these are average values. There are enormous differences in heating requirements depending on the age and renovation status of a building. The difference between a subsidised new building, which achieves 40 kWh/sqm and year, and a poorly insulated old building from the 1960s can quickly be a factor of 5–10. Conversely, zero-energy and plus-energy houses are already being built that are not affected by the energy price crisis. For the income groups particularly affected, however, this means that individual households will probably have to pay twice or even three times as much for energy as the average household. It quickly becomes clear that this can no longer be managed by low- and even middle-income households without drastic cuts in heating, food, and other expenditures. The federal government has already acted and put together the first relief packages. However, so far, they are not targeted enough. The significant reduction of the energy tax for gasoline and diesel for three months in the summer of 2022 was also not targeted in terms of protecting the particularly vulnerable household groups. The same is true for the reduction of the VAT on gas starting from October. It helps every household according to its gas consumption, but the reduction from 19 to 7% will be far from enough.

The federal government must provide much greater relief for the lower income groups that rely primarily on gas, electricity, and mineral oil for heating and appliances. A per capita bonus is seen by many economists as better than general gas and electricity price caps, which the government currently favours. Firstly, the savings incentive of high prices must be maintained because gas and electricity are indeed scarce. And secondly, because consumers with low consumption—that is predominantly those on low incomes—are relieved relatively more than consumers with high consumption. Even more effective would be a relief based on individual last year's income and consumption, but such a measure is currently not administratively feasible in Germany.

The negative macroeconomic effects of high energy import prices are in significant contrast to other scenarios in which the prices of fossil fuels are raised by high CO_2 prices. In this case, the overall economic effects depend crucially on the recycling of the revenues. If the national CO_2 price in Germany is raised to 180 €/t CO_2 by 2030 and further measures such as an increased expansion of renewable energies and more building renovation are financed by the income, there will even be positive GDP effects in the order of 1.4 to 1.7% in 2030 (Lutz et al. 2021b). The main reason is that the money is spent domestically, and also induces indirect effects and additional expenditure there. In such a scenario, the distributional effects could be improved by per capita bonuses for private households. Then private households could significantly reduce their energy expenditures by 2030 not only compared to the reference, but also compared to the expenditure shares in 2015. The analysis of an environmental tax reform from 2011 came to similar conclusions (Blobel et al. 2011).

The government must also organise the decarbonization of the homes of low-income households so that they no longer depend on fossil fuel imports and their possible price fluctuations in the long term. Implementation is of course not easy. Indeed, low-income households usually have neither their own apartments nor the financial means for energy efficiency measures or the use of new technologies such as heat pumps or solar thermal energy for heating. Their landlords/landladies, in turn, will not want to take these measures if they cannot recover the costs from higher rents. State funding programs and regulatory laws will have to contribute to this change.

The comparison of the results with the calculations in Lutz et al. (2021b) makes it clear that ambitious climate mitigation, which comes with a significant reduction in the use of coal, oil, and gas, would significantly increase the resilience of the German economy to changing world market prices for fossil fuels. This could also reduce the associated regressive distribution effects. Climate policy is thus increasingly becoming a central part of environmental and social policy.

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Demographic Shifts, Household Energy Needs and Vulnerability

Rossella Bardazzi and Maria Grazia Pazienza

1 Introduction

Structural changes in the population are bound to be intertwined with the energy transition in determining the evolution of household energy consumption. Most countries are characterized by shrinking total population, very fast ageing and smaller family size. These demographic shifts could enlarge the group of vulnerable individuals who are suffering from energy poverty. When studying the drivers of future energy demand, population dynamics represent a crucial factor (IEA 2017). Moreover, scholarly research has argued that energy consumption behaviour along the life cycle is shaped by cultural factors, considered as a set of social norms, energy practices and material culture and therefore different generations age with specific attitudes towards energy use (Stephenson et al. 2010; Stephenson 2018). Recent empirical studies have shown that age and generation effects on energy consumption are significant (Chancel 2014; Bardazzi and Pazienza 2017) and affect the future paths of energy consumption (Bardazzi and Pazienza 2020), although they are usually overlooked in the estimated long-run projections of energy use.

Population ageing and associated demographic changes mean, as a logical consequence, that the group of elderly people will become more and more influential in determining the future energy consumption. Most of the related literature agrees on the fact that an older population spends more time at home and is more concerned about health issues and comfort. Moreover, the increasing number of households and the decrease in family size contribute to this trend because of a higher number of

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appliances and a loss in the economies of scale. How are these trends going to affect the risk of falling into energy poverty?

In this chapter, we summarize how demographic changes are interlinked with energy transition with an analysis of the main issues related to changes in the composition and the age structure of the population and their expected effects on the future paths of energy consumption. Then we focus on the vulnerability to energy poverty of the elderly and on its main drivers concerning several dimensions related to the affordability of energy expenditures—affected by the disposable income and the price level—and the energy efficiency of buildings and residential equipment—influenced by the propensity to invest in energy efficiency improvements—. Last but not least, we investigate to what extent the condition of limited access to adequate energy services hampers the social activities of the ageing population as an additional facet of this multidimensional phenomenon. Finally, we present the estimates of residential energy demand elasticities for the Italian case to confirm low responsiveness of the electricity and natural gas consumption to the changes in income and prices as a further factor of energy vulnerability for the elderly population. Our conclusion is that, notwithstanding some specific conditions that have partially sheltered the seniors from the risk of energy poverty, the ongoing demographic shifts associated with the ageing of the 'baby boomers'—less protected by the welfare system and more used to energy-intensive practices—will increase the energy vulnerability of the future old generations that should be targeted by specific public policies.

2 Population Trends: Some Features of Ageing

Demographic ageing within the European Union (EU) is likely to be of major significance in the coming decades. The population of the EU on 1 January 2021 was estimated at 447.2 million, older people (aged 65 or over) had a 20.8% share with an increase of 3 percentage points compared with 10 years earlier. Europeans are living longer and in better health: life expectancy has steadily increased, on average, by more than two years per decade since the 1960s. In the same period, the birth rates in the EU member states decreased although at a slower pace in the last two decades than previously. All these trends are transforming the age structure of the population with a demographic shift towards a much older population. This change is reflected in the age pyramids comparing the data of January 2021 with 2006 (Fig. 1). The base of the pyramid appears narrower, while the age classes above 50 years are larger due to the ageing of the 'baby boomer' cohorts. In 2021 more than 20% of the EU population was aged 65 and over, and this share is projected by Eurostat to reach more than 30% up to 2050 and stabilize to 2100, within a trend of shrinking population size.[1] Indeed, Europe's population has grown consistently since 1960, but in the last decade the number of deaths has exceeded the number of births; therefore, without

[1] These figures are based on the Eurostat population projections database EUROPOP2019.

positive net migration, the population has already started to shrink. Eurostat projections state that the population will stabilize and reach a plateau before 2025 and then start to decline progressively after 2030, with an estimated decrease of around 7% by 2100.

This situation is heterogeneous across countries (Fig. 2), with Italy showing the highest share of elderly and therefore the highest median age (47.6 years compared with 44 years at the EU level). Population ageing is a global phenomenon, with the progress at different stages in various countries. For instance, the share of people aged 65 is particularly high in Japan (around 30%) while North America, Australia and South Korea have values slightly below the EU average (UN-DESA 2022).

Another important major trend concerns the number and the size of households. According to the data from the Survey on Income and Living Conditions (EU-SILC), the average household in the EU consists of 2.3 people in 2021, steadily decreasing from 2.4 in 2010. As the average size goes down, the number of European households goes up: in 2021 there were 196,690 families with a 6% increase compared with ten years before. About 39% of all households consist of a single person: as population is ageing, a growing number of elderly is living alone. Member states such as the Scandinavian and the Baltic countries present shares of one-person households above 50%, while the Mediterranean and the Eastern countries rank below the average notwithstanding a significant population ageing. Differences in living arrangements of the elderly across countries could be due to the persistence of traditional family structures and cultural norms albeit in a context of demographic, social and economic change (UN-DESA 2020). However, in Western Europe and in the USA, multi-generational households have declined dramatically and most elderly live either alone or in a couple. As regards location in urban or rural areas, older people in the EU 27 are generally more inclined than the young to live in predominantly rural and

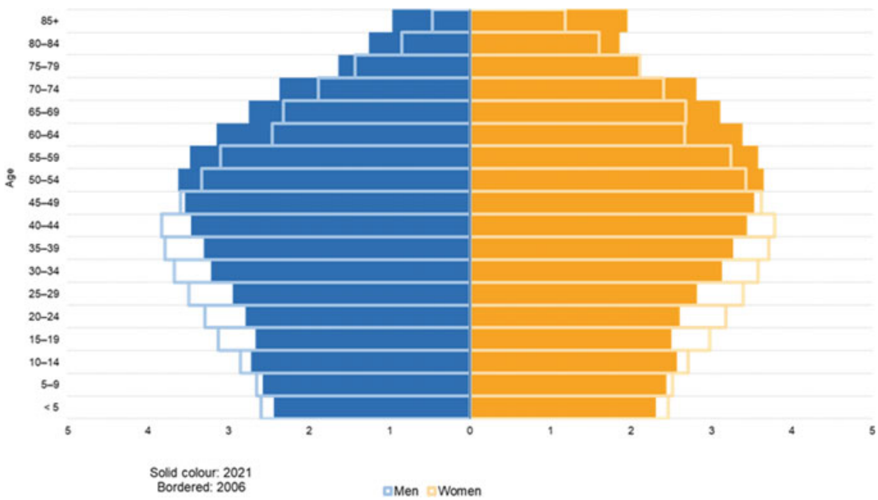

Fig. 1 Population pyramids, EU 2006 and 2021 (% of the total population). *Source* EUROSTAT

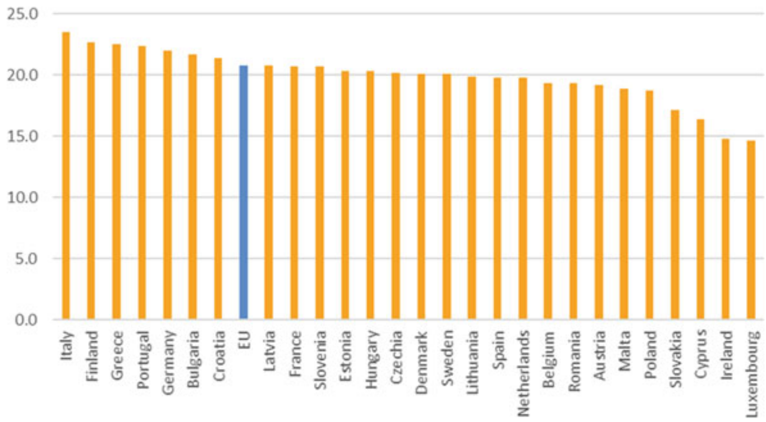

Fig. 2 Share of the population aged 65 years or over (%) (2021). *Source* EUROSTAT

intermediate regions (Eurostat 2020). Looking at the housing conditions, in the EU people aged 65 and over are more likely to live in under-occupied dwellings. While EU total households in 2021 have an average of 1.6 rooms per person (EU-SILC data), older people have an average of 2 rooms per person if living in couple and 3.3 rooms per person if living alone and they are more likely to be homeowners. Spain, Ireland, Belgium and the Netherlands show values above the average, while Central-Eastern countries are below.

These demographic shifts—namely a decrease in the population size, an increase in ageing and a reduction in household size with a change in the structure of the European population—are deemed to affect many dimensions of the economic system, including the use of energy and the green transition. For instance, the living arrangements of older people shape their demand for housing and for services and resources, including energy. When the number of households increases, there will be more appliances and lower efficiency of use per person because of lower economies of scale. In general, understanding these trends is relevant to meet the Sustainable Development Goals related to ending poverty (SDG 1), ensuring health and well-being (SDG 3) and ensuring access to affordable modern energy (SDG 7).

3 Long-Run Energy Forecasts and Population Dynamics

The design of models on long-term energy market developments is a daunting task. In addition to geopolitical instability and the economic growth of new areas of the world, technical factors such as climate change and technological innovation already pose extremely difficult challenges. The rapid evolution of demography in Europe discussed in the previous section—concerning a decrease in the total population and a change in age and family composition—adds a fundamental challenge because modifications in population composition imply changes in aggregate behaviour. Indeed, recent surveys on the limits and prospects of development of energy models (Fodstad et al. 2022, Scheller et al. 2021) identify consumer behaviour as one of the least studied areas. As stated by Fodstad et al. (2022) "it can be expected that more complex theories about this behaviour—such as social practices and collective rather than individual decision making—will be attempted to be integrated into energy modelling".[2] Research in psychology and sociology should contribute to better understand how energy practices interact with technological infrastructures and socioeconomic factors in shaping consumption behaviour, giving rise to a broader approach to overcome the usual dichotomies between technical, human and social perspectives in the study of energy trends and transitions. For all these reasons, the approaches to forecast energy demand on the basis of historical trends adopted in macro or micro-funded models with identical optimizing agents often turn out to be totally inadequate. Moreover, the impact of interactions between energy consumption choices and demographic changes is still underestimated.

By and large, total population growth has been associated with the idea of diminishing per capita resources and with an increase in total energy use and pollution (Club of Rome project and Meadows et al. 1972). In this framework an example is the IPAT class of models, which originated from an accounting formula proposed in the early 1970s, whose simplest version stresses the direct link between total population (P), energy use and the environment (I, impact), with the mediating role of 'affluence' (consumption levels and habits) and technology (T), so that I = P*A*T.[3] However, since the emergence of diverging trends in population dynamics among different areas of the world, researchers in Europe and East Asia have started to focus on population structural changes and their effect on energy forecasts. Assessing the effect of demographics on energy consumption is, nevertheless, far from being an easy task. Age is a multidimensional phenomenon, not only because of its correlation with other socio-demographic variables or life-cycle stages[4]—such as family size, income and residential preferences—but also because of its connection with a social dimension (Shove and Walker 2014). The first example of the new attention to the link between age and energy use comes from Liddle and Lung (2010).[5] By using aggregate data on 17 developed countries over the period 1960–2005, they find that the age effect is nonlinear, with the shares of the youngest and over 65 groups having a positive impact on environmental indicators while a high share of middle-aged group in the population shows a negative influence. More recently the nonlinear link between age and electricity use has been confirmed, among other results, by Estiri

[2] Fodstad et al. (2022), p. 13.

[3] This sort of Malthusian idea was originally sketched in the book 'Population Bomb' written by P. Ehlrich in the late sixties. More specifically, according to Holdren (1991) an elastic relationship between population and energy consumption exists, implying a sort of diseconomy of scales at collective level when population is projected to increase.

[4] The study of the link of life cycle and energy consumption was pioneered by Fritzsche (1981).

[5] Liddle (2004) reviews evidence from cross-country macro-level studies and assesses that only when the level of disaggregation of an age group approximates the life-cycle behaviour are the results significant, although they are complex and nonlinear.

and Zagheni (2019) for the USA, Bardazzi and Pazienza (2017) for Italy and Belaïd et al. (2022) for France. They find an inverted U-shaped curve, peaking when the household head is about 50 years old and the family has reached its largest size and about its maximum income level. However, when considering heating needs the inverted U shape generally vanishes and a constant rise as householder age increases can be observed. These data confirm higher thermal comfort needs and more time spent at home by the elderly and specific electricity needs.

When considering the nonlinear age effect and change in population structures, long-run energy forecasts result more complex, because nonlinear age effects are interlinked with other socioeconomic variables. Indeed, the literature has identified several positive and negative drivers associated with the observed current changes in population structures. Among the main positive drivers—factors increasing energy use—are lower economies of scale due to smaller household sizes,[6] more time spent at home (and the need for heating and cooling comfort) and weaker attitudes to energy-saving investments and environmental protection.[7] Among the negative drivers are the supposed lower incomes of the elderly—a factor mitigating both energy demand and energy-saving investments—partially counterbalanced by a positive wealth effect. Factors linked to social norms and to energy culture (Stephenson 2018)—often captured by generational effects—can act in both ways, depending on the specific institutional and cultural context.

The combination of an ageing population, nonlinear age effect and the other drivers has generally been evaluated as leading to higher energy use. Zagheni (2011) considers several demographic characteristics (age structure, fertility and birth rates) to estimate the age-specific consumption profiles for key CO_2-intensive goods. By combining these results with US population forecasts, he finds a small decrease in total CO_2 production in the USA in 2050 for a bundle of main consumption goods and an increase in consumption and CO_2 levels of energy products.[8] Similarly, Brounen et al. (2012) analyse the influence of dwelling characteristics and demographics on residential energy consumption in the Netherlands and combine their results with projections of future demographic trends up to 2030. As a result, the ageing of Dutch society and its increasing wealth combined with the nonlinear age effects produce forecasts of growing energy consumption. An interesting case study is Japan, where the shift in population composition has been evident since the eighties. As an example, Schröder et al. (2015) estimate that a 5% decline in average household size during the period 2005–10 in Japan resulted in a 3.5% increase in the household-sector energy demand. Using data at the prefecture level for the period 1990–2010, Ota et al. (2018) estimate that a 1% rise in the share of the elderly would result in a 0.8–1.1% reduction

[6] On the long-term evolution of household size, see Bradbury et al. (2014) and Schröder et al. (2015).

[7] The economics literature usually assumes that elderly people are generally less concerned about climate change and are less likely to support climate-friendly policies. However, this kind of correlation is disputed in a part of the literature. Among others, Mingo et al. (2018) find that ageing and the level of education are significant and positive predictors of curtailment behaviours in Italy.

[8] This result is based on a hypothesis of static technology with a fixed CO_2 content of electricity and natural gas.

in electricity consumption, while the impact on gas consumption is non-significant.[9] However, a balancing effect is expected due to the higher number of nuclear families, which will increase total electricity demand. They conclude that both effects must be considered to envisage the overall future pattern of energy demand. More recently, on the effect of shrinking household size, Wu et al. (2021) analyse the Chinese case, finding an elasticity of one household member to per capita electricity consumption around 20%, similar to the average value estimated in previous studies.[10] The use of pseudo-panels or pseudo-cohorts in this line of research has opened new perspectives, allowing the disentanglement of age and generational effects.[11] When looking inside overlapping generations, many studies—firstly marketing studies—have revealed that elderly people may have different consumption behaviour, depending on their cohort of birth.

As an example, Pampel and Hunter (2012) use cohort analysis to study changes in environmental concern over several decades, finding that the link between socioeconomic variables and environmental attitude is nonlinear across cohorts. People belonging to different generations, characterized by orientations being shaped by common experiences (within the group) but different between generations, are carriers of changing perspectives on environmental protection and energy use.

In the economic literature it is possible to find several analyses of population composition shift that include cohort effects. Chancel (2014) estimates a clear cohort effect for energy use and CO2 emissions in France, where the 1930–1955 cohort has been found consuming more than other cohorts. The author explains this finding with the interplay of an income factor (that particular generation experienced better life chances and therefore higher income), a technological factor and a behavioural factor (higher environmental concern of the younger generations and resistance of the baby boom generation to modifying its consumption patterns). Using US household data on total residential energy usage and a methodology based on pseudo-cohorts, Estiri and Zagheni (2019) confirm the existence of an increasing age-energy consumption profile but with a decrease–increase pattern for people younger than 39, with a peak around the age of 55. The positive rate of growth then slows down between 60 and 80 and accelerates again for the oldest cohort. They also find that in the warmer climate, the increase in energy demand at older ages intensifies, signalling the climate change may amplify the trend for an increasing demand. Inoue et al. (2022) estimate a positive impact on energy consumption from the pure ageing effect and from the downsizing of the average household in Japan. However, the cohort effect estimation shows that Japanese younger generations consume less energy than older ones because they live in smaller houses and practice more energy-efficient approaches. This cohort effect may partially offset the increasing factor caused by

[9] Looking at the elasticity of energy to population changes, York (2007) projects a decrease in energy use as population structure changes also because the effect of ageing cannot completely counterbalance the projected total population shrink.

[10] See the comparison in Wu et al (2021)'s Table 8.

[11] Moreover, as we discuss in Sect. 4, the use of pseudo-panels allows a better understanding of price and income effects, since microdata on consumer consumption choices are not collected as panel.

pure age and household size components. A different consumption pattern has been observed for the Italian younger generations. Bardazzi and Pazienza (2020) find that the war and pre-war generations' energy consumption in Italy is lower than that of the post-war generations, implying that overall consumption can increase as society ages, even with decreasing population. Moreover, when disentangling the age and the cohort effect using the pseudo-panel dataset, they find a linear pure age effect also for electricity (consumption steadily increases with age) so that the nonlinear age effect vanishes, coming from two diverging cohort and age effects. The estimated increasing age effects and decreasing cohort effects (meaning that newer generations tend to adapt their demand more to thermal comfort standards and to new electrical appliances) overtake the population decrease the effect and therefore electricity demand is projected to increase by 2050. Due to the projected decline in the Italian population size, energy demand would decrease by 7% if no age and cohort effects were taken into account, whereas the projection with the estimated age and cohort effects results in a remarkable increase in the overall electricity demand by 2050.

4 Energy-Related Vulnerability of the Elderly

The importance of energy and environmental sustainability in ageing societies has attracted researchers' attention, although less than the topic would have deserved.

Indeed, in several countries, especially in the northern and colder areas, energy poverty has been placed within the context of overall poverty, so discharging the multidimensionality of this phenomenon and the complexity of its drivers.

Older persons have peculiar characteristics that affect all the drivers of energy consumption and therefore of energy poverty so putting them more frequently in a vulnerability area. Age does not in itself make individuals more vulnerable to climate risks—excluding extreme climate variation—, but nevertheless it is accompanied by a number of physical, political, economic and social factors that may do so, although the elderly cannot be considered a homogenous group.[12]

Following Bouzarovski and Petrova (2015), energy vulnerability originated from a set of six factors: besides the traditional triad of energy efficiency, prices and income affordability, there are other three important factors such as specific household needs, practices and the actual ability to invest for increasing efficiency. These three additional elements are in turn interrelated with the household socio-demographic characteristics (as for instance the size of the family and the presence of younger generations), health conditions, energy literacy and energy culture and household location (urban/rural location and climate among the most important). Last but not least, the wealth of the household—including, of course, home ownership—is of paramount importance for the investment incentive and the ability to invest.

[12] See UN-DESA (2020).

The empirical literature generally supports the view that elderly households are more energy-intensive than other households on a per capita basis, making them more vulnerable. This is due, as previously discussed, to smaller household size (Cho et al. 2022), larger houses (more rooms per capita), more time spent at home and health-related problems. Other factors, among all energy cultures and accumulated wealth, may partially compensate and act as mitigating forces. As for the effects, the general binding constraint for other expenditures—such as an eat or heat dilemma—and health consequences of an inside temperature below the optimal values are among the most commonly studied.[13] Moreover, it is important to stress the negative consequences on social relations and friendship networks (Abeliansky et al. 2021), which are frequently associated with the energy poverty condition.

In the following, we review some data to assess whether and to what extent the elderly are more exposed to energy poverty in Italy. We will see that the composite effect of ageing population, welfare state structure and energy practices makes the elderly less disadvantaged than expected. Our investigation is constrained by data availability because data sources are far from being adequate as the original surveys have been designed for other purposes. Moreover, older persons (especially those 80 years of age and over) are often neglected in research and data collection, although they have peculiar consumption behaviour, needs and vulnerabilities. Indeed most statistical data, including those from Eurostat, do not distinguish between people over the age of 65, although in several countries the official retirement age is above that threshold.

4.1 Energy Poverty in Older People and Its Drivers

To assess the extent of the energy poverty diffusion among the elderly—specifically households with older householder—we analyse the three main consensual energy poverty indicators,[14] comparing Italy with the average EU situation. As for the EU situation (top panel of Fig. 3), we observe that on the average population aged 65 years and over is less likely to experience arrears in payments for a mortgage or rent and utility bills. In 2020, households in arrears were 9.1% of the total population EU 27, while the share was 4.4% for single individuals aged 65 and over and 3.9% for elderly couples (at least one aged 65 or more). On the other hand, these households experience higher difficulties in keeping their home adequately warm. This indicator is a widespread measure of energy poverty and it is explained by the energy inefficiency of buildings, relatively high energy costs and low income. At the EU level, 6.9% of households were unable to keep their homes adequately warm, rising to 9.4% for single adult aged 65 years and over, while elderly couples seem

[13] Charlier and Legendre (2022).

[14] The huge debate on the efficacy of energy poverty indicators is outside the scope of this chapter. In this case we use the consensual approach indicators because they are easier to compare and more frequently updated.

to cope better (6%). However, there is a lower share of older people compared with the whole population living in dwellings with a leaking roof, damp walls or rot in window frames or floors.

The Italian situation—shown in the bottom panel—presents a very high share of population claiming to live in deteriorated dwellings (with a leaking roof, damp walls or rot in window frames or floor), without significant variation by age groups. As for the possibility to experience arrears in housing-related payments, Italy shows a lower share than the EU and the same profile for the age group distribution. Finally, 8.1% of Italian families claim difficulties in keeping the house adequately warm, 1.2 percentage points above the EU average. However, within the same general age group profile, the solo households aged 65 and over exhibit a situation only slightly above the population average (8.9 compared to 8.1) and closer to the average when compared to the EU (9.4 and 6.9, respectively).

Turning our attention to the drivers of energy vulnerability mentioned above, in the following we present some evidence on how the elderly are characterized in relation

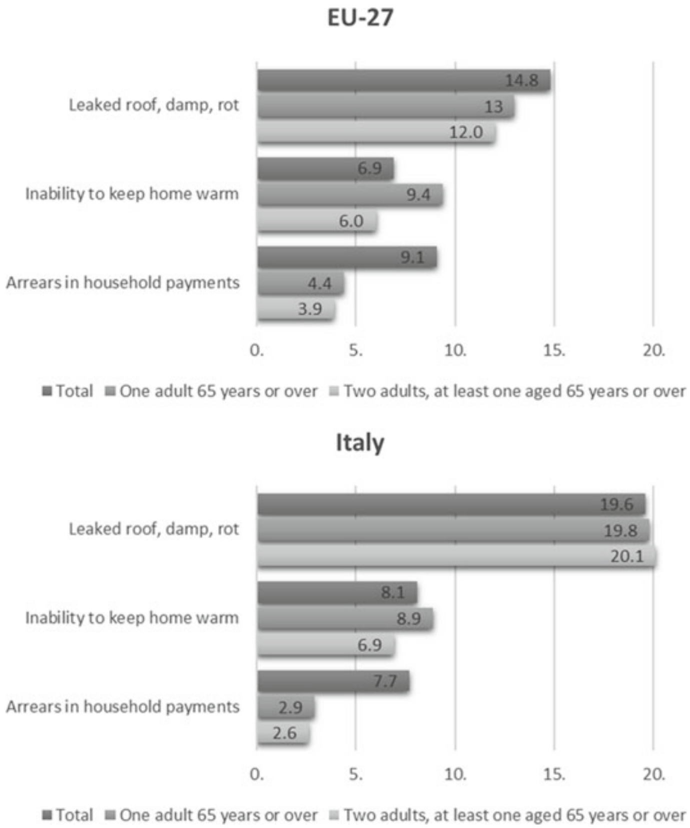

Fig. 3 Energy poverty indicators, EU 27 and Italy (year 2020). *Source* Authors' on EU-SILC data

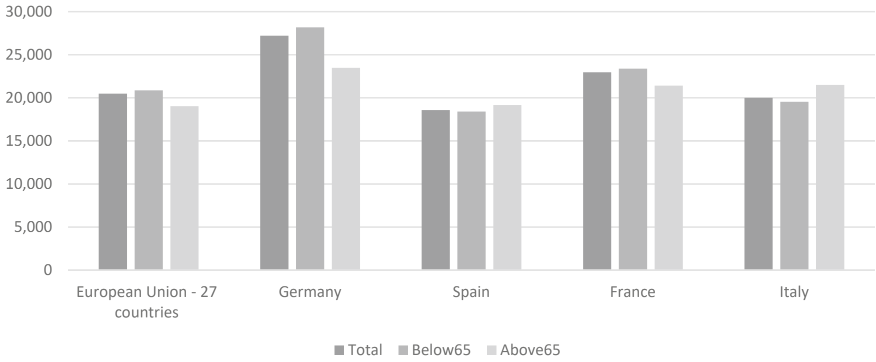

Fig. 4 Average income by age in selected countries (Euros) (2021). *Source* Authors' on EU-SILC data

to several factors that affect the affordability of energy expenditure, the efficiency of their home and its improvement and other social practices deemed useful to identify energy poor households.

(a) **Energy affordability: the income level**

Although one would presume greater income vulnerability of the elderly, given their exit from the labour market, the characteristics of current pension systems—significantly skewed towards protecting the older generations—in the aftermath of the financial crisis have completely reversed the expectation in some countries. Figure 4 shows the average income by age group at the EU level and in selected member states: in Germany and France the average income for people below 65 years is higher than that of the other group. The reverse can be observed for Spain and Italy.

To look beyond the average figures, Fig. 5 shows the percentage of the population at risk of poverty by age in EU countries: in the EU average, the two shares are almost equal, but in most countries there is a significant difference between the two age groups. In particular, in many Eastern and new member countries (such as Malta, Cyprus and Croatia), a higher share of income vulnerability is noted for the elderly, while in Western and Mediterranean countries the situation is reversed. Italy, together with France, Spain, Greece and Sweden, shows a notable difference that favours the older population. Germany, on the contrary, shows a higher income vulnerability in the elderly.

Even more striking is the evolution of average equivalent income by age of the householder, illustrated with index numbers in Fig. 6 for four member countries. For three countries out of four—Italy, France and Spain—the increase in income for people aged 65 and over is always higher than that for the younger population. What is more, in Italy we observe an absolute decrease in disposable income for the younger generation whose level in 2021 is still below that of 2005.

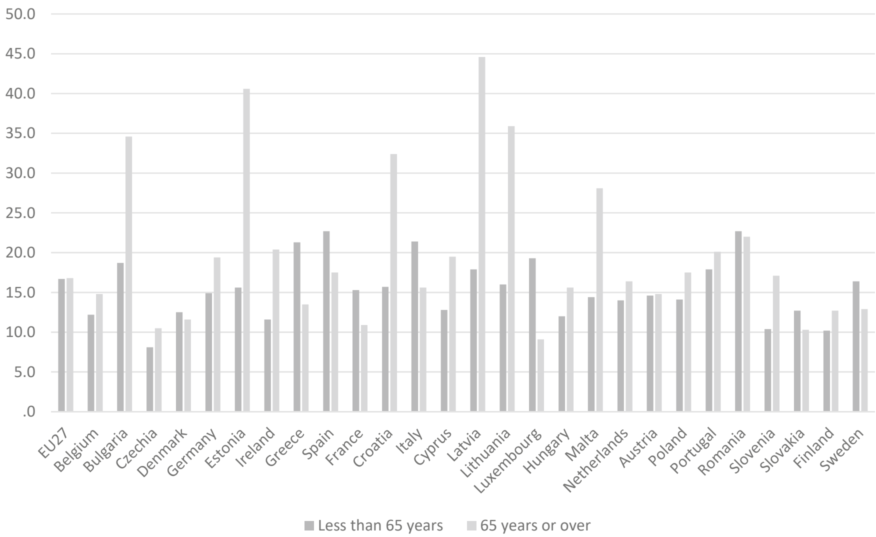

Fig. 5 At risk of poverty rate by age group (Cut-off point: 60% of median equivalised income after social transfers). *Source* Authors' on EU-SILC data

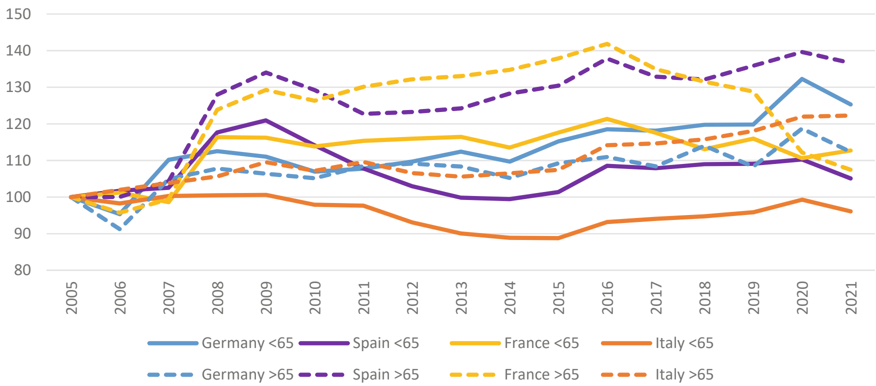

Fig. 6 Mean equivalised net income by age group in selected countries (2005 = 100).[15] *Source* Authors' on EU-SILC data

(b) **Energy affordability: prices**

The general increase in energy prices is putting pressure on all households and probably can cause the shift to an energy poverty condition of many families in Europe. However, behind this general increase in prices there is a vulnerability factor for consumers that are becoming familiar with the increasing competition

[15] The mean equivalised net income in purchasing power standard is deflated using the Harmonized Index of Consumer Prices at the country level (base year 2015).

Table 1 Energy efficiency in Building Stock (2013)

	Share of dwelling built after 2010 (%)	Energy consumption in residential per m^2 (kWh/m^2)	Energy consumption for space heating in residential per m^2 (kWh/m^2)
EU	2.8	182.9	123.9
Italy	1.8	172.7	128.7

Source EU Building Database

among energy services suppliers. In some member states, and particularly in Italy,[16] some consumers may be in the position of paying too high prices, even in non-extraordinary phases of international energy prices, such as the current one. This can happen because they have signed up for overpriced contracts with competitive energy supply companies pressed by door-to-door or telephone aggressive marketing practices. This vulnerability is particularly important to be tackled among older adults and foreigners with limited language skills. Contracts involving new price schemes and new services (such as the leasing of solar panels or a Renewable Energy Community plan) with potentially volatile charging arrangements could, in principle, be very hard to be fully understood and should generate the same need for protection, as the one usually considered for financial products with variable outcomes.

(c) **Energy Efficiency: the propensity to invest**

Social concerns for the threats of climate change and the need to save energy have only recently spread in Italy, also in conjunction with an acceleration of public policies for investment in energy efficiency improvements. As an energy-dependent country, Italy exhibits low energy intensity, but the energy efficiency of the dwelling stock has been considered the weakest segment. Table 1 shows that the share of buildings built in recent years—presumably following higher energy efficiency standards—is very low in the European Union (2.8%) and even smaller in Italy (1.8%).

Moreover, notwithstanding a lower average residential energy consumption per square metre, Italy is characterized by higher energy consumption for space heating. This in spite of the milder climate, which means that there is ample room for further energy efficiency improvement.

Although the literature generally expects lower environmental concern and lower investment in energy efficiency for the elderly,[17] due to the shorter time horizon for the payback of the investment, Italian data present a different picture. In particular, Mingo et al. (2018) find that the subjective environmental concern is positively correlated with older age in Italy. We can also add that Italian older people exhibit a

[16] The competitive energy market in Europe has been designed by a complex set of directives and regulations, but the protection of vulnerable consumers is left to member states within a certain framework. In Italy the transition to a full competitive market is still problematic and the fully regulated contract regime (Mercato tutelato), which was originally scheduled to end in 2020, has been extended several times.

[17] See Abreu et al. (2020) for the Portuguese case.

Table 2 Tax incentives for energy efficiency by income and age classes (2020)

	Income classes				
	<20.000	20.000–40.000	40.000–75.000	>75.000	Total
Absolute number of investors					
0–24	1,411	481	69	36	1,997
25–44	116,605	271,200	81,553	25,761	495,119
45–64	257,614	690,792	324,262	169,664	1,442,332
65–80	188,038	524,414	202,210	100,155	1,014,817
> 80	96,403	146,429	50,212	20,551	313,595
Total	660,071	1,633,316	658,306	316,167	3,267,860
As a share of taxpayers					
0–24	0.1%	0.5%	2.5%	3.8%	0.1%
25–44	1.7%	8.4%	18.3%	24.0%	4.6%
45–64	3.5%	12.4%	22.9%	31.3%	9.8%
65–80	4.0%	15.4%	27.7%	35.1%	11.2%
>80	2.9%	12.1%	23.1%	33.1%	6.5%
Total	2.8%	12.1%	23.4%	31.7%	7.9%

Source Italian Tax Authority

non-negligible elasticity to financial incentives. Since the 2008 crisis, Italian public funds[18] committed to increasing the efficiency of buildings have skyrocketed, mainly by using tax-related incentives. According to the data of the Italian Tax Authority, this generous incentive framework has prompted a 52% increase in the number of investors between 2016 and 2022 (from 2.1 million to 3.3 million). In this group, the number of investors over 65, for example, grew by 65% and that of the over 80 by 90%, reaching more than 300thousands, 10% of the total investors in energy efficiency. Table 2 presents the total number of taxpayers benefitting from energy efficiency tax credits by income classes and as a percentage of total taxpayers (over 41 million in 2020). It is evident that the share of those claiming an energy-efficiency-related tax credit is higher among people aged 65 and above, whatever the income class they belong to.

(d) **Energy efficiency: the residential space**

Economies of scale in energy use are broadly linked to household size and average dwelling space to be heated and illuminated. The ordinary life-cycle pattern, as previously discussed, naturally decreases the household size as age increases, and the growing share of one-person households, observed in several Western countries

[18] Part of the funds came from EU Budget. Cohesion policy operational programmes allocated a budget of around €14 billion to improve the energy efficiency of buildings, equal to 4% of all 2014–2020 Cohesion policy funds. In addition, member states budgeted €5.4 billion for national co-financing, of which €2 billion for residential buildings. See European Court of Auditors (2020).

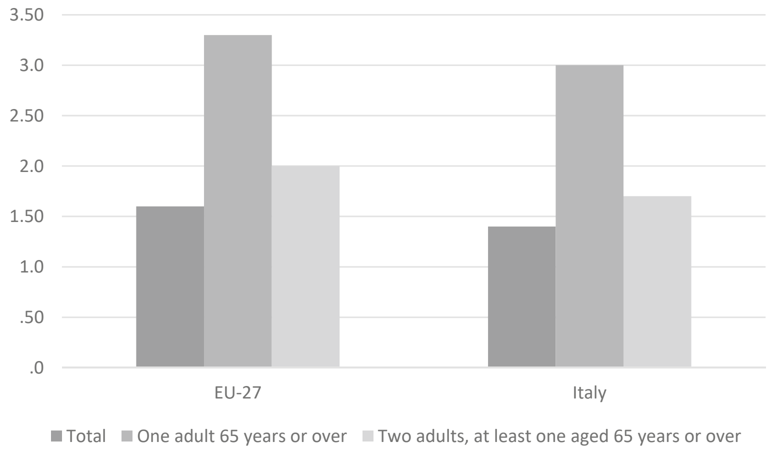

Fig. 7 Average number of rooms per person by type of household (2021). *Source* Authors' on EU-SILC data

and East Asia, will exacerbate the phenomenon. With the shrinking household size, we can observe an increasing per capita space for which energy services are needed. Indeed, Fig. 7 shows that the average space—measured as rooms per person—is higher for one-person households aged 65 and over and for couples with at least one elderly person. However, the average home in Italy is smaller than in Europe for all types of families considered. This smaller residential space component can partially mitigate the ageing and the decreasing family size effects.

(e) **Additional factors: social practices**

In addition to the hampering of the health status (Charlier and Legendre 2022), energy poverty indirectly affects social activities, mental health and the general life satisfaction of household members (Welsch and Biermann 2017; Churchill et al. 2020). Middlemiss (2022) stresses that people in energy poverty report feelings of powerlessness and a lowered sense of agency and belonging in society. This effect is presumed even stronger in older adults where we observe a naturally decreasing sphere of physical mobility and social relations. On the contrary, a healthy ageing[19] would require to be able to take an active part in society and from a societal point of view healthy longevity can also reduce public expenditure in long-term care.

To investigate this particular vulnerability for older households we start by looking at the general EU situation. As expected, younger people usually have a strong preference to frequently go out for a meal or a drink, so that, on average, less than 15% of EU young people (with less than 25 years) declare that they cannot afford to get together with friends or family for drink/meal at least once month; this percentage

[19] The healthy ageing can be described as a "process of optimizing opportunities for physical, social and mental health to enable older people to take an active part in society without discrimination and to enjoy an independent and good quality of life", see Healthy Aging Project (2007).

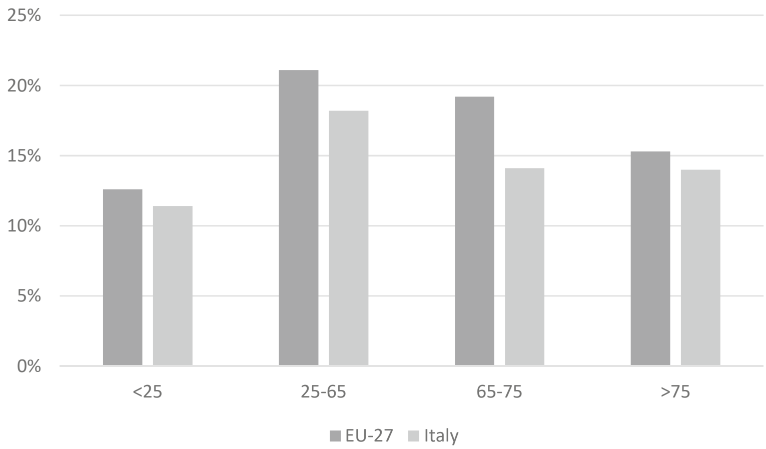

Fig. 8 Persons who cannot afford to get together with friends or family (relatives) for a drink or meal at least once a month by age group (%) (2019). *Source* Authors' on EU-SILC data

is 11.4% for Italian youths (Fig. 8). For people more aged 65 and over, we can see that the share of those who cannot afford to go out for a drink/meal is lower than in working age and decreases for the older group. Italy shows the same pattern but the shares by age of those who declare they cannot afford social activity are always lower than in Europe.

When we distinguish households in each age class according to a consensual indicator of energy poverty (Fig. 9), we observe a huge difference between the two groups. Those declaring the inability to keep the home warm also signal great difficulties in meeting friends and family members and this percentage reaches 50% for the younger group.

The same result has been confirmed by a recent survey on Italian households in energy poverty condition by Rugiero et al. (2022) who note "…a substantial divergence between respondents in conditions of non-discomfort (strongly oriented towards frequent family relations, assiduous frequenting of meeting places, systematic reading and information - also via the Internet -, participation in cultural events and training activities, travel and sporting activities) and respondents falling into classes of discomfort and vulnerability, who tend to be more isolated and less inclined to engage in activities that put them in contact with other actors in the local community. In particular, the energy poor are those who systematically participate less than others in all activities considered, in some cases to very modest proportions. They are closely followed by the energy vulnerable".[20]

Overall, this descriptive analysis draws a picture according to which in Italy the elderly, although suffering from health and social vulnerabilities due to age, are generally able to engage in practices to increase the energy efficiency of their homes and are shielded by welfare and pension systems that even after the financial crisis

[20] Our translation of the Italian text.

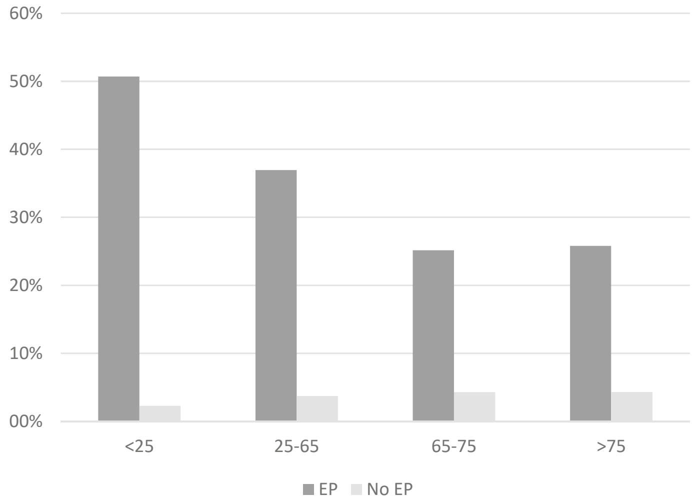

Fig. 9 Persons who cannot afford to get together with friends or family (relatives) for a drink or meal at least once a month by age and Energy Poverty Indicator (%) (2019). *Source* Authors' on EU-SILC data

protected their income. To gain further insights on this issue, in the next section we propose an econometric analysis of Italian households' residential energy demand in order to estimate the responsiveness of demand by age group to changes in prices and income.

5 A Focus on Italian Household Energy Demand Elasticities

We focus on Italian residential energy consumption to analyse to what extent the elderly population has distinctive characteristics in its behaviour with respect to the affordability of energy use linked to income and prices. To exploit this issue, we use data collected through the Italian Household Budget Survey (IHBS) conducted annually by ISTAT. The main focus of the IHBS is on all the expenditures incurred in residential households to purchase goods and services along with socio-demographic characteristics of the household members. Our analysis uses annual observations of these independent cross-sections for the period 1997–2019 concerning demographic characteristics and household expenditure for electricity and natural gas.[21] The original dataset is enriched with energy prices and tax components for the whole timespan. Nominal expenditures are converted to real values using commodity-specific price indexes (base year 2015). Moreover, to consider different demographic compositions, we use the square root of household size as an equivalence scale (as suggested by OECD). We build a pseudo-panel by grouping households on the basis of the age of the household head (between 25 and 85 years old), then means of all the relevant variables of the pseudo-household are computed for each year and cohorts are tracked over time according to the methodology already adopted in Bardazzi and Pazienza (2017, 2020).[22] This technique allows studying a dynamic phenomenon by following the same group of people over time when real panel data are not available.

For studying the interaction of demographic shifts in Italian population and the use of energy we select the units of the pseudo-panel according to three broad age classes of the householder (up to 35 years old, between 35 and 64, 65 and over) and we refer to these categories as 'young', 'adult' and 'elderly'. For each group, we estimate log–log demand equations (Appendix A) where the left-hand-side variable is either the average consumption of electricity in kilowatt-hours (kWh) or of natural gas in cubic metres. Our main variables of interest are disposable income and energy prices as we aim to investigate how responsive is residential energy demand to these 'affordability' indicators and how vulnerable are the different age groups.

Concerning prices, we use the average regional gross price of electricity and natural gas. There is a debate in the literature (Alberini and Filippini 2011) about whether the marginal or the average price is the most appropriate variable in a demand model. As our data are cohort averages, we assume that the potential for the average price to be endogenous—as the average price depends on the quantity consumed in the presence of block pricing schemes—is mitigated by the aggregation of many different individual and local pricing levels, as supported by some empirical studies (Shin 1985; Ito 2014).

As regards household income, the Italian Budget Survey only collects data on total expenditure and not on disposable income, therefore we use the adult equivalent total expenditure in real terms to represent the spending capacity of households. To confirm that this variable is a good proxy of the income trends that we have discussed in the previous section, in Fig. 10 we represent the long-run trends of the equivalent total expenditure in real terms (base year 2015) as index numbers per age group of the householder. The widening gap we have observed between the elderly and the rest of the Italian population in Fig. 6 is confirmed by the household budget microdata.

[21] The survey is based on a harmonised international classification of expenditure items (Classification of Individual COnsumption by Purpose—Coicop). The design of the survey was revised in 2014 when a new HBS replaced the old HBS which was carried out between 1997 and 2013. The data used in this chapter are linked between the two types of survey by means of a correspondence analysis of each variable of interest performed by the authors.

[22] Some assumptions are implicit in building the pseudo-panel. Although migration, ageing and death can change the composition of cohort population over time, here they are assumed to be constant. Moreover, cohorts are defined by the age of the head, therefore the age of the other family members is not considered as a factor influencing consumption decisions.

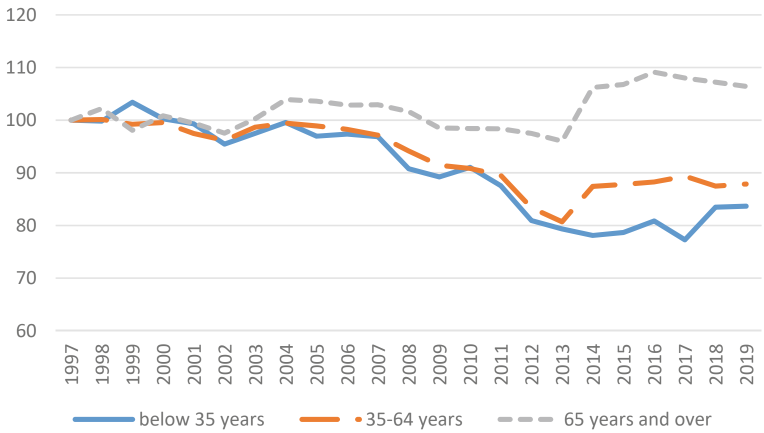

Fig. 10 Mean equivalised total expenditure by age group (1997 = 100). *Source* Authors' on IHBS data

In particular, here we have further split the households with heads below 35 years and those between 35 and 64 that are the groups used in the regression analysis. The data show that since the 2008 financial and economic crisis it is the younger group of households that has suffered more in terms of real spending capacity which in 2019 is still well below that one of 1997.

Other control variables in the estimated equations include socio-demographic characteristics (the educational level, the family size) and climatic conditions represented by the heating and cooling degree days. Although other variables such as the occupational status of the family members, the dwelling characteristics and the heating and cooling appliances are relevant for energy consumption at the household level, these cannot be considered in our model because they lose heterogeneity in the cohort data.

Table 3 shows the descriptive statistics of the variables at the aggregate level for the whole period. When relevant, statistics by age group are presented. As expected, the average consumption of electricity by age mimics the inverted U shape usually estimated in the empirical literature, while natural gas use increases with age. As mentioned in the previous sections, the average family size reflects the life cycle of the head with a maximum age between 35 and 64 years. Finally, the educational qualification attained is lower the older the cohort.

Our estimation results are presented in Tables 4 and 5 for electricity and natural gas, respectively. In each table, different columns refer to the coefficients of the model estimated for each age group and their associated robust standard errors, obtained using OLS.

Focusing on the affordability issue of energy consumption, our main parameters of interest are the total expenditure (as a proxy of disposable income) and the price elasticities that provide information on the responsiveness of household energy demand to changes in income and prices. All the coefficients have the expected sign and are

Table 3 Descriptive statistics

Variable	Mean	Std. Dev	Min	Max
Electricity average adult equivalent consumption (kWh)	1398.93	215.11	718.38	2117.63
hh aged less than 35 years old	1303.09	223.85	718.38	2117.63
hh aged between 35 and 64 years old	1433.32	200.33	925.84	1805.82
hh aged 65 years old and over	1426.25	206.02	856.40	1765.56
Natural gas adult equivalent consumption (cubic metre)	455.46	93.03	0.00	1324.72
hh aged less than 35 years old	382.57	108.89	0.00	1324.72
hh aged between 35 and 64 years old	456.90	68.23	288.76	639.12
hh aged 65 years old and over	514.57	64.94	340.27	639.12
Average adult equivalent total expenditure (2015 euros)	20,621.92	3192.117	7206.155	91,255.34
hh aged less than 35 years old	20,855	4784	7206	91,255
hh aged between 35 and 64 years old	21,909	1633	18,253	25,754
hh aged 65 years old and over	18,432	1949	14,243	22,380
Average household size	2.4	0.6	1.0	4.0
hh aged less than 35 years old	2.0	0.3	1.0	4.0
hh aged between 35 and 64 years old	2.9	0.3	2.0	3.7
hh aged 65 years old and over	1.8	0.2	1.4	2.3
Average educational level (0 = no education; 5 = PhD)	0.10	0.06	0.00	0.30
hh aged less than 35 years old	0.12	0.08	0.00	0.30
hh aged between 35 and 64 years old	0.13	0.05	0.03	0.28
hh aged 65 years old and over	0.05	0.02	0.00	0.14
Average price of electricity per kWh (euros)	0.260	0.085	0.193	0.605
Average price of natural gas per cubic metre (euros)	0.762	0.159	0.555	1.000
Heating Degree Days	1903.16	115.80	1631.87	2162.84
Cooling Degree Days	225.85	65.75	127.45	409.64

Source Authors' on IHBS data

statistically significant with few exceptions. Our results indicate that electricity use is sensitive to income changes with demand elasticity larger for households whose head is in the 'young' and 'adult' groups (0.378 and 0.385, respectively) while it is not significantly different from zero for the elderly. On the contrary, income elasticities of natural gas use are higher than electricity and households with head aged below 35 show a very elastic natural gas demand. Also in this case, the elderly households demand is not statistically sensitive with respect to their spending capacity.

Price elasticities are negative but all below 1 in absolute value for both fuels. For electricity, older households show the lowest value compared with families in

Table 4 Estimation results: electricity

	Under 35 years	35–64 years	65 years and over
Total expenditure (log)	0.378*** (0.052)	0.385*** (0.023)	0.051 (0.041)
Electricity price (log)	−0.765*** (0.025)	−0.816*** (0.012)	−0.653*** (0.012)
Educational level	−0.043*** (0.011)	−0.132*** (0.022)	0.014 (0.013)
Family size	−0.100** (0.045)	0.054 (0.049)	0.228*** (0.027)
Heating Degree Days	0.559*** (0.062)	0.459*** (0.016)	0.320*** (0.018)
Cooling Degree Days	0.009 (0.010)	0.014*** (0.004)	0.037*** (0.005)
Time	0.040*** (0.003)	0.045*** (0.001)	0.034*** (0.001)
Constant	−2.538** (0.893)	−2.261*** (0.295)	2.561*** (0.440)
R^2	0.84	0.83	0.92
N	362	713	459

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

the previous phases of the life cycle, showing that their natural gas demand is more rigid to changes in its own price with respect the electricity use. In general, our price elasticities are larger than those estimated for residential electricity demand in Italy by Dicembrino and Trovato (2013) on monthly data for the period 2000–2012 (−0.013) but they are consistent with results obtained by Faiella and Lavecchia in Chapter 7 of this volume (short-term price elasticity of electricity -0.36 and heating −0.40) on the same data used here. This evidence supports the general finding in the literature that estimated elasticities based on panel data tend to be higher than those estimated on aggregate time series and on cross-sections (Labandeira et al. 2017).

Within a framework of relatively better income performance of the elderly compared to the younger population, our estimates show a lower responsiveness of residential energy consumption (electricity and natural gas) to the changes in income and prices. This can be partly explained by a relatively restrained attitude that characterizes the energy consumption of the current elderly (those born before 1955), as shown by estimates of generational effects (Bardazzi and Pazienza 2017, 2020), and partly by relatively less squeezable and, generally speaking, less flexible needs. This relatively more rigid energy demand is a source of additional vulnerability, as generally highlighted by the empirical literature.[23] However, as for Italy,

[23] Estimations by cohorts, not shown in this chapter, confirm for the older generations (born before 1950s) lower income elasticities and higher price elasticities especially for natural gas demand.

Table 5 Estimation results: natural gas

	Under 35 years	35–64 years	65 years and over
Total expenditure (log)	1.763*** (0.188)	0.253** (0.111)	0.077 (0.180)
Natural gas price (log)	−0.216 (0.227)	−0.405*** (0.057)	−0.248*** (0.061)
Educational level	0.342*** (0.046)	−0.186*** (0.031)	−0.040 (0.042)
Family size	−0.084 (0.274)	0.095 (0.069)	0.572*** (0.172)
Heating Degree Days	0.618 (0.365)	0.407*** (0.075)	0.413*** (0.080)
Cooling Degree Days	0.077 (0.046)	−0.072*** (0.011)	−0.128*** (0.015)
Time	0.024*** (0.007)	0.061*** (0.002)	0.052*** (0.003)
Constant	−17.949*** (3.225)	−2.206 (1.413)	−0.010 (2.139)
R^2	0.39	0.70	0.78
N	362	713	459

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$

we can expect remarkable changes due to the different generational consumption behaviour (especially for the baby boomers) and for the long-run effect of welfare reforms.

6 Conclusions

The fast ageing process and the persistent inequality among European countries make it crucial to provide projections to take action on the many economic and social critical issues. Total population is shrinking in almost all EU countries, within remarkable age and household composition effects. These demographic shifts, characterized by a decrease in household size, could enlarge the group of vulnerable individuals who are suffering for deprivations and energy poverty in particular. At the same time, the need to speed up the energy transition path makes it urgent to consider different attitudes and capability towards new technologies and energy efficiency investments for an older and smaller population.

The link between population and energy consumption has long been considered straightforward, and projections of world population growth—the ’population bomb’ effect—have long raised alarms about the availability of per capita energy resources. It was not until the first signs of a decline in total population that the age and household size effects were taken into account. However, it is now recognized that the age effect is not linear and depends not only on the life cycle but also on energy cultures and the relative wealth position of different contingent age groups. Ageing certainly coincides with a situation of increased vulnerability that needs to be taken seriously when tackling deprivation and energy poverty in particular. Being elderly means that one's income is decoupled from general economic growth, that one has health problems, that it is more difficult to keep up with technological progress, including the provision of energy services, and that one often lives in a small household and in a large house, thus losing economies of scale in energy consumption. Many indicators of income vulnerability and energy poverty signal the higher incidence on the elderly, especially among single households at the EU level. However, the elderly are far from being a homogeneous group. In some European countries—including Italy—the slow economic growth, longer and healthier life courses and welfare system may have protected part of the current older generations with respect to the younger cohorts. In Italy the current older part of the population is characterized by an energy culture still shaped by hard times—the war and the oil shock of the seventies—resulting in an energy-saving attitude. At the same time, on average, the welfare system has sheltered their income and wealth so they also have a positive attitude towards the energy-saving investments. Therefore, the lower responsiveness of residential energy consumption (electricity and natural gas) to the changes in income and prices with respect to the younger population can be interpreted with a relatively better income and wealth situation and a persistent energy-saving attitude. However, the challenges the EU faces to reach the ambitious energy transition targets and the progressive changes in the welfare system will put more hardship on elderly people in the future. Moreover, the baby boomer generation will become old in the next decades with a different lifestyle characterized by higher thermal comfort standards and more electrical appliances. At the same time, the welfare systems are likely to offer lower protection and guarantees to preserve their long-term financial sustainability. All these factors could concur to a higher risk to be exposed to energy vulnerability for the future generations of senior citizens.

Appendix A: Construction of the Pseudo-Panel and the Model

To construct the pseudo-panel for our analysis, we use data from cross-sections for the years 1997–2019 and select households whose head is between 18 and 85 years old. This truncation eliminates those above 85 to avoid a selectivity problem.

The definition of cohorts creates a trade-off between the number of cohorts and the number of observations per cohort. On the one hand, if the number of cohorts is too small, there is a risk of grouping in the same cell households with heterogeneous behaviour. On the other hand, if a large number of cohorts is chosen to preserve variability within the pseudo-panel, it is possible to obtain cells with a very low number of observations, and the cohort means are inaccurate estimates of the true means of the cohort population, thus leading to inconsistent estimators (Verbeek 2008). Moreover, the criteria for the definition of cohorts are also important. Cohorts should be built according to characteristics that are invariant over time and observed for all individuals in the survey, such as date of birth, gender or region.

Consequently, for the construction of the pseudo-panel we take into account these considerations and perform the following steps. After trimming extreme and unreliable values we compute the pseudo-household means of all the relevant variables according to the age of the householder and year. Finally, the large quantity of original data is reduced to a total of about 1534 cells with an average cohort size of 350 households that allows to neglect measurement errors of population means (Verbeek 2008).

To estimate the effects of different covariates on pseudo-household energy demand we consider a set of variables including energy prices, real income and some demographic characteristics. Since we apply the model to a pseudo-panel, all the variables must be averaged by cohort c at time t, and the model can be parsimoniously written in matrix form as:

$$y = \alpha + W\varphi + \varepsilon, \tag{1}$$

where y is the stacked vector of cohort mean observations and W is a matrix of time-varying covariates, including fuel prices, household total expenditure in real terms (as a proxy for income), some control characteristics like the householder's educational level and household size and the climatic conditions measured with the heating and cooling degree days. When we control for variables that change over time, we want to see the extent to which the life cycle and generational behaviour of variable y are explained by these variables. Equation (1) constitutes the basis for our analysis.

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Overlapping Vulnerabilities and Energy Poverty

Energy Poverty and Health Pathologies: An Empirical Study on the French Case

Dorothée Charlier and Bérangère Legendre

1 Introduction

The COVID-19 health crisis has revealed the vulnerability of a part of the population and has brought to the forefront the need to act collectively to address global challenges. Among these challenges are of course the protection of human health, but also the preservation of resources and the mitigation of climate change. Protecting and improving health and mitigation of climate change therefore have a shared agenda. Combating energy poverty is one of the pillars of public action to address global warming, but also to promote the well-being and health of those who live in inefficient housing.

Many studies have established the impact of poor housing on the health of inhabitants. For example, low temperatures over time are associated with increased cardiovascular and respiratory problems, the latter being even more pronounced among children (Platt et al. 1989; Peat et al. 1998; Maidment et al. 2014). They can also aggravate existing health problems, such as arthritis or rheumatism, and weaken the immune system to the point of causing minor but recurrent disorders such as colds or flu (Oliveras et al. 2021). Dampness and mold are also harmful to health as they cause respiratory problems and asthma (Dales et al. 1991; Peat et al. 1998; Jaakkola et al. 2005). When housing is of poor quality, it may even contain substances that are harmful to health. This is particularly the case with radon, or with formaldehyde from combustion or off-gassing which increases the risk of cancer (Braubach et al. 2011). Various channels have also been identified as potential drivers of mental health. For

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example, cold weather can force people to adopt behaviors such as wearing coats indoors, sleeping with pets, or living in one room only. These behaviors create a sense of shame and isolate individuals (Anderson et al. 2012). Social isolation is recognized as an antecedent of anxiety and depression. At the same time, the fear of not being able to pay energy bills also generates stress and anxiety in households suffering from poor housing conditions (Liddell and Morris 2010).

Beyond housing quality, the fear of not being able to pay energy bills shows that there is a wider economic issue, that of energy poverty. Energy poverty covers three dimensions including poor housing, the negative effects of which on health have been widely reported, economic insecurity due to low income, and vulnerability to energy price rises. These three dimensions are closely linked and convey a reality beyond poor housing. Each contributes to the other and thus makes energy poverty a material, economic and social situation from which it is difficult to escape.

The aim of this chapter is first to analyze the strong statistical link between the prevalence of several illnesses, both physical and mental, and energy poverty in France in 2020, and second to discuss the health benefits that could be expected from combating energy poverty effectively.

To achieve the objectives mentioned above, we built a rich and original database. The data was collected in France in October 2020. We used a sample of 5000 individuals representative of the French population, containing socio-demographic information on the household, housing and energy consumption, access to the labor market, transportation habits, and reported health. In particular, it includes the World Health Organization quality of life questionnaire (WHOqol), making it possible to compute different health scores. We also gathered information on a range of pathologies and symptoms such as coughing, asthma, rheumatism, chronic diseases, and so on.

Our data clearly show a significant difference in the health status between energy-poor individuals and others. The descriptive approach allows us to confirm that individuals living in poor-quality housing (inadequate roof insulation, presence of humidity or mold, etc.) suffer more frequently from respiratory pathologies or psychological distress. This results in lower physical and mental health scores. The use of econometric models controlling for unobserved heterogeneity potentially affecting health status and energy poverty simultaneously, and also controlling for a number of other characteristics with an impact on health status, clearly confirms that all other things being equal, falling into energy poverty significantly degrades objective physical and mental health scores, but also self-reported and subjective health.

Our work highlights the health aspects that are adversely affected by energy poverty, but also each of the dimensions from the literature. Thus, whether health is measured objectively or subjectively, whether we focus on specific pathologies, whether we estimate the impact of a binary indicator of energy poverty or a specific aspect of this type of precariousness, all our results converge. In addition, being in energy poverty leads to consuming more health services. Our results show that tackling energy poverty is therefore of the utmost importance in addressing social inequality and in mitigating climate change, but effective policies in this area can also lead to substantial savings in health spending.

The chapter is organized as follows. Section 2 is dedicated to the state of the art on the link between energy poverty and health. The third section presents our recent and original database. In Sect. 4 we discuss the empirical analysis. The results and the discussion are presented in Sect. 5, and Sect. 6 concludes.

2 The State of Knowledge on the Link between Energy Poverty and Population Health

In recent years, the literature has taken up public health issues related to energy poverty. This has resulted in several types of scientific research, beginning with timely and localized studies highlighting the direct impact of renovation, housing rehabilitation programs, or energy efficiency on health (Howden-Chapman et al. 2007; Lloyd et al. 2008; Chapman et al. 2009; Ezratty et al. 2009; Thomson and Snell 2013). Health is sometimes only an indirect outcome of this research which has been more focused on indoor temperature (Pollard et al. 2019), indoor air quality (Rosenow and Galvin 2013), or energy consumption (Rosenow and Galvin 2013; Webber et al. 2015; Grimes et al. 2016).

Part of the existing academic literature also makes it possible to establish a direct causal relationship between energy poverty and health (Liddell and Morris 2010; Lacroix and Chaton 2015; Chaton and Lacroix 2018; Charlier and Legendre 2022) in the absence of specific initiatives such as renovations or public policy. This type of non-experimental research has the advantage of employing suitable tools to control several biases inherent to this question, such as the simultaneous effect of unobservable attributes on health and the risk of energy poverty, or a reverse causality between energy poverty and health. Using instrumental approaches or panel data methodologies for example makes it possible to resolve such problems. In a few studies, the use of panel data also made it possible to consider climate risks and the path dependency of health in the analysis (Charlier and Legendre 2022).

Although not all European countries have adopted an official definition of energy poverty, there nevertheless seems to be a consensus on the constituent dimensions of this type of precariousness: the energy insecure face a problem of low income, have poor quality, energy-inefficient housing, and have difficulty coping with energy costs (European Fuel Poverty and Energy 2006; Devalière 2007; Palmer et al. 2008; Liddell and Morris 2010; Charlier and Legendre 2018). This results in cold homes in winter, moisture problems when homes are poorly insulated, and difficulty paying energy bills. The effect of each of these problems on health has been documented.

2.1 The Effect of Cold on Health

The World Health Organization has established that the indoor temperature of homes should not fall below 18 degrees to protect the health of populations in general. When temperatures remain permanently below this threshold, inhabitants may face respiratory infections, cardiovascular troubles, increased blood pressure, or degradation of existing diseases such as arthritis. An equally established consequence is the increased risk of household accidents within the home. A number of studies confirm this. For example, in Ireland, the installation of central heating systems and the improvement of awareness about energy efficiency have led to a significant decrease in the number of households reporting arthritis/rheumatism and other forms of disease (Shortt and Rugkåsa 2007). The installation of central heating in detached or semi-detached houses would also reduce night cough, childhood asthma, and thus reduce school absenteeism (Barton et al. 2007).

If the temperature in a dwelling affects physical health, the same is true for mental health. Indeed, (O'Brien et al. 2011) have shown that insufficient heat in housing has an impact on mental health, emotional well-being, or social isolation. At the root of some of these disorders, we find a number of behaviors to cope with the cold which can isolate individuals, in particular due to a sense of shame. These behaviors affect well-being and mental health (Anderson et al. 2012). Indeed, individuals are forced for example to heat only one room, or to wear coats indoors, or even to sleep with pets to get warmer. This leads to the social isolation described by Hills (2012).

2.2 The Effect of Moisture on Health

Humidity is a problem often found in households in energy poverty, and which remains closely linked to the cold. It appears that the humidity of insufficiently heated dwellings can cause stress and depression (Lowry 1991; Khanom 2000; Shortt and Rugkåsa 2007). Mold can accumulate in cold, damp homes, causing respiratory symptoms, including asthma, coughing, and wheezing (Dales et al. 1991; Peat et al. 1998; Jaakkola et al. 2005). Fisk et al. (2007) concluded from a meta-analysis that moisture and mold are associated with a 30–50% increase in respiratory tract and asthma-related health problems.

2.3 The Effect of Financial Pressure on Health

The monetary dimension of energy poverty relates to the lack of income needed to pay energy bills, whether due to the physical characteristics of the housing as mentioned in the previous paragraphs, or the excessively high cost of energy. The existence of arrears in the payment of energy bills is a variable often analyzed by the European

Commission in its work on energy poverty. Households who fear that unpaid bills will accumulate or fear that they will not be able to pay them are under increased stress. Moreover, this stress is a breeding ground for the development of anxiety and depression. More broadly, financial pressure is a source of mental distress (Liddell and Morris 2010).

People in energy poverty may experience embarrassment and shame (Longhurst and Hargreaves 2019). What Longhurst and Hargreaves (2019) call emotions is also described in their qualitative survey as a premise of social isolation. The feeling of failure takes a heavy toll on emotional and mental health, whether faced with financial hardship, the threat of job loss, or the threat of suspension of electricity and other energy services.

3 Data

3.1 The PEPSI Database

A rich and original database, representative of the French population,[1] was built to assess the question of energy poverty on physical and psychological health. The PEPSI[2] data were collected in October 2020, i.e., five months after the end of the first pandemic containment measures in France, and about three weeks before the second set of measures. After removing some aberrant observations, the final sample contains 4,194 individuals and remains representative of the French population. Our analysis focuses on individuals, but we also have some information about their households, enabling us to calculate the standard of living within the household, for example.

The survey consists of 302 questions divided into six modules, allowing for a detailed description of individuals and households to which they belong including socio-demographic, health, housing, transport and labor market characteristics, and energy expenditures. Questions to establish the World Health Organization (WHO) Profile are asked in the health module. The World Health Organization quality of life questionnaire (WHOQOL BREF questionnaire) calculates two health scores: a physical health score and a mental health score. The individual has a choice of five responses per question and accumulates more or fewer points depending on the response (very unwell- 1 point to very well- 5 points). To calculate the physical health score, the individual answers seven questions and the points for each response are added to obtain a raw score. Then, to convert it to 100, we refer to the points conversion table provided in the guide. For the psychological health score, the procedure is

[1] The survey is representative of the French population based on the following criteria: sex, age, professional category, region, housing type (individual home or multiple occupancy housing), and homeownership. Proof of the representativeness of the sample can be provided on request.

[2] PEPSI is the acronym for the Energy Poverty, Pollution, and Individual Health project (*Précarité Energétique, Pollution et Santé des Individus* in French) and financed by the region Auvergne–Rhône Alpes.

almost identical except that the individual answers only six questions more focused on their mental well-being.[3] Values range from 0 (for the worst scores) to 100 for the maximum score. Other variables can be used to assess health status. Dichotomous variables, on the existence of diseases (chronic, respiratory, cardiovascular, rheumatism, psychological, and headache), can be used as a control. These variables also make it possible to better understand what the impact of energy poverty is in terms of pathologies. A variable for a perceived health score and the number of visits to the doctor has been used.

We adopt the definition of the French Observatory on Energy Poverty (Observatoire National de la Précarité Énergétique) for energy poverty, which considers energy poverty to be a threshold of 8% in the energy-income ratio for the first three income deciles.[4] The first three deciles are determined by equivalizing the reference tax income of the household.[5] Then, to calculate the energy-income ratio, the annual amount of the total energy bill for all uses and the reference tax income of the household to which the individual belongs is used. These elements allow calculation of the energy-income ratio, which determines the share of income spent on energy. By selecting the poorest 30% of individuals in the sample who have an energy-income ratio higher than 8%, we can build the binary variable of energy poverty *Energy Poor* (0 = not energy poor, 1 = energy poor). To ensure the robustness of our results, we also compared our results with each dimension of energy poverty. Energy poverty is a convergence of three main elements: household income, household energy requirements, or energy efficiency of homes and fuel prices which influence self-restriction behaviors (Boardman 1991; Hills 2012). Thus, qualitative variables to measure housing quality (quality of roof insulation, quality of wall insulation, and presence of moisture) are also considered.

We calculated the level of income poverty to compare our results. Poor households are those whose income equivalent is below 60% of the median. Finally, we introduced additional variables for controlling for health status: socio-demographic characteristics (age, employment status, gender, children, etc.), physical attributes (physical activity, height, and weight), and local conditions (weather).

The relationship between socioeconomic characteristics and health is well-established. Negative health behaviors and psychosocial characteristics are clustered in socioeconomic status groups, often measured by low income (Lynch et al. 1997; Benzeval and Judge 2001; Contoyannis et al. 2004) or by gender (Vlassoff 2007). Older people are also often in poor health (Ohrnberger et al. 2017) and having a caregiving role has a markedly negative impact on physical and mental health scores (Hegewald et al. 2020; Parra-Saavedra and Miranda 2021). Health status is also related to retirement status (Sickles and Taubman 1986) as well as employment conditions (Barnay and Defebvre 2021). Other health controls have been introduced

[3] For more details, please consult the WHO website: https://www.who.int/tools/whoqol/whoqol-bref.

[4] Excluding households above the first three income deciles excludes those with a high income who choose to consume more energy but who have the means to finance it without any hardship.

[5] The OECD equivalence scale is used.

such as the number of psychologists in the region, to take into account access to health care (Charlier and Legendre 2022), and having contracted COVID-19. On the other hand, being physically active prevents the deterioration of physical and mental health (Maller et al. 2009; Pelletier et al. 2017; Fossati et al. 2021). Telecommuting can generate stress, as people are more likely to be overworked and have difficulty separating their work from their private life (Dimitrova 2003; Mann 2003). Plus, being alone at home without social relationships and isolated can lead to a number of psychological problems such as loneliness and depression (Tavares 2017). Finally, information about location is available in the database. This was matched with meteorological data of Meteo France (unified degree days[6]) to provide a proxy for actual meteorological conditions and to obtain unified degree days.

3.2 Descriptive Statistics

The main descriptive statistics are presented in Tables 1 and 2. On average, the physical health score stands at 67 points while the mental health score is slightly lower, at 63 points. The self-assessed health rating (71.8) is quite close to the score measured by the World Health Organization. Individuals consult the doctor 1.5 times a year for seasonal diseases. Nevertheless, there is a high degree of heterogeneity among individuals in terms of health since the minimum is generally around 0 and the maximum is equal to 100. About 10% of respondents report respiratory pathologies and 50% chronic pathologies. Cardiovascular problems affect 14.8% of the individuals in the sample, headaches 12.4%, and rheumatism 14.7%. About 7% of respondents report having a mental health disorder. Some 90% of individuals have a referring doctor. Generally speaking, health scores are quite correlated.

Regarding housing conditions, 11% of individuals report mold problems, on the other hand, 60% report good roof insulation and 57% good wall insulation. The average reference tax income is EUR 33,142 and 12.8% can be considered energy poor. Housing quality is correlated with health similar to the correlation between income and health scores (around 0.20). The correlation coefficient between being energy poor and physical and mental health is positive and around 0.14.

By conducting tests of means comparison between the chronic pathologies reported by individuals, and housing conditions (poor insulation, mold), we see that the difference in the presence of certain pathologies is significant (Table 3). Indeed, individuals reporting problems in housing conditions also report chronic diseases, respiratory diseases, migraines, and psychological problems more often. This observation is confirmed when we look at the differences in health scores and the number of doctor visits (Table 4). These results also translate into being energy

[6] Unified Degree Days express the severity of cold weather in a specific time period taking into consideration actual outdoor temperature and an average reference temperature previously recorded.

Table 1 Main descriptive statistics

Variable	Obs	Mean	Std.Dev	Min	Max
Physical Score WHO	4194	67.374	16.335	0	100
Psychological Score WHO	4194	62.728	18.053	0	100
No. of doctor visits	4194	1.468	1.76	0	24
Health rating	4194	71.84	16.89	0	100
Respiratory disease	4194	0.098	0.297	0	1
Chronic disease	4194	0.499	0.5	0	1
Cardiovascular disease	4194	0.148	0.355	0	1
Headache	4194	0.124	0.33	0	1
Psychological disease	4194	0.069	0.253	0	1
Rheumatism	4194	0.147	0.354	0	1
Age	4194	49.706	15.728	18	99
No. of Children	4194	1.287	1.195	0	9
Female	4194	0.504	0.5	0	1
Single	4194	0.194	0.396	0	1
Retired	4194	0.294	0.456	0	1
Student	4194	0.031	0.175	0	1
Unemployed	4194	0.066	0.249	0	1
Telecommuting	4194	0.293	0.455	0	1
Height	4183	169.863	9.358	124	203
Weight	4194	72.529	15.841	30	200
No. of psychologists	4194	3.656	2.437	0.785	13.258
Referring doctor	4194	0.908	0.289	0	1
COVID	4194	0.044	0.204	0	1
Tenant	4194	0.351	0.477	0	1
Caregiving role	4194	0.11	0.313	0	1
Physical activity	4194	0.826	0.379	0	1
Unified Degree-Day	4194	1803	322	9466	2643
Energy Poor	4194	0.128	0.334	0	1
Heating restriction	4194	0.7065	0.4554	0	1
Income	4194	33,142	20,842	1	129,000
Moisture problem	4194	0.11	0.313	0	1

(continued)

Table 1 (continued)

Variable	Obs	Mean	Std.Dev	Min	Max
Good roof insulation	4194	0.591	0.492	0	1
Good wall insulation	4194	0.566	0.496	0	1
Electricity for cooking	4194	0.546	0.498	0	1
Altitude	4194	158.164	229.19	0	3000
Energy voucher	4194	0.143	0.35	0	1

Source Authors' elaborations, PEPSI
Note The sample has 4194 observations except for height. The estimates will therefore be made on a sample of 4183 observations

poor and monetary poor. We also look at heating restriction behaviors[7] which can be one of the manifestations of energy poverty. Again, households reporting restriction behavior have on average more pathologies and lower health scores. Looking at Figs. 1 and 2, these results are confirmed for the number of doctor visits and energy poverty. Energy-poor people visit the doctor more per year on average.[8] The energy poor are also more likely to report chronic disease (57% against 49%). This results in different reported and measured health scores across population groups (Fig. 3).

4 Model

In this chapter, we assess the impact of energy poverty (EP) and housing conditions on physical and mental health scores (HEALTH) controlling for potential endogeneity more specifically due to unobserved elements that affect EP and health simultaneously (Kahouli 2020; Awaworyi Churchill and Smyth 2021; Charlier and Legendre 2022). Controls for individual characteristics[9] (X) and climate measured by Unified degree days (C) are introduced. Proofs[10] of the robustness are available in

[7] Restrictive behavior is self-reported. Respondents answer the following question: Do you ever restrict heating for cost reasons?

[8] For information, all individuals in France benefit from health coverage, regardless of their employment status or income level.

[9] Age, number of children, female, single, retired, student, unemployed, telecommuting, height, weight, number of psychologists, primary care physician, COVID, tenant, caregiving role, physical activity.

[10] First, we conducted correlation tests, significance tests, and a Wald test to validate the instruments in the endogenous estimate. Then, to demonstrate the validity and exogeneity of instruments, different statistical tests were carried out such as F statistics, Stock and Yogo tests for weak instruments, and the Hansen J test (Lewbel 2012). To ensure the robustness of our results, we used the energy-income ratio instead of the variable for energy poverty. Finally, estimates were F controlled with simple OLS regression. The instruments were implemented directly in the main Eq. (1) to demonstrate the absence of significance directly on health scores.

Table 2 Matrix of correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
(1) Physical Score WHO	1.000														
(2) Psychological Score WHO	0.602	1.000													
(3) No. of doctor visits	−0.213	−0.074	1.000												
(4) Health rating	0.569	0.395	−0.155	1.000											
(5) Respiratory disease	−0.168	−0.068	0.201	−0.129	1.000										
(6) Chronic disease	−0.396	−0.181	0.221	−0.351	0.330	1.000									
(7) Cardiovascular disease	−0.156	0.009	0.033	−0.194	−0.019	0.417	1.000								
(8) Headache	−0.144	−0.112	0.162	−0.077	0.032	0.378	−0.077	1.000							
(9) Psychological disease	−0.275	−0.304	0.099	−0.179	0.025	0.272	−0.004	0.063	1.000						
(10) Rheumatism	−0.239	−0.053	0.079	−0.213	0.038	0.415	0.071	0.001	−0.001	1.000					

(continued)

Table 2 (continued)

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
(11) Energy Poor	−0.141	−0.131	0.062	−0.095	0.045	0.054	−0.014	0.044	0.099	0.015	1.000				
(12) Income	0.191	0.209	−0.065	0.135	−0.030	−0.060	0.023	−0.028	−0.098	−0.011	−0.419	1.000			
(13) Moisture problem	−0.129	−0.149	0.078	−0.128	0.063	0.081	−0.009	0.063	0.085	0.017	0.120	−0.125	1.000		
(14) Good roof insulation	0.183	0.198	−0.047	0.166	−0.059	−0.044	−0.018	−0.042	−0.048	−0.009	−0.083	0.086	−0.202	1.000	
(15) Good wall insulation	0.171	0.214	−0.022	0.166	−0.022	−0.042	0.007	−0.019	−0.080	−0.030	−0.068	0.101	−0.221	0.504	1.000

Source Authors' elaborations, PEPSI

Table 3 Two-sample t test with equal variances between chronic diseases, energy poverty, and housing conditions

Chronic diseases

			Chronic diseases		Respiratory disease (asthma…)		Cardiovascular disease (hypertension…)		Rheumatic disease (arthritis, arthrosis)		Headache		Psychological disease	
		Obs	Means	*t*-value	Means	*t*-value	Means	*t*-value	Means	*t*-value	Means	*t*-value	Means	*t*-value
Poor roof insulation	0	3947	0.498	−0.35	0.093	−3.5***	0.146	−1.05	0.144	−1.45	0.125	0.35	0.069	0
	1	247	0.51	(0.72)	0.162	(0.001)	0.17	(0.305)	0.178	(0.149)	0.118	(0.73)	0.069	(0.992)
Poor wall insulation	0	3842	0.494	−2.15**	0.096	−1.8*	0.147	−0.5	0.144	−1.5	0.122	−1.2	0.063	−5.05***
	1	352	0.554	(0.032)	0.125	(0.072)	0.157	(0.633)	0.174	(0.14)	0.145	(0.226)	0.134	(0.000)
Presence of mold	0	3684	0.486	−4.5***	0.093	−2.75***	0.149	0.55	0.147	0.1	0.118	−3.8***	0.059	−6.95***
	1	510	0.592	(0.000)	0.132	(0.007)	0.139	(0.57)	0.145	(0.916)	0.176	(0.000)	0.141	(0.000)
Noise exposure	0	3399	0.485	−3.65***	0.089	−3.6***	0.151	1.5	0.149	0.95	0.111	−5.65***	0.059	−5.2***
	1	795	0.557	(0.001)	0.132	(0.001)	0.131	(0.139)	0.136	(0.34)	0.183	(0.000)	0.111	(0.000)
Heating restriction	0	1231	0.441	−4.85***	0.081	−2.45**	0.152	0.6	0.148	0.15	0.103	−2.7***	0.044	−4.1***
	1	2963	0.523	(0.000)	0.105	(0.015)	0.145	(0.546)	0.146	(0.887)	0.134	(0.007)	0.079	(0.000)
Energy poverty	0	3658	0.489	−3.45***	0.092	−2.9***	0.149	0.95	0.144	−0.95	0.119	−2.85***	0.059	−6.45***
	1	536	0.569	(0.001)	0.133	(0.004)	0.135	(0.354)	0.161	(0.334)	0.163	(0.005)	0.135	(0.000)
Income poverty	0	3249	0.486	−3***	0.092	−2.2**	0.154	2.35**	0.148	0.5	0.117	−2.75***	0.051	−8.4***
	1	945	0.542	(0.003)	0.117	(0.029)	0.124	(0.019)	0.142	(0.633)	0.15	(0.007)	0.129	(0.000)

Source Authors' elaborations PEPSI
Note Robust standard errors in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Table 4 Two-sample *t* test with equal variances between health scores, energy poverty, and housing conditions

Health scores			Number of visits to the doctor		Psychological health score (WHO)		Physical health score (WHO)		Health rating (self-reported)	
		Obs	Means	*t*-value	Means	*t*-value	Means	*t*-value	Means	*t*-value
Poor roof insulation	0	3947	1.46	−1.25 (0.214)	63.095	5.3*** (0.000)	67.67	4.7*** (0.000)	7.221	5.65*** (0.000)
	1	247	1.603		56.858		62.63		6.595	
Poor wall insulation	0	3842	1.452	−2** (0.045)	63.547	9.8*** (0.000)	67.954	7.65*** (0.000)	7.234	6.4*** (0.000)
	1	352	1.647		53.784		61.04		6.633	
Presence of mold	0	3684	1.417	−5.1*** (0.000)	63.711	9.6*** (0.000)	68.132	8.15*** (0.000)	7.245	6.3*** (0.000)
	1	510	1.841		55.623		61.896		6.743	
Noise exposure	0	3399	1.375	−7.15*** (0.000)	63.798	8*** (0.000)	68.325	7.85*** (0.000)	7.24	4.5*** (0.000)
	1	795	1.867		58.151		63.309		6.944	
Heating restriction	0	1231	1.382	−2.05** (0.041)	64.591	4.3*** (0.000)	68.438	2.7*** (0.007)	7.25	1.6 (0.106)
	1	2963	1.504		61.953		66.932		7.157	
Energy poverty	0	3658	1.427	−4*** (0.000)	63.633	8.55*** (0.000)	68.258	9.25*** (0.000)	7.245	6.2*** (0.000)
	1	536	1.752		56.545		61.34		6.765	
Income poverty	0	3249	1.405	−4.3*** (0.000)	64.602	12.7*** (0.000)	68.844	10.95*** (0.000)	7.293	7.85*** (0.000)
	1	945	1.683		56.285		62.319		6.809	

Source Authors' elaborations, PEPSI
Note Robust standard errors in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

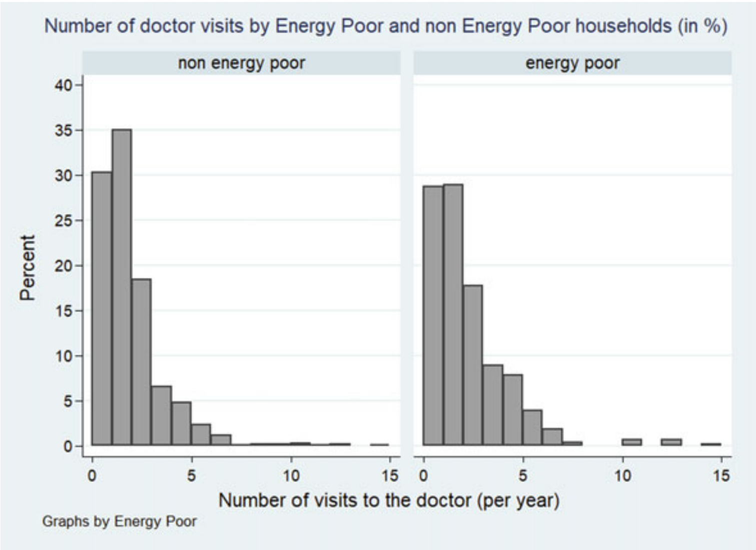

Fig. 1 Number of doctor visits and energy-poor status.
Source Authors' elaborations, PEPSI

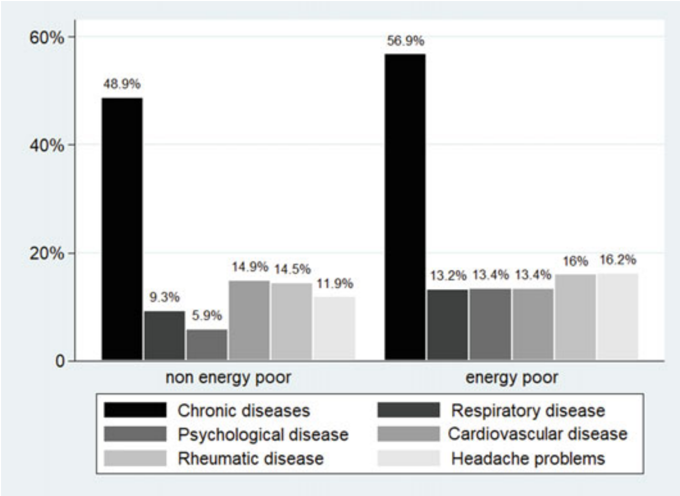

Fig. 2 Pathologies and energy-poor status.
Source Authors' elaborations, PEPSI

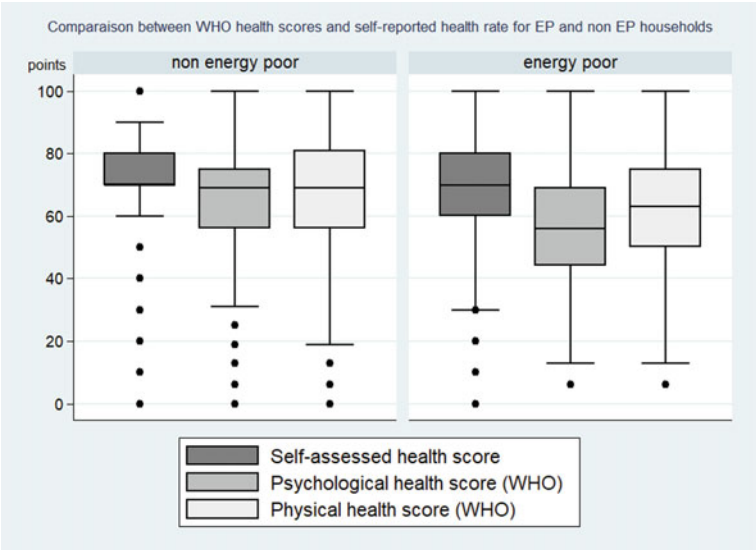

Fig. 3 Health scores, Self-assessed health score, and energy-poor status.
Source Authors' elaborations, PEPSI

Appendix A.2. Thus, we estimate for different health scores (physical, psychological, self-reported, and number of visits to the doctor):

$$H_i = \alpha_i + \beta \widehat{EP}_i + \gamma X_i + \delta C_i + \varepsilon_i \tag{1}$$

$i = 1, \ldots, n$

where H, the individual health status, is measured using different indicators (WHO scores, health self-assessment, and number of visits to a primary care physician), X_i the vector of individual characteristics, C_i the climate control (unified degree days), and $\widehat{EP_i}$, the estimated value of energy poverty indicating if individual i is energy poor determined as follows:

$$\begin{aligned} EP_i = \alpha_i' + \gamma' X_i + \delta' C_i + \zeta COOK_i \\ + \theta ALTITUDE_i + \vartheta VOUCHER_i + \varepsilon_i' \end{aligned} \tag{2}$$

with COOK (electricity for cooking), ALTITUDE (the altitude at which the dwelling is located), and VOUCHER (when an individual benefits from financial support for energy costs) used as instrumental variables. Indeed, we need exclusion variables that directly explain energy poverty but not health scores (both physical and mental).

Altitude at which the dwelling is located seems perfectly exogenous, and intuitively nothing leads us to believe that altitude can affect health scores, yet it is expected to influence energy needs for heating through the numerator of the energy-income ratio (Katsoulakos and Kaliampakos 2014; Li et al. 2022). Energy cost is also dependent on the quality of building insulation and the energy source. One way to deal with this is to introduce the energy source for cooking (COOK): fuel source and efficiency of appliances during cooking can affect energy use (Hager and Morawicki 2013).

Finally, it is necessary to control for budget (the denominator of the energy-income ratio). French households can benefit from income-based financial support, which directly increases their income level and can decrease the burden of energy expenditures (Hancevic and Sandoval 2022). This subsidy is available to all households whatever the energy source. Only 42% of the energy poor in our dataset benefit from this financial support. We then introduce the instrument VOUCHER in (2). Additional regressions also can be provided to explain the occurrence of different pathologies namely chronic, cardiovascular, respiratory, rheumatic, headache, and psychological diseases, in this case we have the following specification:

$$D_i = \alpha_i'' + \beta'' \widehat{EP_i} + \gamma'' X_i + \delta'' C_i + \varepsilon_i'' \tag{3}$$

where D_i is the pathology.

Equations (1) and (2) are estimated simultaneously using a conditional mixed-process (CMP) (Roodman 2011). One main advantage of a CMP is the ability to deal with the different nature of the dependent variable. Conditional mixed-process is employed to estimate simultaneous equations where instruments allow the construction of a recursive set of equations, as in two-stage least squares (2SLS). As energy poverty (Eq. 2) is not a continuous variable, standard IV methods can lead to misspecification. The CMP enables consideration of the binary nature of the variable. The model allows us to jointly estimate a binary variable and a continuous variable. In our case, Eq. (1) is estimated as an OLS, so coefficients can be directly interpreted as margins and in Eq. (2) we interpret only the sign of coefficients and their significance. It is possible to jointly estimate Eqs. (2) and (3). In this case, we have two probits and we only interpret the sign of coefficients and their significance.

In order to provide additional elements, we will also look at the dimensions of energy poverty to explain health scores and the occurrence of pathologies. For this, we will study the impact of the different dimensions (heating restriction, income, quality of the dwelling measured by moisture problems, or quality of roof and wall insulation) measured by vector Z on health scores: physical, psychological, self-reported, and number of visits to the doctor on one hand:

$$H\prime_i = \alpha_i''' + \beta''' Z_i + \gamma''' X_i + \delta''' C_i + \varepsilon_i''' \tag{4}$$

and on the probability of developing chronic, cardiovascular, respiratory, rheumatic, headache, and psychological diseases on the other hand:

$$D_i = \alpha_i'''' + \beta'''' Z_i + \gamma'''' X_i + \delta'''' C_i + \varepsilon_i'''' \tag{5}$$

In these last two cases, Eq. (3) is a simple OLS and Eq. (4) is a probit.

5 Results and Discussion

5.1 The Effects of Energy Poverty on Health

Our estimates clearly show that energy poverty affects health (Table 5). The estimate of Eq. (2) is reported in the Appendix (Table A.1). The results remain valid whatever the method of capturing the health status (objective health scale, subjective rating, proxy such as doctor visits), and whatever the variables used to measure energy poverty. Whether we use being fuel poor or the energy effort rate directly, our results converge. Being in energy poverty thus reduces the WHO physical health score by 8.14 points. The negative and significant effect on the mental health indicator is 3.78 points. When individuals are in a situation of energy poverty, they also give themselves a lower health score on average (3.37 points lower than the score reported by individuals who are not energy poor). Finally, this poor health consistently translates into increased care consumption, since people in a situation of energy poverty report 2.23 more visits to the doctor on average than others.

Table 5 Estimation results with CMP for health scores and number of visits to the primary care physician

Variables	Physical health score WHO	Psychological health score WHO	Health rating (self-reported)	Number of visits to the primary care physician
Energy poor	−8.144*** (2.209)	−3.781** (1.684)	−3.337** (1.535)	2.231*** (0.341)
Age	0.0553** (0.0273)	0.119*** (0.0292)	−0.0589** (0.0287)	−0.0116*** (0.00327)
Number of children	−0.195 (0.220)	0.912*** (0.233)	−0.0296 (0.237)	0.0759*** (0.0270)
Female	−1.498** (0.707)	−3.741*** (0.753)	−0.559 (0.749)	0.202** (0.0816)
Lives alone	−2.070*** (0.665)	−3.955*** (0.731)	−3.193*** (0.714)	−0.193*** (0.0701)
Retired	−3.934*** (0.865)	0.613 (0.941)	−3.457*** (0.918)	0.288*** (0.101)
Student	−4.059*** (1.450)	−2.924* (1.634)	0.341 (1.442)	0.114 (0.153)
Unemployed	−6.696*** (1.262)	−6.871*** (1.293)	−6.205*** (1.282)	−0.114 (0.156)
Telecommuter	−2.014*** (0.629)	0.143 (0.692)	−1.177* (0.623)	0.244*** (0.0701)
Height	0.140*** (0.0410)	0.101** (0.0442)	0.0930** (0.0465)	0.00360 (0.00476)
Weight	−0.139*** (0.0191)	−0.0871*** (0.0216)	−0.146*** (0.0222)	0.0106*** (0.00232)
No. of psychologists	0.129 (0.105)	0.260** (0.111)	0.104 (0.104)	0.0388*** (0.0136)
Has a primary care doctor	−0.909 (0.911)	1.637* (0.974)	0.859 (1.036)	0.845*** (0.0921)
Had COVID	−4.411*** (1.312)	−0.406 (1.359)	−7.443*** (1.601)	0.787*** (0.208)
Tenant	−0.772 (0.586)	−2.122*** (0.624)	−1.375** (0.599)	−0.161** (0.0706)
Helping role	−3.196*** (0.818)	−3.407*** (0.864)	−2.422*** (0.894)	0.350*** (0.110)
Physical activity	5.898*** (0.713)	5.891*** (0.750)	6.400*** (0.768)	0.203*** (0.0781)
Unified degree days (C)	0.000177 (0.000835)	0.000441 (0.000875)	−0.000399 (0.000816)	−7.56e-05 (8.78e-05)
Constant	51.74*** (7.358)	41.32*** (7.878)	68.07*** (7.998)	−0.893 (0.874)
Observations	4183	4183	4183	4183

Note Results can be interpreted directly as marginal effects
Robust standard errors in parentheses
***$p < 0.01$, **$p < 0.05$, *$p < 0.10$

In Table 5, we show that several vulnerability factors have an impact on health. Thus, it appears that being a student, retired or unemployed negatively affects physical health scores. The strongest impact corresponds to being unemployed (−6.7 points), followed by being a student (−4 points), and being retired (−3.9 points). Our results also control for the supply of care to populations, since the medical density is integrated (number of psychologists in the region). Increasing the supply of psychologist services improves the mental health score.

Table 6 allows us to delve a little deeper into different dimensions of energy poverty. For comparison purposes, we directly compare our results with a traditional OLS model in which the variable of interest, energy poverty, has been replaced by variables describing energy poverty, namely income, heating restrictions, dampness in the dwelling, and having good quality wall and roof insulation. The results show that insufficient income is not the only cause of deteriorating health. Certainly, the higher the income, the better the objective and subjective health scores, and the less individuals visit the doctor. But this analysis in terms of living standards is far from sufficient. Indeed, each of the variables qualifying the energy efficiency of housing is also statistically significant, just as the variable capturing the restriction is statistically significant for objective health scores.

Table 6 OLS estimates of health scores with dimensions of energy poverty

Variables	Physical health score WHO	Psychological health score WHO	Health rating (self-reported)	Number of visits to the primary care physician
Heating restriction	−1.026* (0.528)	−1.710*** (0.566)	−0.764 (0.539)	0.0213 (0.0604)
Income (log)	2.136*** (0.270)	1.250*** (0.289)	1.556*** (0.320)	−0.142*** (0.0313)
Moisture problem	−2.833*** (0.837)	−3.094*** (0.939)	−4.217*** (0.943)	0.202* (0.108)
Good roof insulation	3.807*** (0.570)	3.558*** (0.618)	3.291*** (0.568)	−0.161*** (0.0589)
Good wall insulation	2.559*** (0.566)	3.908*** (0.614)	2.781*** (0.583)	0.0121 (0.0591)
Controls†	Yes	Yes	Yes	Yes
Constant	28.16*** (7.052)	27.53*** (7.914)	53.11*** (7.824)	2.160*** (0.787)
Observations	4183	4183	4183	4183
R-squared	0.135	0.159	0.133	0.070

Note Results can be directly interpreted as marginal effects
Robust standard errors in parentheses
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$
†Controls: Age, Number of children, Female, Lives alone, Retired, Student, Unemployed, Telecommuter, Height, Weight, Number of psychologists, Has a primary care doctor, Had COVID, Tenant, Helping role, Physical activity, Unified degree days

Thus, having good isolation improves objective mental and physical health scores from 2.6 to 3.9 points. It appears that people living in well-insulated housing feel the benefits since their self-reported score is also higher. The problem of humidity seems to lead to a substantial deterioration in subjective health since the score reported by those concerned is on average 4.22 points lower while the negative effect on the objective scores of physical and mental health are lower by 2.83 and 3.09 points, respectively.

Now we can also look the relationship between being energy poor and the type of pathology in more detail (Table 7). We note that being energy poor increases the likelihood of developing chronic, respiratory, and psychological diseases. But energy poverty is not significant in explaining cardiovascular problems, rheumatism, or headaches (Table 7).

On closer examination, the impact of the dimensions of energy poverty on the different pathologies (Table 8) shows that all the dimensions of energy poverty have an impact on chronic diseases, which means that suffering from a chronic disease is not only a problem of income. It is even shown that the most important marginal effect on the probability of suffering from chronic diseases is related to the presence of humidity in the dwelling followed by heating restriction (11.61% and 7.9%, respectively). Combined cold and humidity are therefore the two factors responsible for this type of pathology. For rheumatism-related pathologies, once again, the marginal effect is stronger for humidity (5.2%) than for an increase in income (-1.4%). Heating restriction increases the probability of suffering from psychological diseases by 24.8%.

Additionally, if we were to prioritize a type of renovation to address health pathologies, we would have to focus on roof insulation, which seems to have more of an impact on the reduction of chronic, cardiovascular, or respiratory diseases. Wall insulation plays a significant role in rheumatism-related problems and psychological problems.

5.2 Policy Recommendations

Our results suggest the importance of tackling energy poverty in reducing the direct and indirect health costs it generates. There is little research estimating the health costs associated with energy poverty. Only a few countries have already addressed the issue. Existing work generally does not make it possible to form a link between energy poverty and health, but more precisely between poor housing and health. Indeed, it seems easier to link observable physical characteristics of housing to the development of pathologies and disorders than to assess a monetary effect whose causality is demonstrated only due to non-experimental studies. When such analysis does exist, it is often informed by work originating in the United Kingdom, which is a pioneer in tackling energy poverty. As early as 1996, the Housing Health and Safety Rating System (HHSRS) method was developed in England. It makes it possible to calculate an indicator of the health risk suffered by the occupants of a dwelling

Table 7 Estimation results with CMP for pathologies

Variables	Chronic diseases	Cardiovascular problems	Respiratory problems	Rheumatic problems	Headache problems	Psychological disease
Energy poor	0.458** (0.217)	−0.0753 (0.292)	0.486* (0.274)	−0.0394 (0.329)	0.311 (0.237)	0.464** (0.230)
Age	0.00279 (0.00224)	0.0250*** (0.00343)	−0.0104*** (0.00318)	0.0235*** (0.00327)	−0.0195*** (0.00278)	−0.00598* (0.00311)
Number of children	0.0509*** (0.0182)	0.0444** (0.0221)	0.0288 (0.0246)	0.0416* (0.0222)	0.0866*** (0.0237)	0.00587 (0.0271)
Female	0.0962* (0.0570)	−0.394*** (0.0779)	−0.0552 (0.0740)	0.327*** (0.0753)	0.371*** (0.0756)	0.156* (0.0907)
Lives alone	0.0941* (0.0538)	0.0459 (0.0679)	0.0316 (0.0734)	0.0146 (0.0684)	−0.0413 (0.0743)	0.301*** (0.0776)
Retired	0.484*** (0.0726)	0.303*** (0.0959)	0.296*** (0.100)	0.217** (0.0929)	−0.0652 (0.0983)	−0.162 (0.112)
Student	0.276** (0.128)	0.803*** (0.195)	0.106 (0.164)	–	−0.0148 (0.138)	−0.00607 (0.180)
Unemployed	0.145 (0.0941)	0.0421 (0.141)	0.0414 (0.126)	0.197 (0.124)	−0.121 (0.112)	0.248** (0.122)
Telecommuter	0.150*** (0.0514)	0.132* (0.0762)	0.139** (0.0703)	0.0440 (0.0722)	0.102 (0.0628)	0.123 (0.0762)

(continued)

Table 7 (continued)

Variables	Chronic diseases	Cardiovascular problems	Respiratory problems	Rheumatic problems	Headache problems	Psychological disease
Height	−0.00554* (0.00331)	−0.0275*** (0.00464)	−0.00420 (0.00437)	−0.000837 (0.00433)	0.00687* (0.00411)	0.00312 (0.00483)
Weight	0.00836*** (0.00153)	0.0183*** (0.00196)	0.00442** (0.00204)	0.00566*** (0.00184)	3.41e-05 (0.00203)	0.00183 (0.00226)
No. of psychologists	−0.00490 (0.00887)	−0.0105 (0.0126)	0.0148 (0.0117)	−0.00516 (0.0114)	−0.00564 (0.0119)	−0.0290 ** (0.0144)
Primary care doctor	0.377*** (0.0734)	0.0261 (0.113)	0.308*** (0.104)	0.268** (0.114)	0.211** (0.0955)	0.249** (0.114)
Had COVID	0.570*** (0.106)	0.618*** (0.115)	0.336*** (0.117)	0.462*** (0.119)	0.0849 (0.121)	−0.223 (0.155)
Tenant	0.0295 (0.0486)	0.0525 (0.0637)	−0.0293 (0.0635)	0.00922 (0.0659)	0.0173 (0.0617)	0.170** (0.0719)
Helping role	0.505*** (0.0694)	0.305*** (0.0814)	0.306*** (0.0787)	0.169** (0.0804)	0.156** (0.0791)	0.381*** (0.0859)
Physical activity	−0.0280 (0.0541)	−0.0261 (0.0679)	−0.163** (0.0697)	−0.113* (0.0657)	0.0342 (0.0709)	−0.151* (0.0784)
Unified degree days (C)	−7.28e-05 (6.59e-05)	0.000153* (8.83e-05)	−0.000114 (8.93e-05)	−0.000148* (8.35e-05)	−4.34e-05 (8.45e-05)	−0.000162 (0.000104)
Constant	−0.461 (0.605)	0.525 (0.843)	−0.657 (0.795)	−2.819*** (0.842)	−1.924** (0.754)	−1.944** (0.878)
Observations	4183	4183	4183	4183	4183	4183

Note Only coefficients are reported. The value of the coefficient can be also considered to be a predicted linear effect
Robust standard errors in parentheses
***$p < 0.01$, **$p < 0.05$, *$p < 0.10$

Table 8 Marginal effects with probit for pathologies and dimensions of energy poverty

Variables	Chronic diseases	Cardiovascular problems	Respiratory problems	Rheumatic problems	Headache problems	Psychological disease
Heating restriction	0.079*** (0.01769)	0.0085 (0.01013)	0.01481 (0.00956)	0.00627 (0.01141)	0. 0114 (0.0105)	0.248*** (0.0715)
Income (log)	−0.0325*** (0.0908)	9.44e-06 (0.00621)	−0.00365 (0.00478)	−0.01362* (0.0064)	0. 0036 (0.0050)	−0.113*** (0.0335)
Moisture problem	0.1161*** (0.02644)	0.0275 (0.01889)	0.0257 (0.0158)	0.0522** (0.02078)	0.0198 (0.01633)	0.0207* (0.0125)
Good roof insulation	−0.03577* (0.01897)	−0.0312*** (0.01209)	−0.0332*** (0.01121)	−0.01123 (0.01281)	−0.0185* (0.01126)	0.0009 (0.008)
Good wall insulation	−0.01374 (0.01913)	0.0100 (0.01179)	0.0083 (0.1073)	−0.02279* (0.01277)	0.0038 (0.0111)	−0.023*** (0.0842)
Other controls†	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.472 (0.591)	0.383 (0.797)	−0.109 (0.794)	−2.321*** (0.805)	−1.787** (0.756)	−0.745 (0.897)
Observations	4183	4183	4183	4051	4183	4183

Note The estimate of rheumatism-related problems has fewer observations (4051) because of non-responses. For the sake of clarity, the tables of results have not been reproduced here but they are available on request

Robust standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$

†Controls: Age, Number of children, Female, Lives alone, Retired, Student, Unemployed, Telecommuter, Height, Weight, Number of psychologists, Has a primary care doctor, Had COVID, Tenant, Helping role, Physical activity, Unified degree days

based on its physical characteristics. In its latest report in 2021, the Building Research Establishment concluded that poor housing conditions in England cost the country £1.4 billion each year to treat the affected population. Direct costs include the medical treatment of illnesses that are more prevalent in poor housing situations, and even more so in winter, and more frequent domestic accidents. Indirect costs cover a much wider spectrum, ranging from the persistence of certain pathologies over time to social costs. Moreover, the increase in the prevalence of certain pathologies and the frequency of accidents leads to work stoppages and school absenteeism, which in turn results in a loss of productivity and economic potential in the medium and long term. The total estimated societal cost reaches £ 18.5 billion each year.

By applying our results, it is possible to make a comparative analysis of the direct costs and benefits of a few measures for the French case. In France, there are 30 million primary residences in 2022 (homes, apartments) for 67 million people (Source: INSEE). The total health cost for chronic disease and psychological disease is EUR 104 billion and EUR 23.3 billion each year, respectively. If the roofs of all homes were renovated for example,[11] France could expect to save EUR 36.4 million

[11] The total cost of such a measure is equal to EUR 245 billion. This figure is the result of the following calculus: the average cost of roof renovation multiplied by dwellings with poor roof

related to chronic disease over a year (104 billion multiplied by −0.0325%, the coefficient in Table 8).

Humidity could be addressed by equipping all homes with mechanical ventilation, resulting in a potential savings of EUR 120 million in spending on chronic diseases alone (+0.1161% multiplied by 104 billion) for a total investment of EUR 58.5 billion.[12] It would also save EUR 4.82 million for mental health spending (+0.0207% % multiplied by 23.3 billion). A measure that would consist of increasing income by EUR 331, i.e., 10% of the average income (the energy subsidy to help the poorest households is at most equal to EUR 277), would lead to health-related savings (chronic diseases and mental health problems) of about EUR 60.1 million (+ 0.079% multiplied by 104 billion and +0.248% multiplied by 23.3 billion; see Table 8 for percentages). In the end, being energy poor increases the probability of developing a chronic disease by 0.458%, which could represent a cost of EUR 476 million (0.458% multiplied by EUR 104 billion; see Table 7 for percentages), and an additional cost for health pathologies of EUR 10.6 million (+0.464% multiplied by EUR 23.3 billion; see Table 7 for percentages). Restricting one's energy consumption would entail a total additional cost of about EUR 140 million (0.079% multiplied by 104 billion so 82.16 million plus 0.248% multiplied by EUR 23.3 billion so 57.7 million; see Table 8 for percentages). In addition to the results obtained in the study, a Eurofound study focusing on nine types of housing problems established that 2.5 million homes in France have low indoor temperatures, or 9.1% of all private housing. The Housing Health and Safety Rating System (HHRS) method was then employed to identify the health cost related to these cold temperatures. The average health cost associated with the cold would be EUR 726 per dwelling, but EUR 33 would be direct costs related to care. In other words, cold housing in France would cost EUR 1.85 billion per year for health care, of which EUR 84.7 million would be linked to direct spending. The health studies department of Electricité de France (EDF) has estimated that the health costs related to low temperatures in housing would be EUR 639 million (Ezratty et al. 2017).

6 Conclusions

The academic and institutional literature, and also the work of practitioners, has extensively explored the determinants of energy poverty and evaluated the various measures to combat the phenomenon. Other issues have emerged which are much broader than those related to the comfort within housing and the fight against social inequality. Indeed, the COVID-19 health crisis has significantly strengthened the belief that it is necessary to preserve global public goods such as public health.

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insulation, so EUR 20000 (*Source* Effy) × 0.409 × 30,000,000). The number of dwellings with poor roof insulation is deduced from descriptive statistics, i.e., Table 1.

[12] Cost of mechanical ventilation is EUR 4500 (*Souce*: Effy) multiplied by the share of dwellings with moisture, based on Table 1 for the total housing stock (0.566 × 30,000,000).

In recent years, considerable work on energy poverty has highlighted the multiple and indirect challenges of the fight against the phenomenon. While many ad hoc and local experiments have established clear links between poor housing and poor health, there is still little non-experimental work in the general population, to make it possible to highlight the causal effects of energy poverty on health, evaluated quantitatively, and objectively, or subjectively. Accordingly, we have used the World Health Organization mental health indicators, as well as the self-reported health ratings of respondents. The richness of our database also enables us to look at the impact on the incidence of certain pathologies in more detail.

The implementation of econometric models clearly confirms that falling into energy poverty significantly degrades objective and subjective health scores. Being in energy poverty thus reduces the WHO physical health score by 8.14 points. The negative and significant effect on the mental health indicator is 3.78 points. When individuals are in a situation of energy poverty, they also give themselves a lower health score on average: 3.37 points lower than the score reported by individuals who are not energy insecure.

In other words, these results show that at the national level, and not just at the level of a specific region, positive spillover effects can be expected from a reduction in energy poverty. Knowing the cost and index of chronic diseases in France, it appears that reducing energy poverty by 1% would save about EUR 476 million each year. Regarding mental disorders, this savings could rise to 10.6 million. It is therefore time to consider the environmental, social, and health issues of the fight against energy poverty simultaneously.

Appendix

Table A.1 First step—impact of variables and instruments on being energy poor

Variables	Physical health score
Age	−0.00733** (0.00292)
Number of children	−0.00475 (0.0250)
Female	−0.109 (0.0751)
Lives alone	−0.0289 (0.0716)

(continued)

Table A.1 (continued)

Variables	Physical health score
Retired	0.0753 (0.0985)
Student	−0.0947 (0.157)
Unemployed	0.389*** (0.0991)
Telecommuter	−0.136* (0.0713)
Height	−0.0187*** (0.00415)
Weight	−0.00101 (0.00197)
Number of psychologists	−0.0342** (0.0138)
Has a primary care doctor	−0.318*** (0.0845)
Had COVID	0.114 (0.120)
Tenant	0.251*** (0.0588)
Helping role	0.124 (0.0845)
Physical activity	−0.106 (0.0664)
Unified degree days	−1.48e-05 (8.99e-05)
Cooking with electricity	−0.131** (0.0536)
Altitude	0.000222* (0.000114)
Recipient of energy subsidy	0.862*** (0.0674)
Constant	2.724*** (0.746)
Observations	4,183

Source Authors' elaborations PEPSI
Note Robust standard errors in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Table A.2 Tests of endogeneity and instrument validity

	2SLS—EIR 3D 8 (binary variable)		2SLS—Energy-income ratio (continuous variable)	
	Statistics	*p*-value	Statistics	*p*-value
Test for endogeneity				
Robust score χ^2 (1)	24.5514	0.0000	27.107	0.0000
Robust regression F(1,4179)	25.4526	0.0000	27.9114	0.0000
Test of instrument validity				
F(3,4162)	44.80	0.0000	28.91	0.0000
Kleibergen-Paap rk LM statistic	118.209	0.0000	81.442	0.0000
Stock-Yogo				
5% maximal IV relative bias	44.798	–	28.907	–
10% maximal IV relative bias	13.91	–	13.91	–
20% maximal IV relative bias	9.08	–	9.08	–
30% maximal IV relative bias	6.46	–	6.46	–
10% maximal IV size	5.39	–	5.39	–
15% maximal IV size	22.30	–	22.30	–
20% maximal IV size	12.83	–	12.83	–
25% maximal IV size	7.8	–	7.8	–
Overidentification tests				
Hansen J Statistic	3.444	0.1787	1.598	0.4497

Source Authors' elaborations PEPSI

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Vulnerability to Motor Fuel Price Increases: Socio-Spatial Patterns in Italy

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1 Introduction

Energy poverty is increasingly recognised as an important research topic (Bouzarovski and Petrova 2015) and as an area of policymaking in the European Union (EPOV 2020). Yet, the notion of energy poverty remains overwhelmingly focussed on energy consumption within the home, while similar issues related to transport energy have been overlooked. In a policy context where the energy- and low-carbon transition is a priority, the exclusion of transport from the energy poverty debate can hardly be sustained.

A number of metrics show that transport energy consumption is as much, if not more relevant than energy consumption within the home. In 2020, transport accounted for 11.6% of household expenditure in the EU-27, second only to housing and food (Eurostat 2021), and down from the even higher levels observed prior to the COVID-19 pandemic. The average share of expenditure on the 'operation of personal transport equipment' (mostly cars) was higher than that on 'electricity, gas and other fuels' within the home in the EU-27 (6.5% vs. 4.3%) as well as in 22 member states. In 2020, transport (both passenger and freight) accounted for 28.4% of final energy consumption in the EU-28, as compared to 28.0% for households (Eurostat 2022a), with the vast majority of transport energy coming from oil and petroleum products

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(EEA 2019a). 61.5% of EU oil consumption in 2020 was for transport, with electricity accounting for just 0.1% of fuel used in road transport. In 2019, the transport sector accounted for 25.8% of greenhouse gas emissions in the EU, the same share as fuel consumption by energy users for other purposes (Eurostat 2022c). Persistent reliance on fossil fuels and growing levels of travel activity, notably by car, explain why EU greenhouse gas emissions in the transport sector have increased by +19% between 1990 and 2018, in contrast with other sectors where they have declined (e.g. −22% in the residential and commercial sector) (EEA 2019b). In Europe and beyond, transport is thus the sector where effective climate policy is most urgently needed (Creutzig et al. 2015; Lamb et al. 2021).

Current EU policy aims at achieving decarbonisation through carbon pricing, which would encourage both energy efficiency and a shift from high- to low-carbon modes of energy consumption. In the transport sector, the European Commission has proposed the extension of the Emissions Trading System to road fuels from 2026 (EC 2021), which is expected to result in higher fuel prices at the pump for internal combustion engine vehicles. More broadly, the increase of taxes on (and removal of subsidies to) road fuel is considered a key climate policy measure globally (Ross et al. 2017).

Yet, transport systems in much of the EU are ‘car dependent’, as access to and the ability to use car-based travel is often essential for accessing services and opportunities and achieving social inclusion (Mattioli 2016, 2021). Despite a recent boom in electric vehicle (EV) sales, and EU plans to phase out combustion engine vehicles by 2035, the vast majority of cars on European roads still run on petrol or diesel (95.2% in 2019, see ACEA 2021). This will continue to be the case for many years, as vehicle fleet turnover is slow.

The affordability of road fuel thus looms large in the public and political debate. This is most apparent when fuel tax increases trigger mass protests or disruptions, as in the UK in 2000 (Lyons and Chatterjee 2002) or in France in 2018 with the ‘Yellow Vest’ movement (Mehleb et al. 2021). In the aftermath of Russia’s invasion of Ukraine and the resulting fuel price spike in 2022, most EU governments substantially cut fuel taxes to ensure the ongoing affordability of car use, despite the negative geopolitical implications of doing so (Gars et al. 2022; Transport and Environment 2022a). Concerns about the social and distributional impact of making car use more expensive (whether genuine or feigned) are also often raised by opponents of carbon pricing (Maestre-Andrés et al. 2019; Lamb et al. 2020). This helps explain why governments struggle to introduce CO_2 pricing in the transport sector, despite the pressing need to reduce transport emissions.

The paradox here is that, while concerns about vulnerability to motor fuel price increases are widespread and consequential, the ‘transport equivalent of energy poverty’ is overlooked by energy research and has not coalesced into its own area of policymaking. This is now starting to change, with researchers calling for a broader understanding of energy poverty that includes transport (e.g. Martiskainen et al. 2021; Mattioli et al. 2017; OpenExp 2019), and the EU considering the adoption of an official definition of ‘transport poverty’ (Taylor 2022). To date, however (to the best of our knowledge), no EU country except France (Cochez et al. 2015; ONPE

2014) officially recognises transport as a dimension of energy poverty. This results in a dearth of definitions and indicators, so that in practice we know little about how many people are vulnerable to fuel price increases, who they are and where they live.

Spatial patterns in the distribution of vulnerability to fuel price increases are of particular interest, as the use of and reliance on cars differs dramatically between urban, periurban and rural areas, as do income levels and political leanings (Mattioli and Colleoni 2016; Walks 2015). In the public and political debate, the strong impact of fuel price spikes on the residents of car-dependent (and sometimes less affluent) peripheral areas is often contrasted with that on the generally more environmentally minded urban population. And yet, these discussions are rarely grounded in sound analysis of vulnerability to fuel price increases and its various dimensions. There is a need for a more rigorous empirical basis to inform and raise the level of these debates.

In this chapter, we present findings on spatial patterns of vulnerability to fuel price increases in Italy, a country where the problem is likely to be particularly pronounced due to high motorisation rate relative to income, as well as high fuel prices. In doing this, we have two goals. First, to provide an illustration of how a composite spatial indicator of vulnerability to fuel price increases can be built based on data from official sources. Second, we explore the spatial relationship between the different factors underlying vulnerability to fuel price increases in Italy, and contrast the findings with previous research from other countries.

The chapter is structured as follows. We start by reviewing the literature on the affordability of car use and vulnerability to fuel price increases, discussing the concepts, empirical indicators and patterns of spatial variability identified in the literature to date (Sect. 2). We then provide information on the case study country with regard to factors that might influence vulnerability. In Sect. 4, we explain our methodological approach to building the composite spatial indicator, and then present the empirical findings in Sect. 5. We conclude by contrasting our findings with previous research and discussing implications for future research and policy-making (Sect. 6).

2 Literature Review

2.1 Affordability of Car Use and Vulnerability to Fuel Price Increases: Concepts and Indicators

Transport research has long recognised that low-income households who own and use cars can end up spending disproportionate amounts on motoring. This can lead them to curtail travel to save on running expenses, and/or to cut expenditure in other areas (e.g. domestic heating), all of which can reduce social inclusion and well-being (Froud et al. 2002; Lucas 2011).In the literature, various terms are used to point to this problem, including 'forced car ownership' (Banister 1994; Carroll et al.

2021; Curl et al. 2018; Currie and Senbergs 2007; Jones 1987; Mattioli 2017), 'car-related economic stress' (Belton-Chevallier et al. 2018; Mattioli et al. 2018; Mattioli and Colleoni 2016; Rock et al. 2016), 'transport energy precarity' (Cochez et al. 2015; Jouffe and De Massot 2013) and 'transport energy poverty' (OpenExp 2019; Robinson and Mattioli 2020). What these notions have in common is that they present the problem as a 'static state'. Other concepts such as 'oil vulnerability' (Dodson and Sipe 2007; Leung et al. 2018; Lovelace and Phillips 2014; Rendall et al. 2014; Runting et al. 2011), 'transportation energy vulnerability' (Liu and Kontou 2022) and 'vulnerability to fuel price increases' (Mattioli et al. 2019) emphasise the dynamic aspect of the problem, highlighting which people and places would be more likely to experience hardship if the costs of motoring were to increase.

Our contribution in this chapter fits into the second strand of the literature, i.e. we adopt a vulnerability perspective. However, all indicators of the affordability of car use can inform a discussion of vulnerability to fuel price increases and, more broadly, of energy poverty in the transport sector. In the European literature, several quantitative indicators have been proposed to assess the affordability of car use. They can be classed into three categories, as illustrated in Table 1:

(i) adaptations of domestic energy poverty indicators for use in the transport sector; these are typically based on a ratio between expenditure and household income (or total household expenditure as a proxy for income), based, e.g. on household budget survey data
(ii) 'forced car ownership' indicators typically identify households who own cars despite being in deprivation, which it is assumed might lead to affordability problems;
(iii) composite indicators capture the multidimensional nature of the phenomenon; this group includes indicators of vulnerability to fuel price increases, where vulnerability is often conceptualised as the product of exposure, sensitivity and adaptive capacity (as discussed).

One can also distinguish whether the indicators are based on survey, census or modelled data (or combinations thereof); and whether the unit of analysis is households/individuals and/or spatial units. Considering all these aspects gives the complex picture illustrated in Table 1.

While many of the affordability indicators proposed in Europe (Table 1) consider the costs of car use only (e.g. Berry et al. 2016; Cochez et al. 2015; Mattioli et al. 2018), others include expenditure on public transport as well[1] (e.g. Nicolas et al. 2012; Lovelace and Philips 2014; Verry et al. 2017). In practice, however, car use tends to account for most transport-related expenditure in high-income countries, both in the aggregate and for most households (Kauppila 2011). Studies on vulnerability to fuel price increases typically focus on the direct impact on the cost of car use.

[1] Despite their name, most indicators of 'forced car ownership' in the international literature do not consider the availability of public transport, although there are exceptions (BMVBS 2012; Carroll et al., 2021). To the best of our knowledge, no indicator of 'forced car ownership' in the literature considers the cost or affordability of public transport.

Table 1 Overview of indicators of the affordability of car use in the European context

		Unit of analysis		
		Household/ individual	Sub-national spatial unit	Country
Type of indicator	**Adaptation of (domestic) energy poverty indicators**	• Nicolas et al. (2012) [*] • Lovelace & Philips (2014) [*# +] • Cochez et al. 2015 [*# +] • Berry et al. (2016) [*] • Verry et al. (2017) [*] • Mattioli et al. (2018) [*] • Madre and Bussière (2020) [*]	• Nicolas et al. (2012) [*] • Lovelace & Philips (2014) [*# +] • Cochez et al. 2015 [*# +]	
	'Forced car ownership' indicators	• BMVBS (2012) [*] • Mattioli (2017) [*] • Curl et al. (2018) [*]	• Carroll et al. (2021) [# +]	
	Composite indicators	• Berry (2018) [*]	• Sustrans (2012) [# +] • Büttner et al. (2013) [# +] • Mattioli et al. (2019) [# +]	• OpenExp (2019) [*]

Legend * Survey data; # Modelled data; + Census data

While fuel price rises have an indirect impact on the costs of some public transport modes like buses, this is more indirect and of smaller magnitude, as labour costs account for a large share of final costs.

As shown in Table 1, most household-level studies use adaptations of indicators of domestic energy poverty. Studies focussed on spatial units (e.g. municipalities or census units) often use composite indicators. The first studies in this vein were conducted in Australia and used the concept of 'oil vulnerability' (Dodson and Sipe 2007; Runting et al. 2011), which is essentially equivalent to vulnerability to fuel price increases. As argued by Leung et al. (2018) and Mattioli et al. (2019), most of these indicators conceptualise vulnerability as being constituted by three components: exposure, sensitivity and adaptive capacity (see Adger 2006). This is illustrated in Table 2, along with examples of indicators for the sub-dimensions from the literature.

In a nutshell, spatial indicators of vulnerability to fuel price increases identify as most vulnerable areas characterised by high levels of car use (high exposure),

Table 2 The three dimensions of vulnerability to fuel price increases: definitions and examples of indicators

	*General definition (*Adger, 2006*, p. 270)*	*Specific definition (for fuel price increases)*	*Examples of indicators*
Exposure	'The nature and degree to which a system experiences (…) stress'	Exposure to fuel price increases is proportional to expenditure on fuel and (more indirectly) to car use	• estimated average share of income spent on motor fuel (Liu and Kontou 2022; Mattioli et al. 2019) • share of households with two or more vehicles + car modal share for commuting (Dodson and Sipe, 2007)
Sensitivity	'The degree to which a system is modified or affected by perturbations'	Sensitivity to fuel price increases is inversely related to the economic resources available to accommodate the increased expenditure without having to change travel patterns	• median income (Mattioli et al. 2019; Rendall et al. 2014) • unemployment rate (Büttner et al. 2013)
Adaptive capacity	'The ability of a system to evolve in order to accommodate (stress) and to expand the range of variability with which it can cope'	Adaptive capacity to fuel price increases is inversely related to the availability and viability of modes alternative to the car. Switching to alternative modes would allow reducing expenditure while maintaining travel and activity patterns. Car-dependent areas have low adaptive capacity to fuel price increases	• estimated time required to access essential services by public transport or walking (Mattioli et al. 2019) • access to public transport + active travel mode share for commuting (Leung et al. 2018)

low economic resources (high sensitivity) and with reduced opportunities to shift from car use to other modes (low adaptive capacity). In practice, however, the adaptive capacity dimension is not always taken into consideration, whether due to data availability limitations or to the assumption that it correlates strongly with exposure—i.e. those areas with high levels of car use are also characterised by high levels of *car dependence* (low availability and viability of alternative transport modes).

For a review of indicators of exposure, sensitivity and adaptive capacity used in the literature see Leung et al. (2018) and Mattioli et al. (2019).

2.2 *Spatial Patterns of Vulnerability to Fuel Price Increases*

Most studies on the affordability of car use find that the problem is worse in peripheral, periurban and rural areas as compared to city cores (e.g. Cochez et al. 2015; Liu and Kontou 2022; Lovelace and Philips 2014; Mattioli and Colleoni 2016; Nicolas et al. 2012; Simcock et al. 2021; Verry et al. 2017). This is mainly due to higher levels of car use and car dependence. From a vulnerability perspective, this means greater exposure and less adaptive capacity to fuel price increases. However, some studies show that low-income households can be reliant on and reluctant to do without cars even in large cities, which results in economic stress (e.g. Curl et al. 2018).

This pattern is compounded when suburban and periurban areas are less affluent than city cores, which makes residents less able to afford the costs of car use. From a vulnerability perspective, this means that greater sensitivity to fuel price increases adds on to greater exposure and lower adaptive capacity, in a 'triple whammy' of sorts. Research has found this to be the case in several constituencies including Australian cities (Dodson and Sipe 2007; Runting et al. 2011) and the Munich city region in Germany (Büttner et al. 2013).

However, the opposite pattern has been observed as well, i.e. when the periphery is more affluent than the core of the metropolitan area. That is the case, e.g. in New Zealand (Rendall et al. 2014), in Lyon, France (Büttner et al. 2013) and in most of England (Mattioli et al. 2019). From the perspective of vulnerability to fuel price increases, this means that city cores tend to compensate higher sensitivity with less exposure and better adaptive capacity. Conversely, in periurban areas higher income (i.e. low sensitivity) can protect residents from the worst consequences of fuel price increases even if car use is high (i.e. high exposure) and there are little modal alternatives to the car (i.e. low adaptive capacity). These counteracting effects explain for example why household-level studies in the UK have found an even incidence of 'car-related economic stress' and 'forced car ownership' across the urban–rural spectrum (Mattioli 2017; Mattioli et al. 2018).

From this perspective, the trend towards the gentrification of city cores and the 'suburbanisation of poverty' is to be regarded critically, as it leads less affluent groups to find affordable housing in the car-dependent areas. This exacerbates problems of transport affordability and vulnerability to fuel price increases (Allen and Farber 2021; Coulombel 2018; Currie and Delbosc 2011; Dodson and Sipe 2007; Mullen et al. 2020; Polacchini and Orfeuil 1999; Sterzer 2017).

Most spatial studies on vulnerability to fuel price increases look at differences within metropolitan areas, and as such are unable to compare different regions to each other. Interregional differences can be important though, especially in countries with regional divides in terms of economic development. A recent study in England (Mattioli et al. 2019), e.g. found that metropolitan areas in the North are more vulnerable to fuel price increases than London and the South-East, on account of both lower levels of income and worse public transport provision. The study also highlights the complex interplay of vulnerability dimensions at multiple spatial scales: adaptive capacity and sensitivity tend to compensate each other within English metropolitan areas (as car-dependent periurban areas tend to be more affluent) but they compound each other at the interregional scale (as poorer regions also have worse public transport provision).

3 Case Study

Our study focusses on Italy. This is a country for which little evidence of vulnerability to fuel price increases exists, even though it is likely to be particularly vulnerable. While there is a moderate correlation between income and motorisation rate for EU regions (Pearson's R = +0.44), most Italian regions have higher motorisation rates than one would expect based on income alone[2] (Fig. 1). This suggests that many households in Italy own and operate vehicles despite low income, which may lead to affordability problems. In other words, Italian regions are characterised by a combination of relatively high exposure and relatively high sensitivity to fuel price increases in European comparison.

Until the 2022 war in Ukraine, Italy had some of the highest petrol and diesel prices in the EU, partly due to high taxes (Fuels Europe 2021). This reduces the affordability of motor fuel, even though the high share of taxation in the end consumer price might also cushion the impact of global oil price fluctuations and of additional environmental taxes (as the final price is less sensitive to these changes in relative terms).

Kokoufikis and Uihlein (2022) find that Italy had the second-highest average share of household expenditure on transport fuels of all EU countries in 2015 (4% in densely populated areas, and over 6% in sparsely populated areas). The average share of household expenditure on personal transport was particularly high for working households and for couples (over 6%). In 2018, Italy was third in the EU-28 for the share of transport energy expenditures out of total expenditures of the first income quintile of the population (5.2%) and was ranked seventh-worst performer for its overall performance in alleviating transport energy poverty (OpenExp 2019). Recent modelling work finds that, in a scenario where oil prices double, Italy would be one of the most impacted EU countries in terms of average additional household expenditure (nearly +10%, and over +20% for the 5% of households that are most

[2] Three Italian NUTS2 regions (Valle d'Aosta and the autonomous provinces of Trento and Bolzano/Bozen) are outliers in Fig. 1, with motorisation rates near or more than 1,000 vehicles per 1,000 inhabitants. This is likely due to the lower rate of vehicle registration tax there, which leads to a high number of company cars and hired cars registrations, even though these are then used in the rest of the country (Ghezzi 2012). Given the small population size of the three regions, this skews the motorisation rate. Incidentally, this implies that the motorisation rate in other Italian regions is slightly underestimated.

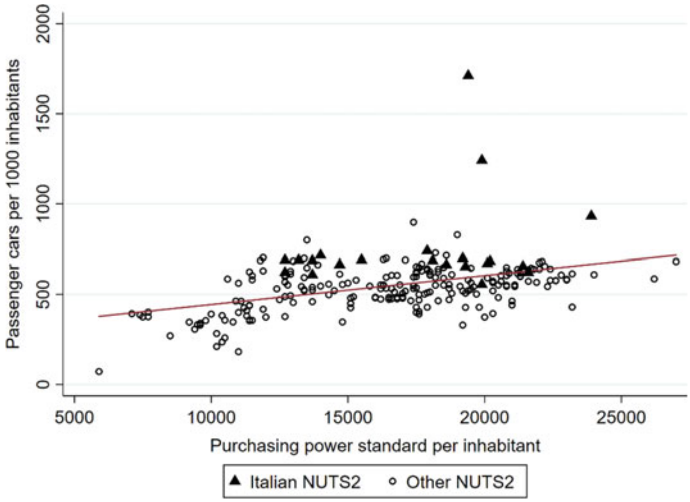

Fig. 1 Relationship between motorisation rate and income of households for EU regions (NUTS2) in 2019, with line of fit. *Source* Authors on Eurostat data (Eurostat 2022d, 2022e)

affected) (Steckel et al. 2022). The Italian parliament estimated that between June 2021 and September 2022, the spike in energy and other prices increased average household expenditure by +3.7%, even when mitigation measures are taken into account (Ufficio Parlamentare di Bilancio 2022). Even though there is no official definition or indicator of transport energy poverty in Italy at present, the second report of the Italian Energy Poverty Observatory recognises transport as an important dimension (Faiella et al. 2020).

Italy is characterised by profound spatial inequalities, which are likely to have a bearing on the geography of vulnerability to fuel price increases. The country is well-known for the strong and long-standing North–South divide, with the latter being worse off in economic, infrastructural, and socio-institutional terms (Felice 2018). The typical 'urban socio-spatial configuration' of Italian cities is a concentric one, with the core being richer than the periphery, although this pattern is less clear in the South (Kesteloot 2005).

4 Methods

We propose a composite indicator of vulnerability to fuel price increases for Italian municipalities that includes four variables covering two dimensions: exposure and sensitivity. Ideally, the composite indicator should cover adaptive capacity as well. However, information on the availability of transport modes alternative to the car is available for only a few Italian municipalities.

We measure *exposure* with indicators of car ownership and use. We draw this information from the 2011 Census of population and housing (ISTAT 2011), which asks respondents about the number of household cars, as well as the destination and main travel mode (in terms of distance) of the journey to work or education for those who habitually make such trip. This information is made available for Italian municipalities, but not for more disaggregate spatial units. We derive three variables: (i) the percentage of households owning at least one car; (ii) the share of workers or students who regularly travel to work or education who use a private car (either as driver or passenger) for that trip; (iii) an estimate of the average distance of commuting from home to the place of work or study by car.

We derive the last variable from an origin/destination matrix reporting commuting flows between Italian municipalities by travel mode, derived from the Census. We distinguish between two types of commuting trips: external journeys, where people move between two different municipalities, and internal journeys, where people commute within the same municipality. For the first type, the distances by car between each pair of municipalities were calculated in kilometres considering the two centroids and a road graph.[3] For the second type, two random points (origin/destination) for each internal movement were randomly defined within each municipality, which is an approach adopted by previous research (e.g. Lovelace et al. 2022). Then, the distance between these pairs of points was used for determining an estimate of the length of internal journeys. The sum of travel distance for internal and external trips for each municipality was divided by the number of commuters to calculate the average commuting distance by car.

Both journey-to-work variables were adjusted to address the skewness of their distribution and mitigate the effect of extreme outliers. First, a logarithmic transformation was applied. Second, the minimum values of each variable plus a constant equal to 0.001 were added to the obtained values in order to avoid the presence of negative and null values without altering the distribution of the transformed variables. All three variables were then further normalised using a z-score transformation to allow their comparability (calculated by subtracting the mean from the original value and then dividing by the standard deviation) and aggregated using their arithmetic mean. The resulting indicator is considered a measure of exposure.

The indicator of exposure covers 7,876 Italian municipalities (about 98% of the municipalities in 2011). The remaining municipalities were excluded for two main reasons. Firstly, it was impossible to reasonably estimate commuting distance in two types of municipalities: border areas and islands. In some municipalities bordering other countries (namely, Switzerland, France and San Marino) a large share of the population works abroad and crosses the border daily. However, the Census does not collect precise information on the place of work when this is abroad, thus making the estimation of travel distance impossible. Therefore, we excluded those municipalities with a share of cross-border commuters on the total number workers or students that is higher than the national average plus one standard deviation. Municipalities

[3] Distances greater than 150 km were considered as occasional business trips and, consequently, excluded from the analysis as unreasonable for proxying regular commuting journeys.

located on small islands were excluded as a large share of the population commutes to the mainland, and the journey by sea does not allow for a precise estimate of car distance. Secondly, we had to merge some small municipalities in order to match the Census data with the IRPEF income data, which takes into account the fusion of some contiguous municipalities happened after 2011 that established new administrative divisions.

To measure *sensitivity* to fuel price increases we use estimates of average per capita income at the municipal level drawn from the Italian Ministry of Economy and Finance (2012) data on the personal income tax (IRPEF) of individuals for the year 2012 (referring to 2011 income). The variable is normalised using a z-score and then multiplied by -1 so that higher values of this indicator (i.e. lower average incomes) correspond to higher degrees of sensitivity. Figure 2 (in Sect. 5) shows the distribution of the four transformed variables in the Italian municipalities.

The final score of the composite indicator of vulnerability is given by the combination of the obtained exposure and sensitivity indicators. Two alternative versions of the composite indicator were calculated. In the first one, exposure and sensitivity indicators were weighted equally assuming that both have the same relevance for vulnerability to fuel price increases. In the second one, a double weight was attributed to the exposure component. This version of the indicator assumes that actual levels of car use for commuting can also be used as a proxy of how car dependent the municipality is, capturing to some extent the adaptive capacity dimension that we are unable to assess directly. Previous research provides two justifications for this. First, there is evidence that indicators of exposure and adaptive capacity are typically more correlated to each other than to sensitivity indicators (Mattioli et al. 2019). Also, it is not uncommon for studies on vulnerability to fuel price increases to use measures of actual travel behaviour as indicators of adaptive capacity (e.g. Lovelace and Philips, 2014; Leung et al. 2018) or to merge the exposure and adaptive capacity dimensions into one (e.g., Akbari and Habib 2014; Dodson and Sipe 2007). In practice, most composite indicators of vulnerability assign a weight ranging from 50% (e.g. Dodson and Sipe 2007; Akbari and Habib 2014; Runting et al. 2011) to 66% (Büttner et al. 2013; Leung et al. 2018; Mattioli et al. 2019) to variables measuring car ownership, car use and car dependence, with the remaining 33% to 50% weight assigned to socio-economic variables such as income. Our approach in this study is consistent with this practice, while also allowing us to explore the robustness of the findings to different weighting schemes.

To ease interpretation, both versions of the composite indicator were indexed to their maximum values. The municipality with the highest value received a score of 1,000 and all the other values were rescaled accordingly. In simple terms, our composite indicator identifies as vulnerable to fuel price increases municipalities characterised by low income, high car ownership, high car mode share for the journey to work or education, and high average distance of commuting trips by car.

The methodology used for normalising and aggregating the single variables can affect the final composite indicator (Greco et al. 2019). Liu & Kontou (2022) demonstrate how this can affect metrics of vulnerability to fuel price increases. Therefore, this study adopts a strategy to evaluate the impacts of the chosen approach against

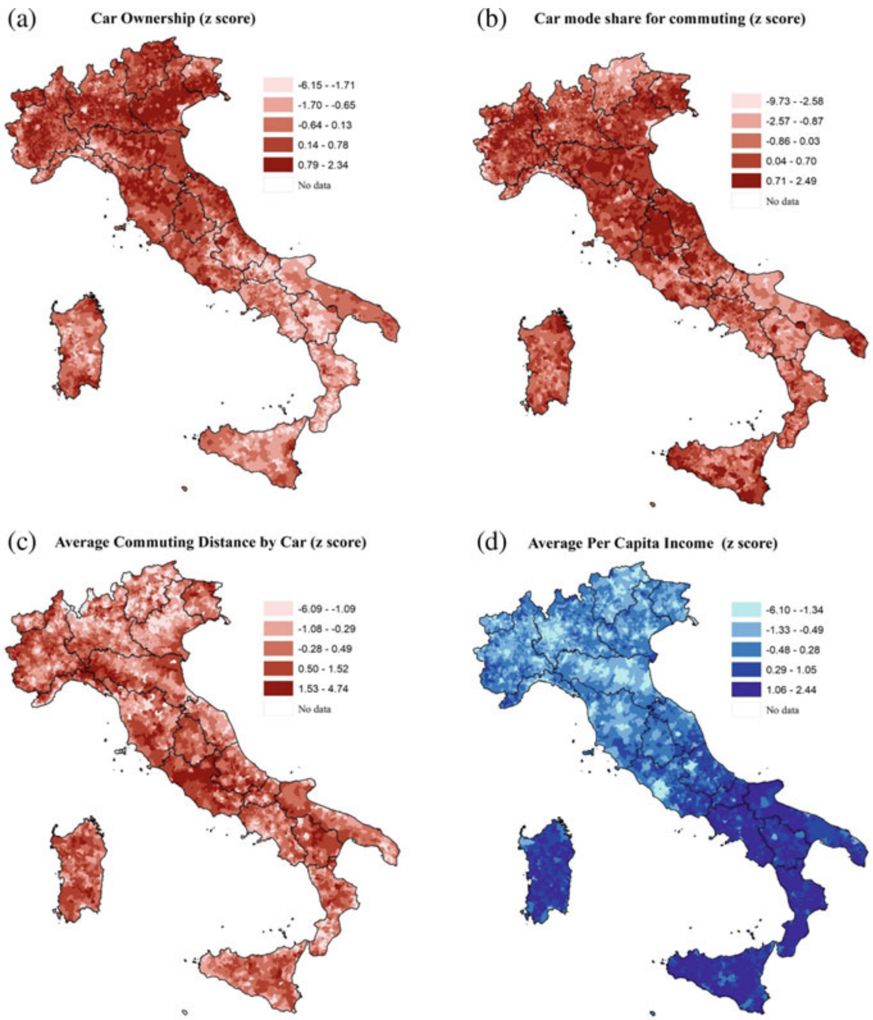

Fig. 2 Variables included in the composite indicator (in red the exposure dimension and in blue the sensitivity dimension; darker shading indicates values associated with higher vulnerability to fuel price increases). *Note* that the values in panel D were multiplied by -1, so that higher values indicate *lower* income (which is associated with higher vulnerability)

alternative ones, i.e. the robustness of our findings to alternative methodological choices. Specifically, we compared the results of the composite indicator obtained by using z-scores as a normalisation approach and arithmetic mean as aggregation methods to the results based on other normalisation (i.e. indexing, ranking or min–max transformation) or aggregation (i.e. geometric mean) techniques (Dugato et al.

2014; Saisana et al. 2005). These alternatives are applied to either the calculation of the exposure sub-indicator and of the final composite indicator.[4]

Overall, our indicator has some limitations that must be considered when interpreting the results. First, we lack a direct indicator of adaptive capacity. Second, the ideal measure of exposure would be an estimate of household expenditure on fuel for all travel purposes (see e.g. Liu and Kontou 2022; Mattioli et al. 2019). Since such information is not available for Italian municipalities, we use indicators that refer to car ownership and car use for commuting. While this is a common approach (e.g. Leung et al. 2018; Dodson and Sipe 2007; Lovelace and Philips 2014; Runting et al. 2011) one must keep in mind that travel to work and education accounts for only a low share of trips—i.e. 32–36% in Italy (ISFORT 2021). Third, we estimate car travel distance for commuting based on data on the municipality of origin and destination, using centroids and random points. Although common, this method could lead to biased values, particularly for municipalities with a large area. Fourth, our spatial unit of analysis is the municipality, which is relatively coarse and varies widely in terms of population size in Italy (from a few dozen inhabitants to more than 2,5 million in Rome). A study using smaller and more consistent spatial units such as census tracts would better capture patterns of vulnerability within metropolitan areas, and especially within large municipalities. These limitations notwithstanding, our study illustrates how a composite indicator of vulnerability can be derived even in countries where data availability is less than ideal. Finally, while we use the most recent data available, these are already more than ten years old. While it is possible that the situation has changed since then, we believe that our indicator captures structural features of the geography of vulnerability to fuel price increases in Italy. These are relevant for current debates, and our methodological approach can be used to update the analysis as soon as more recent data is made available.

In the next section, we present the findings using univariate and bivariate choropleth maps as well as hotspot maps and crosstabulations. While most of our analysis focusses on the entire Italian territory, we also show spatial patterns of vulnerability within two of the largest Italian metropolitan areas (Milan and Naples). A focus on metropolitan areas is in line with previous research on this topic, and can potentially inform policy-making at the local and regional level, which is where many transport policy decisions are made.

[4] This procedure results in 15 alternative indicators in addition to the primary one. Then, the results of the chosen approach are compared with the median values of all the other possible combinations. The average variations in the ranks of the municipalities between these two values show the extent to which the chosen methodology affected the final result of the composite indicator (Dugato et al. 2020). Smaller variations indicate a lower influence of the methodology on the final ranking. The results of the robustness tests support the relative stability of the composite indicator. The median difference between the rank position of each municipality in the primary indicator and the median position of the same municipality considering all the other alternative methods is 137 positions for version one and 325 positions for version two. These figures indicate that the version one indicator is relatively less sensitive to methodological variations. However, both values are relatively low considering the 7,876 possible positions in the rank.

5 Results

To properly interpret the composite indicator of vulnerability, it is essential to first consider the spatial distribution of the constituent variables (Fig. 2). These show that exposure and sensitivity to fuel price increases have rather different spatial patterns in Italy.

Regarding car ownership (Fig. 2, panel A), we find a clear North–South divide, with higher shares of households with cars in the North, likely due to greater affluence. Major cities stand out from their surrounding areas as they have lower levels of car ownership, particularly in the North (e.g. Milan, Turin, Genoa, Bologna, Venice, Florence and Bolzano). This pattern is less clear in the Central and Southern part of the country, although it can be observed in the metropolitan area of Naples. The highest shares of households with cars are observed in periurban areas in the Po Valley, as well in Tuscany and in some (but not all) alpine regions. The lowest levels of car ownership are mostly in inner areas in the South, particularly along the Apennine Mountain range.

The second indicator of exposure, i.e. car mode share for commuting, shows a rather similar spatial pattern, with some differences (Fig. 2, panel B). South Tyrol has some of the lowest car mode shares in the North, despite high levels of car ownership. Besides periurban areas in the Po Valley, some of the highest levels of car use are observed in the central regions of Marche, Umbria and Lazio. There are also some areas with very high car mode share in the Southern region of Apulia and in the island of Sicily. Overall, the North–South divide is slightly less pronounced for car use than for car ownership.

Average commuting distance by car shows a more complex geography (Fig. 2, panel C). The longest estimated commuting distances by car are found in inner, mountainous and sparsely populated areas, as well as in the Lazio region around Rome. Distances are relatively low in most of the densely populated Po Valley in the North, despite the high levels of car ownership and use there.

The income indicator (Fig. 2, panel D) shows the well-known divide between North and South of the country. Note also how large cities and their immediate surroundings stand out as richer than periurban areas in the North, in Tuscany and in and around Rome, while this pattern is much less clear in the South. This is consistent with what is known from urban research (Kesteloot 2005).

Figure 3 shows the two versions of the composite indicator of vulnerability according to the alternative weighting procedures. The results are consistent and highly correlated (Pearson's $R = +0.87$). The Central and Southern regions of the country concentrate most of the highly vulnerable areas. This is mostly due to the influence of the sensitivity dimension, as these regions are traditionally poorer and less economically developed (as shown in Fig. 2, panel D). Further, the indicators show how large cities are usually less exposed than other minor municipalities. In this case, the reason is likely to be due to the lower exposure of urban populations versus rural or suburban ones who rely more on car use. These considerations are confirmed by observing the variations between the two versions of the indicator.

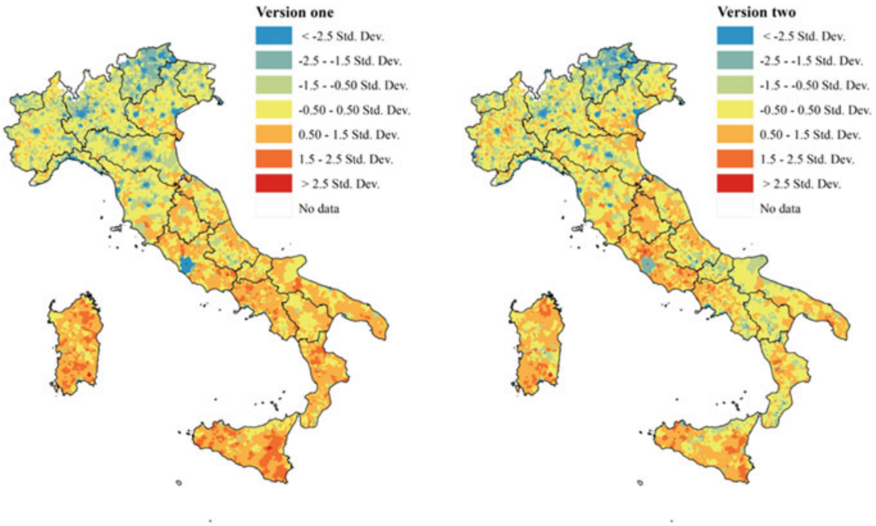

Fig. 3 Two versions of the composite indicator of vulnerability to fuel prices. Version one (left) with equal weights between the two dimensions and version two (right) with a double weight for the exposure dimension

Giving more importance in the final indicator to car ownership and use (exposure dimension) reduces the macro-regional differences and highlights the urban–rural divide.

In both versions of the composite indicator, large cities in the North and parts of the Centre stand out as less vulnerable than their surrounding areas. This is because exposure and sensitivity tend to compound each other: large city residents are both less exposed (i.e. they own and use cars less) and less sensitive (i.e. they have higher incomes) than the residents of the surrounding region. This pattern is particularly pronounced in Rome and is still visible in Naples, but much less so in the rest of the South.

Overall, the first version of the indicator suggests that most of the South of Italy is rather vulnerable to fuel price increases, with some scatters of very high vulnerability in, e.g. the Eastern part of Sicily and the inner part of Sardinia. Version two shows a similar pattern but highlights more vulnerable areas in the Centre (particularly around Rome and in Umbria), as well as in some periurban and low-density areas in the Po Valley. Interestingly, in both versions the Trentino-South-Tyrol region stands out as the least vulnerable, due to a combination of high income and low car use for commuting, despite very high car ownership.

To better understand the drivers of vulnerability and what can be done about them, it is important to consider the influence of the two dimensions on the final indicator. Figure 4 shows a scatterplot and a bivariate map that categorise Italian municipalities into four clusters according to the joint distribution of the exposure and sensitivity indicators. The map shows a clear opposition between most of the South,

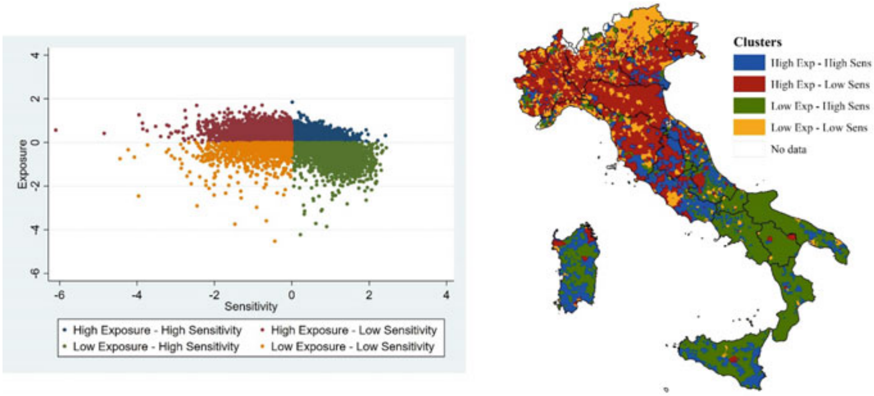

Fig. 4 Classification of Italian municipalities according to exposure and sensitivity to fuel price increases

where higher-than-average sensitivity is compensated to some extent by lower-than-average exposure (green areas), and much of the Centre-North, where high exposure is compensated by low sensitivity (red areas). This is consistent with the scatterplot, showing a moderate inverse relationship between exposure and sensitivity at the national level (Pearson's $R = -0.42$).

The most critical municipalities (depicted in blue) record values higher than the national mean for both dimensions. They are a minority and largely located in rural areas, mainly in the Centre of the country and in the two main islands (Sardinia and Sicily). There are however small clusters of this type of municipalities scattered throughout the whole country (e.g. in the Southern part of Veneto and in Apulia). The least vulnerable areas combine low values for both exposure and sensitivity and are depicted in orange. They are concentrated in cities or large metropolitan areas in the Centre and North of the country. Most of the Trentino-South-Tyrol region falls into this category.

The results of the bi-dimensional analysis are further confirmed by observing that 46% of the municipalities in Central regions have high levels of both exposure and sensitivity. This percentage is significantly higher than for the other Italian macro-areas, except Islands (30%), and much higher than the national average (17%) (Table 3). Just 16% of municipalities in the South combine high exposure and high sensitivity, demonstrating that high values for the composite indicator of vulnerability in these regions are driven largely by economic deprivation.

When looking at municipality size (Table 4), the results confirm that large cities are less likely to experience serious vulnerability to fuel price increases. Municipalities larger than 10,000 inhabitants (accounting for 68.9% of the population in 2011) are disproportionately more represented in the lower quartile of the distribution of the vulnerability indicator, as well as in the cluster combining low exposure and low sensitivity. Smaller municipalities, on the other hand, are more vulnerable to fuel price increases, particularly in terms of exposure. Municipalities with less than 5,000

Table 3 Distribution of Italian municipalities by cluster in each macro-area. Note: the regions are allocated as follows: North-West (Aosta Valley, Liguria, Lombardy and Piedmont), North-East (Emilia-Romagna, Friuli-Venezia Giulia, Trentino-South Tyrol and Veneto); Centre (Lazio, Marche, Tuscany and Umbria); South (Abruzzo, Apulia, Basilicata, Calabria, Campania and Molise); Islands (Sicily and Sardinia)

	Clusters				
Macro-area	High Exposure High Sensitivity	High Exposure Low Sensitivity	Low Exposure High Sensitivity	Low Exposure Low Sensitivity	Total
North-West	9%	66%	6%	20%	100%
North-East	10%	55%	6%	29%	100%
Centre	46%	31%	13%	9%	100%
South	16%	2%	79%	2%	100%
Islands	30%	2%	67%	1%	100%
Total	**17%**	**39%**	**29%**	**15%**	**100%**

inhabitants (accounting for 16.9% of the population) are notably overrepresented in the cluster that combines high exposure and high sensitivity. For context, only about one out of seven Italians (14.9%) live in large cities of more than 250,000 inhabitants (the least vulnerable), with most of the population (54.0%) residing in small- and medium-sized municipalities between 10,000 and 250,000 inhabitants.

Table 4 Distribution of Italian municipalities by size, vulnerability value and cluster. Note: version one of the composite indicator of vulnerability is used for this analysis

		Vulnerability value		Clusters			
Municipality size (no. of inhabitants)	Share of municipalities by size	First quartile (Higher values)	Fourth quartile (Lower values)	High Exposure High Sensitivity	High Exposure Low Sensitivity	Low Exposure High Sensitivity	Low Exposure Low Sensitivity
<2,000	43.6%	39.8%	31.5%	45.3%	40.9%	48.8%	38.1%
2,000 – 4,999	26.3%	29.0%	24.3%	28.9%	27.2%	25.5%	22.0%
5,000 – 9,999	14.9%	16.3%	19.5%	13.5%	17.9%	12.2%	14.3%
10,000 – 19,999	8.8%	9.1%	12.3%	7.5%	10.1%	7.5%	9.5%
20,000 – 59,999	5.1%	5.3%	8.8%	4.4%	3.3%	5.1%	11.2%
60,000 – 249,999	1.1%	0.5%	3.0%	0.4%	0.6%	0.8%	4.1%
≥ 250,000	0.2%	0.0%	0.6%	0.0%	0.0%	0.1%	0.8%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Analysing the results of the vulnerability indicator at the national level helps to identify the areas that would be more impacted by a rise in fuel prices. In Italy, this largely mirrors some structural characteristics of the country and regional socio-economic divides. However, specific vulnerable situations may also be identified at the micro- or meso-level. For example, municipalities with an average value of the composite indicator relative to the national average may be still considered as disadvantaged if located in overall low-vulnerability region, and vice versa. These patterns can be overlooked when looking at national maps. Indeed, most published spatial analyses of vulnerability to fuel price increases (reviewed in Sect. 2) focus on specific metropolitan areas or city regions.

For these reasons, we conducted a more specific analysis focussed on two Italian metropolitan areas, highlighting relative hot and cold spots of the vulnerability indicator (version one). The selected case studies are the metropolitan areas around the cities of Milan and Naples as defined by Boffi and Palvarini (2011). The selection of these two areas follows two main criteria. First, they are respectively the first and the third Italian metropolitan areas in terms of the overall population (OECD 2022). This allows for considering complex and extensive urban systems. Second, they are located in different socio-economic contexts in the North-West (Milan) and in the South of the country (Naples). Figures 5 and 6 depict the presence of statistically significant clusters of high (hot spots in red) or low (cold spots in blue) values of vulnerability within the two urban areas. These clusters are defined using the Getis-Ord G* statistic (Getis and Ord 1992) and consider only the municipalities belonging to each of the two metropolitan areas. The maps also report the railway and motorway networks, as these tend to influence patterns of car use.

In the Milan metropolitan area, there is a large cold spot for vulnerability in the core of the urban area, comprising the municipality of Milan plus a large number of bordering municipalities to the North, stretching toward the North-East and around some primary rail lines. Some secondary cold spots emerge around other medium-large cities that represent secondary poles of the metropolitan area, such as Bergamo and Lecco. The most vulnerable situations are concentrated in an extended area across the provinces of Bergamo and Brescia. The maps for the constituent variables (not reported here for the sake of brevity) suggest that this is due to a combination of low income, high share of car use for commuting and long average length of car commutes.

The metropolitan area of Naples shows a similar cold spot of vulnerability in the municipality of Naples, although it does not extend much into the surrounding municipalities. Other cold spots are located along the Sorrentine Peninsula and around the city of Salerno (a sub-pole in the metropolitan area). Both are characterised by relatively better socio-economic conditions and lower levels of car ownership and use than the rest of the metropolitan area, and are well-served by railway. The main hot spot of vulnerability is located in the Northern part of the metropolitan area, at the border with the province of Caserta, namely in a cluster of municipalities around Casal di Principe. This is characterised by a concentration of low income, as well as by high levels of car ownership and use.

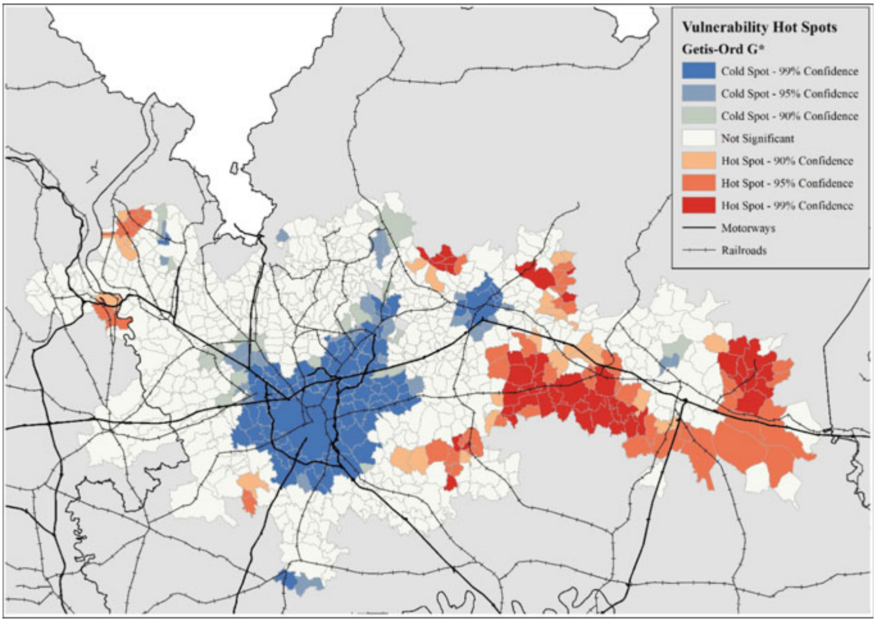

Fig. 5 Relative hots spots and cold spots of vulnerability to fuel price increases in the metropolitan area of Milan (based on version one of the indicator)

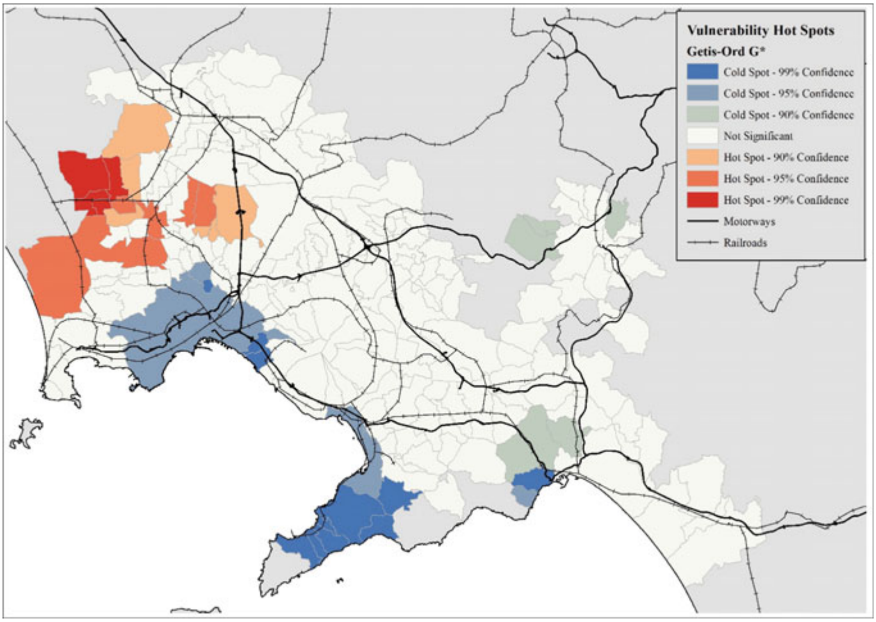

Fig. 6 Relative hot spots and cold spots of vulnerability to fuel price increases in the metropolitan area of Naples (based on version one of the indicator)

6 Discussion and Conclusions

Questions of vulnerability to motor fuel price increases are rather present in public and political debates, but are yet to catch the attention of energy poverty researchers and policymakers. This chapter has provided an overview of quantitative empirical approaches to assessing the affordability of car use with indicators, both from a static and dynamic perspective. We encourage researchers to build on this body of knowledge and conduct further empirical investigations on this important topic. This would improve our understanding of who is vulnerable to fuel price increases in Europe, raising the level of debates about this issue.

Our study illustrates how a composite spatial indicator of vulnerability can be built even for countries with limited data availability, like Italy. As such, the lack of 'perfect' data should be no excuse not to conduct similar studies in other countries. From all we know, Italy is likely to be one of the EU countries that are most vulnerable to fuel price increases, which highlights the relevance of our study.

From a methodological perspective, to the best of our knowledge, this is only the second study (after Liu and Kontou 2022) to conduct a robustness test of how variable aggregation, normalisation and weighting affect the patterns highlighted by the composite indicator of vulnerability to fuel price increases. Like them, we find that these methodological choices (e.g., in our case weighting) can lead to slightly different results, which must be considered when interpreting the findings. At the same time, the test results reassure us that our composite indicator is relatively robust to methodological choices concerning variable aggregation and normalisation.

In terms of substantive findings, a key message from our study is that the South of Italy is particularly vulnerable to fuel price increases. The fact that regions in Southern Italy have higher levels of motorisation than most EU regions with similar income levels suggests that this macro-region may well be one of the most vulnerable in the entire union.

At a closer look, however, our findings are more nuanced. We find that exposure and sensitivity to fuel price rises have a different geography within Italy, with the former being most severe in the Centre-North, and the latter in the South. The main factor behind higher vulnerability in the South (relative to the North) is lower income, which in many (but by no means all) municipalities is compensated to some extent by lower car ownership and use. The opposite happens in much of the North, where higher exposure through car ownership and use is mitigated in most places by higher income. In other words, high vulnerability in the South is largely driven by economic deprivation and as such, it is to some extent a manifestation of a long-standing economic divide within Italy.

Our analysis of the joint spatial distribution of exposure and sensitivity suggests that perhaps the areas of most concern are in the Centre of the country. In this in-between area, nearly half of municipalities combine high exposure and high sensitivity to fuel price increases. This is also the case in around a third of municipalities in the islands of Sicily and Sardinia. This is a novel finding, and one that warrants policy attention and further investigation.

When focussing on patterns of vulnerability within metropolitan areas, we find that exposure and sensitivity to fuel price increases tend to compound each other. The typical 'urban socio-spatial configuration' of Italian metropolitan areas (at least in the Centre-North) means that peripheral areas are both poorer and more car-dependent than the core. This pattern is consistent with Dodson and Sipe's pioneering research on 'oil vulnerability' in Australia (2007). In Australian metropolitan areas, this is the product of a relatively recent and dramatic reversal of the earlier geographical patterns of income distribution, whereby poverty was shifted to suburban areas as a result of neoliberal reforms (Randolph and Tice 2014, 2017). For cities in the Centre-North of Italy, this configuration is rather a long-standing characteristic, which continued to this day (Kesteloot 2005). Still, trends towards a further 'gentrification' of inner cities and 'suburbanisation of poverty', as observed in many countries (Allen and Farber 2021; Baley and Minton 2018; Kneebone and Berube 2013; Lunke 2022), would make vulnerability to fuel price increases worse, even in Italian metropolitan areas.

It is interesting to compare our findings to Mattioli et al.'s (2019) study of England. In England, the different dimensions of vulnerability to fuel price increases tend to compensate each other within metropolitan areas (as periurban areas are more car-dependent but also more affluent than cities), but to compound each other at the interregional scale (as Northern city regions are both poorer and more car-dependent than Greater London). What we find for Italy is precisely the opposite pattern: within metropolitan areas, the factors tend to compound each other (at least in the Centre-North), while at the interregional scale, they compensate each other—as the North has more car-oriented travel patterns, but is more affluent and thus less sensitive to price increases.[5]

We draw three implications from these comparisons. First, research on vulnerability to fuel price increases must carefully consider the interplay between the different dimensions of vulnerability, rather than just composite indicator scores. This helps to better understand what is causing the problem or what solutions might work in different places. Second, researchers must be attentive to both urban socio-spatial configurations and interregional inequalities, and how these vary between countries. Third, international comparison can provide useful insights into the causes of spatial patterns of vulnerability, which might not be apparent if one focusses on one country only. Research in this area would thus benefit from broadening the range of places where this type of analysis is conducted, as this could lead to a broader understanding of possible causes and policy responses.

With regard to policy implications, our analysis shows that fuel price increases, whether policy-induced or not, have a differential impact across the Italian territory. This must be taken into account when designing policy measures, be they aimed at increasing the cost of fuel for environmental reasons or at mitigating price rises due

[5] Note that the different findings might partly reflect differences study design. Mattioli et al. (2019) look at the joint distribution of sensitivity and adaptive capacity to fuel price increases—with the latter measured as accessibility to key services by public transport or walking. In our study, we were unable to measure adaptive capacity directly, so we investigated the joint distribution of sensitivity and exposure (in terms of car ownership and use).

to market volatility or geopolitical events. Policymakers are also advised to consider the different factors behind vulnerability and their configuration, which can vary from place to place. Places where vulnerability is mainly the result of economic deprivation, such as the South of Italy, call for different interventions than places where vulnerability is mainly the result of excessive levels of car use. Measures aimed at improving adaptive capacity and reducing car dependence can be helpful in both types of area though.

An interesting question in this context is how the electrification of the vehicle fleet will affect vulnerability to fuel price increases. Liu and Kontou's (2022) modelling study finds that the diffusion of electric vehicles would reduce both absolute levels of vulnerability and spatial disparities in vulnerability in Illinois (US). This happens because EVs reduce exposure to fuel price increases, i.e. the average share of income spent on running motor vehicles. Current trends in EV adoption, however, also have the potential to widen inequalities, particularly in the Italian case. First, high-income households, who are already less sensitive to fuel price increases, are the most likely to buy EVs (Wicki et al. 2022). Second, as of 2022, Italy has the second-lowest electric vehicle market share in Western Europe (Transport and Environment 2023). This is likely to widen the gap between Italy and other EU countries in terms of vulnerability to fuel price increases, by reducing other countries' exposure more rapidly than Italy's. Third, to date, the number of EVs per capita is much higher in the Centre-North of Italy as compared to the South (InsideEVs 2022). A continuation of this trend would reduce spatial inequalities between Italian regions in terms of exposure, but might increase them in terms of vulnerability, by widening the gap between the (already disadvantaged) South and the rest of the country.

With regard to future research, our analysis of the Italian case could be improved or built upon in three ways. First, an indicator of adaptive capacity to fuel price increases could be developed by leveraging publicly available spatial data on public transport departures or similar to generate accessibility metrics. This would be key to refine the composite indicator of vulnerability and might well bring to light different spatial patterns. We expect however that the inclusion of adaptive capacity would widen the gap between the North and the South of the country, as well as between urban and periurban and rural areas. Second, a more disaggregated analysis could be possible if Italian Census and income data were made available at the census tract level, or if it were possible to model them, as it is the case for England (Mattioli et al. 2019) and the US (Liu and Kontou, 2022). Finally, a replication of this study with more recent Census data (if and when they will become available) would help keeping track of how patterns of vulnerability to fuel price increases have evolved in a decade characterised by economic stagnation, fuel price fluctuations and further growth in motorisation.

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The Gender–energy–poverty Nexus Under Review: A Longitudinal Study for Spain

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1 Introduction

Energy is a driver of economic development underpinning all forms of economic activity and everyday life, that is connected with climate change due to the combustion of fossil fuels. The current political situation, especially in Eastern Europe, has repercussions on the global energy system. It has pushed up energy prices for many consumers and businesses around the world, hurting entire economies, industries, and households, especially in low-income families where energy is a large share of the budget (Birol 2022). The situation has been further exposing the problems of energy inequality and energy poverty being a recognised challenge across the world that might be even more urgent due to this scenario.

The definition of energy poverty is still under debate (Bouzarovski et al. 2012). Considering that access to affordable energy resources is not guaranteed for everyone, most economists agree that energy poverty can be defined as the inability of households to satisfy basic/domestic energy needs (Thomson et al., 2016), being inextricably connected with social, health, and economic levels (González-Eguino 2015; Awaworyi Churchill et al. 2020). Links between gender, poverty, and energy have been hinted at in many studies mainly focused on livelihood strategy and economic development of low-income countries. However, there are few studies that tackle the gender–energy–poverty nexus head on (Galvin and Sunikka-Blank 2018). These studies mainly show that women are one of the most exposed groups to the so-called energy poverty, since they carry out a major part of activities related to cooking and household work that are directly linked to the need of energy access.

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Moniruzzaman and Day (2020) proved that the consequences of energy poverty may vary between women and men mainly because women are more exposed to deal with energy-related activities. Some examples are collecting domestic energy resources with a higher probability of physical injury while collecting fuel, and indoor cooking that implies to be exposed to indoor air pollution and extremely high indoor temperatures (Kaygusuz 2011; Sovacool 2012; Maji et al. 2021). These situations are usually worsened due to the lack of refrigeration and medical care. Studies as Pueyo and Maestre (2019) and Robinson (2019) pointed to the fact that women may be impacted by energy poverty more than men, the situation even worse when it is a female breadwinner, racialized, and poor household (Hernández and Bird 2010; Sovacool 2012; Kontokosta et al. 2019; Bohr and McCreery 2019; Bednar and Reames 2020; Brown et al. 2020; Wang et al. 2021; Adua et al. 2022).

At the European Union (EU) level, where more than 50 million people are unable to afford proper indoor thermal comfort, the main constraint of applied studies is the lack of public access to gender-disaggregated data on energy poverty, although in 2016 the European Parliament adopted a resolution that explicitly specified to include the gender dimension in the analysis of the energy poverty phenomenon (European Union 2017). Studies have shown that poverty has a female face in the EU where the gender income gap stands at 16%, the gender pension gap at close to 30%, and women with low incomes are by far more often the heads of households either in single-parent families or, due to their higher life expectancy rates, as individuals living alone at pensionable age, and therefore they are far more likely to be suffering fuel poverty than household in general (Eurostat 2021).

Available data such as the one provided by the EU Energy Poverty Observatory lacks the gender perspective and cannot confirm the fact that female population is more likely to experience or fall into energy poverty. This lack of information persists even though projects need to be designed and targeted after careful attention to local energy availability and household decision-making processes to have significant gender benefits by improving the quality of life of women (Köhlin et al. 2011). A significant reduction in energy poverty would reduce important gender inequality issues (Zhu and Chang 2020; Nguyen and Su 2021).

This chapter contributes to literature on gender–energy–poverty nexus with a descriptive quantitative analysis of the gender differences of energy consumption from a longitudinal perspective to empirically support previous studies on the gender-energy-poverty issue. Particularly we focus on Spain from 1998 to 2018 as a case study. This period allows for a longitudinal analysis of the different social and economic developments that the country has undergone over the years, characterized by the introduction of the euro as a unitary currency (Gil et al. 2003) in 2002, and an increasing demand for employment in the construction sector and some basic services (Alonso and Furió 2010) that had different effects on women and men. Spain's annual gross domestic product growth rate between 1998 and 2007 ranged between 2.7% and 5.2% (World Bank 2022); this growth came to a halt with the financial crisis of 2008 (Padros de la Escosura and Sánchez-Alonso 2020). Since 2008, the Spanish economy suffered a fall in its macroeconomic indicators (Ortega and Peñalosa 2012), giving way to a period of recession and crisis from which it only recovered from 2014 onwards, only to be halted again by the crisis caused by the COVID-19 in 2020 (Hernández de Cos 2021). The study of such two decades will provide information about how energy expenditures are distributed over the years, the impact of the different economic events, and identifying how a potential increase of energy prices might affect women and men differently.

To this aim, we consider female and male breadwinner[1] households given that intrahousehold bargaining power and gender roles may influence the understanding of energy and energy consumption (Clancy et al. 2012; Lewis and Pattanayak 2012). However, the behavior of such types of households might be influenced by other characteristics of the breadwinner different from gender and it also might be influenced by characteristics of other members of the households. To better analyze the gender effects, in this chapter, we also study the energy consumption patterns of female and male one-person households in the analysis (Toro et al. 2019) and we apply an Ordinary Least Square (OLS) regression model to analyze the significance of gender and expenditure level considering the expenditure on energy products and controlling for other household characteristics. We use longitudinal data from the Spanish Household Budget Survey (HBS) to compute expenditures on residential energy products, as well as on energy goods used for private transport, transport fuels, enlarging traditional analyzes that mainly focus on residential energy.

Our results complement a previous study for Spain conducted by Aristondo and Onaindia (2018), who use a different database, the European Union Survey on Income and Living Conditions in 2005, 2008, 2012, and 2016, studied energy poverty under three energy accessibility indicators and its evolution for different household classifications and characteristics of the main breadwinner such as gender, type of house, education, etc. They found that energy poverty, in terms of accessibility and housing conditions, is higher for households whose breadwinners are divorced women. On average, women are 10% more likely to suffer energy poverty than men, and when energy poverty increase tends to penalize Spanish women more than men, increasing the inequality between both groups.

2 Methodology

To study the significance of gender differences, we first analyze the available database in detail. We calculate the consumption shares among the 39 COICOP products that constitute the 12 COICOP categories over the total annual expenditure for each household between 1998 and 2018. We analyze the differences by total expenditure quintile as well as the expenditure on energy-related products over the two decades with a descriptive analysis. For illustrative purposes, we show results for the so-called

[1] Breadwinner is the member of the household aged 16 or over, whose regular (not occasional) contribution to the common budget is used to cover household expenses to a greater extent than the contributions of each of the other members.

12 COICOP categories[2] showing separate results for two groups closely related to energy: C4.5. *Electricity, gas, and other fuels* that include specifically residential energy products; and C7.2.2. *Fuels and lubricants* that include energy products for private transport.

Second, we apply an OLS[3] model to analyze the significance of gender and expenditure level (and its interaction) controlling by other household characteristics. In Eq. 1, the expenditure share of residential and transport energy products (C4.5. *Electricity, gas, and other fuels*; and C7.2.2. *Fuels and lubricants*) of each household (*EES*) is the endogenous variable that is explained by gender (the covariate *GEND* is a binary categorical variable), total annual expenditure (*EXP* represents the household's annual monetary and non-monetary expenditure measured in thousands of euros), the interaction effect between the gender and expenditure (*GEND*EXP*), the breadwinner age (*AGE*), the number of household members (*NMEMB*),[4] the breadwinner's education (*STU* is a categorical variable),[5] the region to control for climate differences (*RE* is a categorial variable),[6] the municipality density to differentiated rural and urban areas (*DENS* is a categorial variable),[7] and finally the year (*YEAR*).

$$\begin{aligned} EES = {} & \beta_1 GEND + \beta_2 EXP + \beta_3 GEND * EXP + \beta_4 AGE + \beta_5 NMEMB \\ & + \beta_6 STU + \beta_7 RE + \beta_8 DENS + \beta_9 YEAR + \varepsilon \end{aligned} \tag{1}$$

3 Data Set

The Spanish HBS from the National Statistical Institute (INE by its Spanish acronym) is national surveys that focus primarily on household spending on goods and services. It provides information on the nature and destination of consumption expenditures, as well as various characteristics of household living conditions. In particular, the INE delivers three types of files: a household file, a member file, and an expenditure file. The household file collects data on household characteristics such as household

[2] The 12 COICOP categories are: (C1) Food and non-alcoholic beverages; (C2) Alcoholic beverages and tobacco; (C3) Clothing and footwear; (C4) Housing, water, gas, electricity, and other fuels; (C5) Furnishings, household equipment, and routine maintenance of the house; (C6) Health; (C7) Transport; (C8) Communication; (C9) Recreation and culture; (C10) Education; (C11) Restaurants and hotels; (C12) Miscellaneous goods, and services.

[3] We apply the *lm* command of RStudio software.

[4] In the case of one-person household analysis, this covariate is not taken into consideration.

[5] *STU* has three categories according to the level of complemented studies: (1) first cycle or less; (2) secondary; (3) university.

[6] *RE* refers to the 17 Spanish Autonomous Communities: Andalusia, Aragon, Asturias, Balearic Islands, Canary Islands, Cantabria, Castilla-Leon, Castilla-La Mancha, Catalonia, Valencia, Extremadura, Galicia, Madrid, Murcia, Navarra, Basque Country, and La Rioja.

[7] *DENS* has three categories: (1) densely populated area; (2) medium densely populated area; (3) sparsely populated area.

size, composition, and other general information about the residential area such as autonomous community, size of municipality, population density, etc. The member file shows information on all the individuals who are members of the households. Finally, the expenditure file shows, as already mentioned, the expenditures at the household level. The Spanish HBS over the years varies in its sociodemographic and socioeconomic information. To obtain a homogenized database we retain the common variables between 1998 and 2004 and 2006 and2018.[8]

Bearing in mind that the objective of the survey is to study household consumption expenditures, the basic units of analysis are private households living in the main dwelling. Consumption is organized according to the COICOP European classification, which structures consumption into 12 large product categories with a level of 39 different products.

The complete size of the sample comprises 348,989 households. From this sample, however, our analysis only focuses on two types of households that allow us to analyze consumption energy differences from a gender perspective: female and male breadwinner households, and female and male one-person households. To compare households with different sizes and composition as well as the economies of scale in consumption, households' expenditures are corrected by the OECD scale of equivalence to obtain equivalent consumption units that are comparable. According to the theory of economies of scale, the increase in the number of members of a household is not usually accompanied by a proportional increase in spending to maintain the same pattern of consumption, since there are shared expenses that are not proportional to the number of members (for example, dwelling expenditures). Additionally, the theory of equivalent consumption units in households maintains that the consumption patterns of children are different from those of adults. Following these ideas, the consumption units of that household are calculated following the modified equivalence scales defined by OECD, which it is calculated by adding the household members weighted according to different coefficients: 1 for the main breadwinner (first adult in the household), 0.5 for each additional adult (over 13 years), and 0.3 for each child (13 years and under).

4 Results and Discussion

To study the consumption energy differences from a gender perspective of Spanish households' consumption over twenty years between 1998 and 2018, first, we analyze expenditure shares on 12 COICOP categories including detailed information for residential and transport energy consumption (C4.5 *Electricity, gas, and other fuels*,

[8] Data prior to 1998 is published by quarters with no household tracking. From 1998 to 2004 the series is delivered by quarters. In 2005 a reform was implemented to fulfil the needs of users and the recommendations of the Statistical Office of the European Union and adapted longitudinally, leaving 2005 without available longitudinal data. Since then, the Spanish HBS are delivered annually. Expenditures are in purchaser's prices in pesetas from 1998 to 2000 and in euros from 2001 to 2018; an exchange rate of 1: 0.00598 was applied to convert all the series in euros.

and C7.2.2 *Fuels and lubricants*).[9] Second, we discuss the results of the OLS model that allow us to analyze the significance of gender and expenditure level (and its interaction) controlling by other demographic household characteristics.

In the analysis, we consider all households grouped into female breadwinner households (FBH) and male breadwinner households (MBH). However, a descriptive analysis based exclusively on female and male breadwinner households might have an important drawback because the differences observed between FBH and MBH can be explained by other issues not related to gender differences such as the educational level of the breadwinner, the population density or region where the household live. The differences can be also influenced by the characteristics of other household members. To partially overcome this limitation, the descriptive analysis also includes differences between a female and male living alone, let say—female one-person households (FOPH) and male one-person households (MOPH). Additionally, the regression analysis further refines the study of gender differences by controlling for other household characteristics such as location, climate, and education (Toro et al. 2019).

The complete size of the longitudinal series comprises 348,989 households. From this total, FBH represents 28% and MBH, 72%. One-person households are a subsample of this series representing 21% of households (FOPH, 12% and, MOPH, 9%). Additionally, FOPH represent almost 42% of the total FBH, in contrast to MOPH that just represents 12% of the total MBH. Table 1 shows the average household characteristics by type of household and gender between 1998 and 2018. The differences between female and male breadwinner household in the expenditure level is almost imperceptible (around 260 euros per year), female breadwinner have a slightly higher level of education, are older, live in less dense areas and with less members that their male counterpart. Otherwise, FOPH spend around 1,800 euros less per year than MOPH and have a slightly lower level of education. Finally, FOPH are older than MOPH—probably explained by a higher life expectancy—and live in less dense areas.

Figure 1 presents the mean expenditure share by products and expenditure quintile (computed separately by gender) between 1998 and 2018 of Spanish FBH and MBH.[10] As expected, the proportion of product expenditure related to energy consumption depends directly on the quintile by expenditure irrespective of the breadwinner's gender. In other words, the share spent on residential energy (C4.5) decreases as the total expenditure rises, as it is a basic and daily product, while the proportion spent on transport fuels (C7.2.2) increases with total spending.

Consumption patterns between FBH and MBH do not seem to be very different in general; however, some discrepancies are observed in categories related to energy

[9] Results are obtained for a total of 15 product groups because category (C4) *Housing, water, gas, electricity, and other fuels* is divided into (C4.5) *Electricity, gas, and other fuels* and the rest of products of category C4 (C4r). The same rationally holds for category (C7) *Transport*, that is divided into (C7.2.2) *Fuels and lubricants,* the rest of group C7.2 (C7.2r) *Otherperation of personal transport equipment* and the rest of category C7 (C7r) *Transport*.

[10] This analysis uses total expending as a proxy of income since information about disposable income is not available.

Table 1 Average descriptive statistics of household characteristics, Spain 1998–2018

	Breadwinner household		One person household	
	Mean	St. Deviation	Mean	St. Deviation
Annual expenditure				
Female	15,628.480	39.407	15,981.730	71.769
Male	15,367.510	23.925	17,819.750	104.518
Education level				
Female	1.726	0.004	1.570	0.006
Male	1.658	0.002	1.807	0.008
Age				
Female	56.369	0.072	64.103	0.124
Male	52.745	0.038	52.574	0.147
Density				
Female	1.655	0.003	1.667	0.005
Male	1.792	0.002	1.771	0.007
Household members				
Female	2.092	0.005	–	–
Male	2.953	0.003	–	–

Source Own elaboration from Spanish Household Budget Survey from 1998 to 2018 (INE 2019)

purchases. Regardless of the expenditure quintile, FBH tend to spend a higher share than MBH in their expenditures on products for household maintenance (C4r: *Housing and water*) as well as in the case of residential energy (C4.5: *Electricity, gas, and other fuels*). Moreover, MBH tend to spend more than FBH on products related to private transport (C7.2r *Other* o*peration of personal transport equipment*) as well as with transport fuels (C7.2.2 *Fuels and lubricants*). For one-person households, these patterns are almost identical (See Fig. A.1 in the Annex).

Expenditure shares on C4.5: *Electricity, gas, and other fuels* hold over the twenty years period (Fig. 2). When it comes to residential energy (C4.5) the lower quintiles spend a higher share than the higher quintiles independent of the year or gender. When comparing the differences between FBH and MBH in the same quintile, FBH always spend a higher share of their expenditure on energy commodities than their male counterpart. After the 2008 crisis, both types of households are affected considerably increasing their share of expenditure on such goods and have not decreased in the following years. For instance, FBH belonging to quintile 1 experienced an increase in 2010 by 21% compared to 2009, while MBH belonging to the same quintile perceived an increase of 12% for the same period. Looking at the richest quintile, the differences between FBH and MBH are smaller compared to the poorest households, especially in the post-crisis years, although FBH belonging to quintile 5 also spend a higher expenditure share on residential energy than their male counterpart.

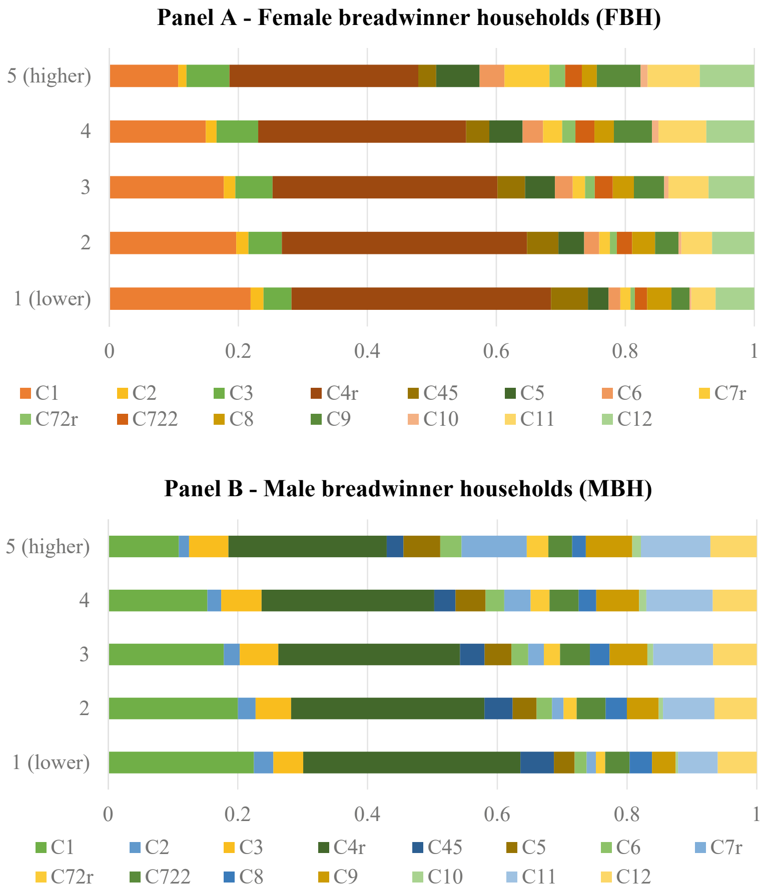

Fig. 1 Mean expenditure shares by quintile and COICOP product, Spain 1998–2018. *Source* Own elaboration from Spanish Household Budget Survey from 1998 to 2018 (INE 2019). *Notes* C1. *Food and non-alcoholic beverages*; C2. *Alcoholic beverages and tobacco*; C3. *Clothing and footwear*; C4r. *Housing and water*; C4.5. *Electricity, gas, and other fuels* that include specifically energy products used at home; C5. *Furnishings, household equipment, and routine maintenance of the house*; C6. *Health*; C7r. *Other transportation*; C7.2r. *Other operation of personal transport equipment*; C7.2.2. *Fuels and lubricants*; C8. *Communication*; C9. *Recreation and culture*; C10. *Education*; C11. *Restaurants and hotels*; C12. *Miscellaneous goods, and services*

However, patterns differ for private transport energy C7.2.2 *Fuels and lubricants*. The differences between quintiles tend to change over the years, FBH quintiles tend to have more modest differences than MBH quintiles. While the MBH three middle quintiles tend to compete for the largest share of spending on this type of good, and the higher and the lower quintile are disputed for the lower proportion. FBH, otherwise, shows that quintile 4 tends to have a higher proportion in this type of goods, while quintile 1 and quintile 2 tend to have a lower proportion.

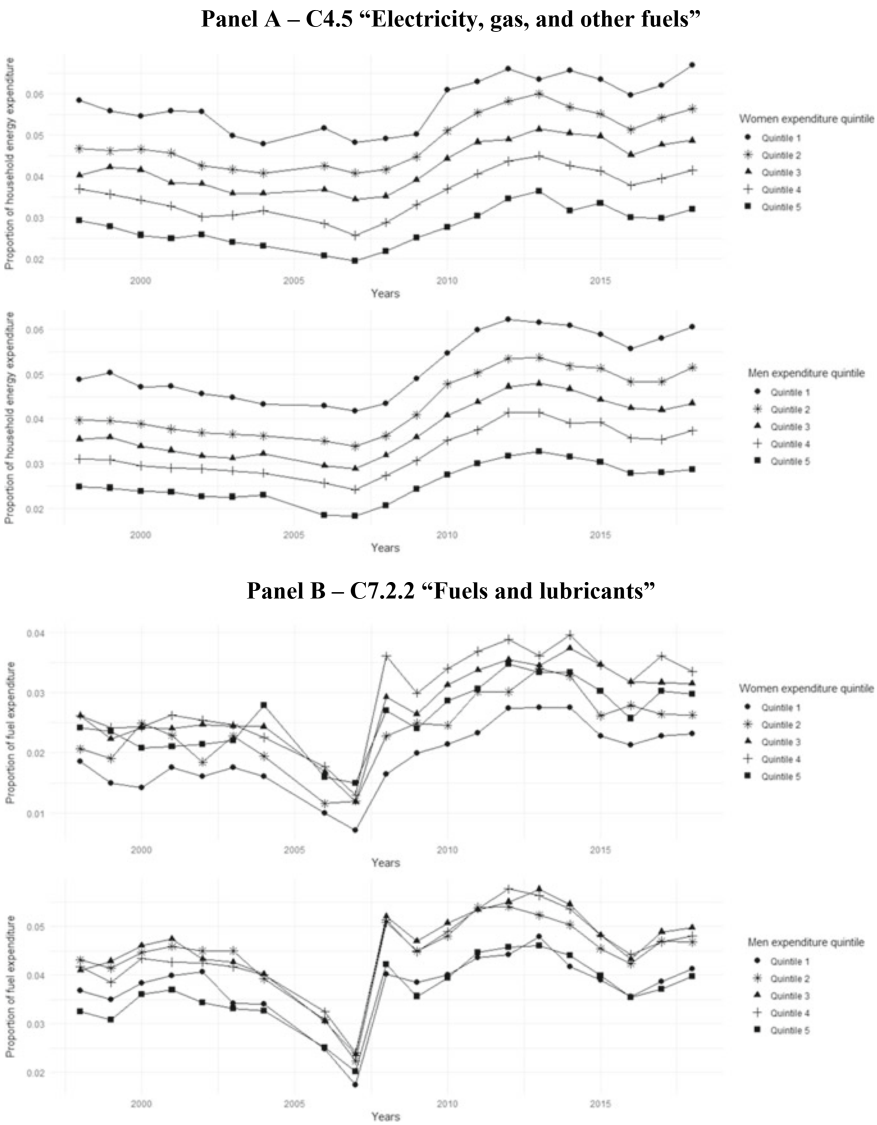

Fig. 2 Expenditure shares by quintile on C4.5 "Electricity, gas, and other fuels" and C7.2.2 "Fuels and lubricants" of female and male breadwinner households, Spain 1998–2018. *Source* Own elaboration from Spanish Household Budget Survey from 1998 to 2018 (INE 2019)

Results for one-person households are in the same line as breadwinner households in general (see Fig. A.2 in the Annex). Regardless the year and gender, the lowest quintiles spend a higher share of their expenditure on residential energy (C4.5) and a lower share on transport fuels (C7.2.2). We only find differences in the share of expenditures on transport fuels for quintile 2, where MOPH tend to expend a considerably lower proportion than MBH belonging to the same quintile.

To further analyze the effect of the economic crisis of 2008, Table 2 shows the cumulative pre and post-crisis growth rates.

In the case of residential energy (C4.5), the economic crisis of 2008 had different effects on FBH and MBH. All households, regardless of the breadwinner gender and quintile, decreased their share of expenditure on residential energy before the crisis (1998–2008) but increased it afterward (2008–2018). Between 1998 and 2008, households with an FBH experienced a greater fall compared with MBH regardless of the quintile. However, after the 2008 crisis, FBH experienced a greater increase than MBH since the third quintile. During the pre-crisis period, expenditure share on transport fuels (C7.2.2) increased independently of the breadwinner gender, except for quintile 1 of FBH; however, after the crisis, expenditures share of FBH increased in almost all the quintiles, while MBH expenditures shares decreased, enlarging the gender expenditure gap in transport fuels.

This general tendency also held for one-person households (see Table A.1 in the Annex). Like the breadwinner case, the expenditure share on household energy use (C4.5) decreased during pre-crisis years, and increased afterward, regardless of the gender or quintile. On the other hand, the expenditure share on transport fuels

Table 2 Cumulative growth rates of expenditure shares on residential energy and on private transport fuels by expenditures quintile of female and male breadwinner households, Spain (1998–2008 and 2008–2018)

	1998–2008		2008–2018	
	Female	Male	Female	Male
	C4.5 "Electricity, gas, and other fuels"			
Quintile 1	−0.0173	−0.0117	0.0313	0.034
Quintile 2	−0.0113	−0.0091	0.0307	0.0359
Quintile 3	−0.0133	−0.0107	0.033	0.0317
Quintile 4	−0.0242	−0.0128	0.0368	0.0319
Quintile 5	−0.0287	−0.0181	0.0392	0.0331
	C7.2.2 "Fuels and lubricants"			
Quintile 1	−0.0116	0.0089	0.0343	0.0029
Quintile 2	0.0099	0.0168	0.0145	−0.0082
Quintile 3	0.0112	0.0242	0.0076	−0.0045
Quintile 4	0.0326	0.0211	−0.0074	−0.0066
Quintile 5	0.0114	0.0267	0.0098	−0.0059

Source Own elaboration from Spanish Household Budget Survey from 1998 to 2018 (INE 2019)

(C7.2.2), with some exception, always increased, independent of the gender or years. Like breadwinner case, FOPH spend a higher share of their expenditure on household energy use (C4.5) than MOPH. Before the crisis, the share of FOPH decreased faster than that of MOPH (except for FOPH quintile 1). After the crisis, FOPH belonging to the poorest quintile suffer a smaller increase than the richest FOPH, while MOPH belonging to the poorest quintile suffer a larger increase than the richest MOPH.

For the case of transport fuels (C7.2.2), during the pre-crisis years, the lowest quintile suffers a higher increase in the expenditure share that the richest independent of gender. In contrast to the case of female and male breadwinner households, FOPH belonging to the poorest quintile suffer the highest increase, in both pre- and post-crisis years. In fact, in most cases, FOPH show a larger increase in the proportion spent on such products than MOPH, although as Fig. 2 shows, far from reaching the expenditure levels of their male counterparts.

Finally, to capture the significance of gender and expenditure level (and its interaction) we run an OLS regression model controlling by other demographic household characteristics such as age, number of household members, year, region, density, and level of studies. Table 3 shows the model results for all households, that is for FBH and MBH, on expenditure shares on residential energy and transport fuels independently.

In this analysis, gender (*GEND*) is our variable of interest, and it denotes female by one. Gender is statistically significant and positive for expenditure share on residential energy, and significant and negative for transport fuels. In other words, holding all other household characteristics constant (expenditure level, age, number of members, year of survey, region, density, and education), a household with a female breadwinner allocates a significantly higher proportion of its total expenditure to residential energy and a significantly lower share to transport fuel than a household with the same characteristics but with a male breadwinner. Moreover, looking at the interaction of gender and expenditure (*GEND* * *EXP*), we see that it is significant meaning that there is an interaction effect and that the impact of extra expenditure on the expenditure share on energy products differs with respect to gender and type of energy product. For residential energy (C4.5), the interaction of gender and expenditure is negative and significant, meaning that each extra thousand euros have a lower effect on FBH than for MBH. However, the interaction is the opposite for transport fuels (C7.2.2), that is to say that each extra thousand euros in FBH have a significantly higher effect than each extra thousand euros in MBH.

In the case of one-person households, the interaction is significant and negative in both residential energy and transport fuels, being higher the effect for residential energy than for transport fuels (see Table A.2 in the Annex).

Table 3 Ordinary Least Square (OLS) model on expenditure shares on residential energy (C4.5) and transport fuels (C7.2.2) for female and male breadwinners' households, Spain 1998–2018

Covariates		Residential energy (C4.5)	Transport fuels (C7.2.2)
		Coefficient	
	(Intercept)	−2.27***	−1.5***
Gender	*GEND (female)*	0.003277***	−0.01227***
Expenditure	*EXP*	−0.0009848***	0.0000382***
Gender * Expenditure	*GEND (fem)*EXP*	−0.00008803***	0.0002138***
Age	*AGE*	0.0002096***	−0.0005043***
Number of Members	*NMEMB*	−0.002422***	0.005771***
Year of survey	*YEAR*	0.001151***	0.0007711***
Region: Aragon	*RE 2*	0.01333***	−0.006918***
Region: Asturias	*RE 3*	0.005685***	−0.00196***
Region: Balearic Islands	*RE 4*	0.002601***	−0.0008928*
Region: Canary Islands	*RE 5*	−0.008352***	0.00358***
Region: Cantabria	*RE 6*	0.0045***	0.001475**
Region: Castilla-Leon	*RE 7*	0.01614***	0.003319***
Region: Castilla-La Mancha	*RE 8*	0.01682***	−0.003836***
Region: Catalonia	*RE 9*	0.007869***	−0.005866***
Region: Valencia	*RE 10*	0.002097***	0.0001535
Region: Extremadura	*RE 11*	0.002085***	−0.0005745
Region: Galicia	*RE 12*	0.005071***	0.0009095*
Region: Madrid	*RE 13*	0.009517***	−0.00218***
Region: Murcia	*RE 14*	0.0007027**	0.001951***
Region: Navarra	*RE 15*	0.01005***	−0.009693***
Region: Basque Country	*RE 16*	0.002944***	−0.01032***
Region: La Rioja	*RE 17*	0.01439***	−0.006968***
Density: Medium	*DENS 2*	0.00438***	0.006814***

(continued)

Table 3 (continued)

Covariates		Residential energy (C4.5)	Transport fuels (C7.2.2)
Density: Sparsely	*DENS 3*	0.009695***	0.01147***
Studies: Secondary	*STU 2*	−0.000347**	0.000343
Studies: University	*STU 3*	−0.0003754**	−0.0009363***

Legend 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Notes Gender (*GEND*) denotes female by one; density (*DENS*) has three categories: (1) densely populated area; (2) medium densely populated area; (3) sparsely populated area, and denotes densely populated area (1) by one; level of studies (*STU*) has three categories according to the level of complemented studies: (1) first cycle or less; (2) secondary; (3) university, and denotes first cycle or less (1) by one; and region (*RE*) includes the 17 Spanish Autonomous Community and denotes Andalusia (1) by one

Source Own elaboration from Spanish Household Budget Survey from 1998 to 2018 (INE 2019)

5 Conclusions

Previous studies show that women are more at risk of energy poverty, even in developed countries. Additionally, policies aimed at reducing energy poverty with a gender perspective will help to reduce the inequality between women and men on different issues.

Results presented in this chapter contribute to the discussion of energy poverty with a quantitative analysis. By using data from the Spanish HBS for a period of twenty years from 1998 to 2018, this study contributes to the literature by collecting data and providing empirical evidence of the energy consumption by different household structures under a gender approach. Specifically, besides the analysis of female and male breadwinner households, we also provide results for female and male one-person households, and we run an OLS model to further refine the gender differences and avoid differences in energy consumption due to the influence of the household structure.

Previous studies usually focus on the gender energy poverty analysis by looking only at the consumption and effect of the use of residential energy products, mainly recorded by expenditures on COICOP product C4.5 *Electricity, gas, and other fuels*. This chapter, however, goes beyond the analysis of residential energy consumption by analyzing the differences between women and men and how these differences prevail energy gender gap and gender energy poverty also in another group of energy goods used for a different purpose. Particularly, we extend the analysis to the use of transport fuels included in the COICOP group C7.2.2 *Fuels and lubricants*.

Along consumption patterns, the results show that FBH and FOPH spend a significantly higher share on residential energy than their male counterparts observed both over the years and on average independently of the quintile to which they belong. The poorest FBH (quintile 1) allocate more of their total expenditure than the poorest MBH belonging to the same quintile. However, these differences decrease as the expenditure quintile increases. Our results confirm that poorest FBH are those who suffer from greater inequality where their spending capacity is mostly influenced by the consumption of a basic good related to residential energy. On the contrary, MBH assign a significantly higher share than FBH to products related to private transport energy. In other words, the gender gap in the consumption of transport fuels is even worse by comparing the most disadvantaged households. Looking at differences between FOPH and MOPH the conclusion goes in the same direction but with results of different dimension: women living alone, who are older than their male counterparts, suffer a higher energy gap.

To summarize, both from the descriptive analysis and through the OLS regression, in the case of Spain from 1998 to 2018, we conclude that households with a female breadwinner spend a higher share of their total expenditure on residential energy, while male breadwinner households tend to spend a higher share on transport fuels. We also established that the 2008 crisis affected female and male breadwinner households differently. Finally, the level of expenditure affects FBH and MBH differently. When there is an increase in the expenditure level, MBH decrease their expenditure share on residential energy faster than FBH; while for energy fuels it is the contrary: FBH increase the expenditure share faster than MBH. In the case of one-person household, an increase in the expenditure level makes the MOPH to decrease the expenditure share on residential energy and increase the share on transport fuels faster than FOPH.

Concluding, the inequality between women and men also affects energy issues where women are more exposed as they need more effort to obtain residential energy goods that have almost not good substitutes, while men demand significantly more transport fuels that might have alternative substitutes in public transport. This gender energy inequality is even worse in the case of the most disadvantaged households, where women are still far from being able to spend on energy products, particularly those related to private transport.

Annex: Results for One-Person Household Analysis

Source Own elaboration from Spanish Household Budget Survey from 1998 to 2018 (INE, 2019).

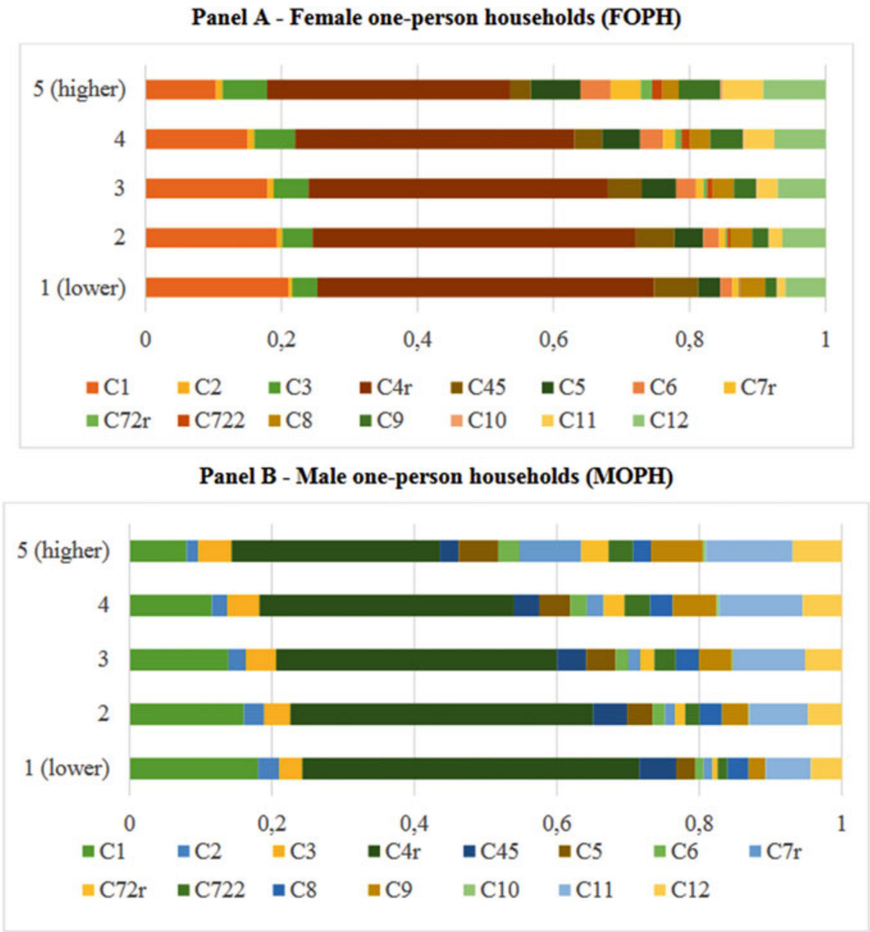

Fig. A.1 Mean expenditure shares by quintile and COICOP product, Spain 1998–2018 (*Source* Own elaboration from Spanish Household Budget Survey from 1998 to 2018 (INE, 2019) (*Notes* C1. Food and non-alcoholic beverages; C2. Alcoholic beverages and tobacco; C3. Clothing and footwear; C4r. Housing and water; C4.5. Electricity, gas, and other fuels that includes specifically energy products used at home; C5. Furnishings, household equipment, and routine maintenance of the house; C6. Health; C7r. Other transportation; C7.2r. Other operation of personal transport equipment; C7.2.2. Fuels and lubricants; C8. Communication; C9. Recreation and culture; C10. Education; C11. Restaurants and hotels; C12. Miscellaneous goods, and services)

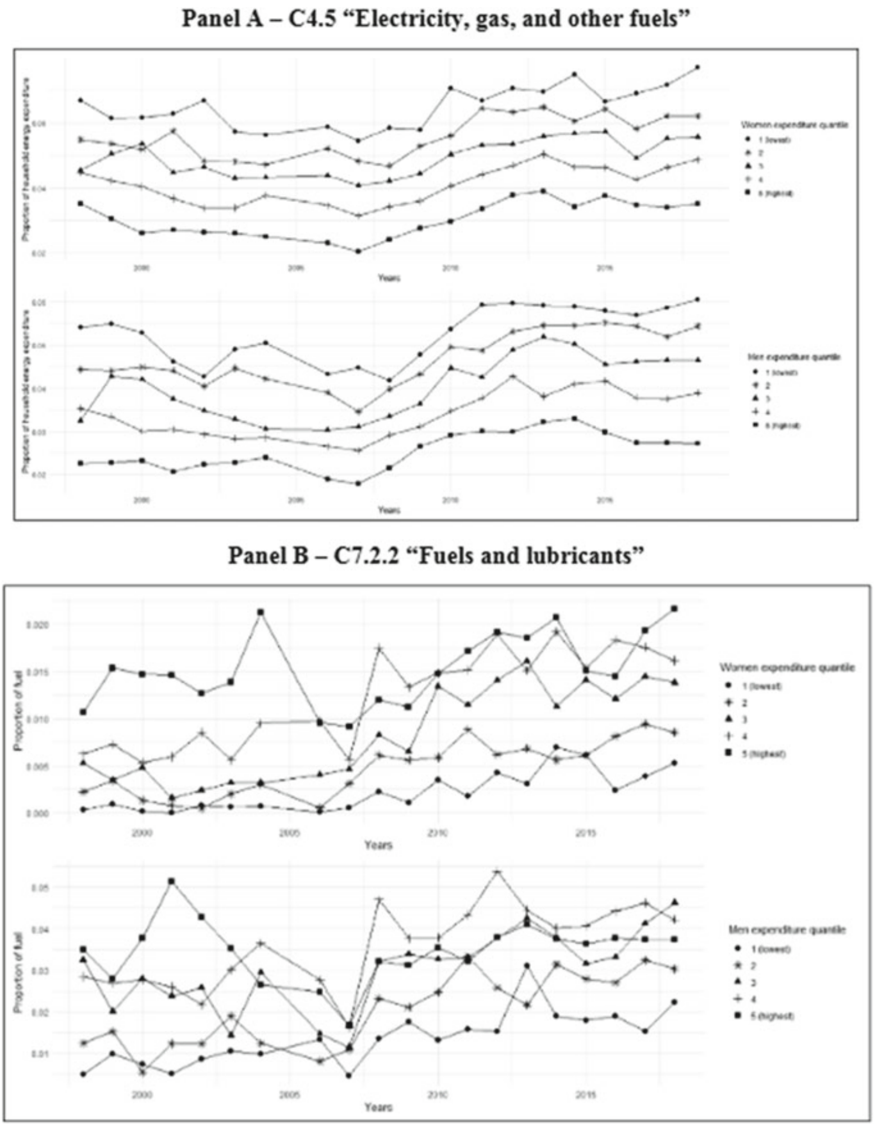

Fig. A.2 Expenditure shares by quintile on C4.5 “Electricity, gas, and other fuels” and C7.2.2 “Fuels and lubricants” of female and male one-person households, Spain 1998–2018 (*Source* Own elaboration from Spanish Household Budget Survey from 1998 to 2018 [INE, 2019])

Table A.1 Cumulative growth rates of expenditure shares on residential energy and on private transport fuels by quintile of female and male one-person households, Spain (1998–2008 and 2008–2018)

	1998–2008		2008–2018	
	Female	Male	Female	Male
	C4.5 "Electricity, gas, and other fuels"			
Quintile 1	−0.0159	−0.0187	0.0356	0.0354
Quintile 2	−0.0108	−0.0098	0.0310	0.0358
Quintile 3	−0.0108	−0.0050	0.0330	0.0354
Quintile 4	−0.0292	−0.0176	0.0406	0.0339
Quintile 5	−0.0383	−0.0101	0.0411	0.0256
	C7.2.2 "Fuels and lubricants"			
Quintile 1	0.2036	0.1048	0.0887	0.0505
Quintile 2	0.1056	0.0646	0.0340	0.0269
Quintile 3	0.0464	−0.0015	0.0523	0.0372
Quintile 4	0.1081	0.0513	−0.0077	−0.0107
Quintile 5	0.0121	−0.0080	0.0604	0.0149

Table A.2 Ordinary Least Square (OLS) model on expenditure shares on residential energy (C4.5) and on transport fuels (C7.2.2) for female and male one-person household, Spain 1998–2018

Covariates		Residential energy (C4.5)	Transport fuels (C7.2.2)
		Coefficients	
	(Intercept)	−2.52***	−0.7469***
Gender	*GEND (female)*	0.01048***	−0.009659***
Expenditure	*EXP*	-0.0006556***	0.0003222***
Gender * Expenditure	*GEND (fem)*EXP*	−0.0003199***	−0.0001407***
Age	*AGE*	0.0002865***	−0.000584***
Year of survey	*YEAR*	0.001267***	0.0003965***
Region: Aragon	*RE 2*	0.01716***	−0.002138**
Region: Asturias	*RE 3*	0.007799***	−0.0003198
Region: Balearic Islands	*RE 4*	0.003433***	0.0009563
Region: Canary Islands	*RE 5*	−0.007016***	0.002367**
Region: Cantabria	*RE 6*	0.006901***	0.0005332
Region: Castilla-Leon	*RE 7*	0.02387***	−0.0003309

(continued)

Table A.2 (continued)

Covariates		Residential energy (C4.5)	Transport fuels (C7.2.2)
Region: Castilla-La Mancha	*RE 8*	0.02084***	−0.001282
Region: Catalonia	*RE 9*	0.01076***	−0.003852***
Region: Valencia	*RE 10*	0.002686***	0.001559*
Region: Extremadura	*RE 11*	0.002514**	0.0008562
Region: Galicia	*RE 12*	0.008234***	0.0007124
Region: Madrid	*RE 13*	0.01238***	−0.002707***
Region: Murcia	*RE 14*	0.001426	0.001552
Region: Navarra	*RE 15*	0.01457***	−0.002012*
Region: Basque Country	*RE 16*	0.005627***	−0.006307***
Region: La Rioja	*RE 17*	0.01976***	−0.001651
Density: Medium	*DENS 2*	0.005506***	0.005815***
Density: Sparsely	*DENS 3*	0.01162***	0.007307***
Studies: Secondary	*STU 2*	−0.001087*	0.004095***
Studies: University	*STU 3*	−0.001655***	0.005251***

Legend: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

Notes Gender (*GEND*) denotes female by one; density (*DENS*) has three categories: (1) densely populated area; (2) medium densely populated area; (3) sparsely populated area, and denotes densely populated area (1) by one; level of studies (*STU*) has three categories according to the level of complemented studies: (1) first cycle or less; (2) secondary; (3) university, and denotes first cycle or less (1) by one; and region (*RE*) includes the 17 Spanish Autonomous Community and denotes Andalusia (1) by one

Source Own elaboration from Spanish Household Budget Survey from 1998 to 2018 (INE, 2019)

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Carbon Pricing and Energy Poverty Mitigation Policies

Effects of Carbon Tax Redistribution Schemes on Energy Welfare of Households in Germany

Audrey Dobbins and Ulrich Fahl

1 Introduction

The German '*Energiewende*', or energy transition, aims to transform the energy system from fossil and nuclear-based energy sources to include more renewable energy sources and energy efficiency (Bundesregierung 2010). Efforts from the household sector will contribute towards achieving the targets in 2050 of an overall reduction in GHGs of -80 to -95% (compared to 1990 levels), 60% share of renewable energy in the final energy consumption, 80% share of renewables in gross electricity consumption, 50% less energy and 25% less electricity compared to 2008 levels, and 80% less primary energy demand in buildings compared to 2008 (BMWi 2018). This move towards a more renewable and energy-efficient energy system is well-founded and even required in order to avert the most detrimental effects of climate change, which are already felt around the world. Underpinned by the Paris Agreement, action on climate includes the transition to a low carbon economy, which entails alternative, clean technologies resulting in the reduction of emissions. The next 10 years will be critical for climate action, recognised by the fact that on the EU level climate milestone targets have been increased to a reduction by 55% by 2030. Given this urgency to act, Germany—within the European energy policy framework—has defined targets to achieve carbon neutrality by the mid-century with milestones in 2030 of 30% renewables in the total energy consumption and a reduction of energy consumption of 30% (BMU 2019; BMWi 2020). The national target to reduce emissions was increased from 55 to 65% in 2022 and sector targets will

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be redefined in 2024 to align with this more ambitious national objective (BMWK 2022). The strategies relevant to the household sector developed from these aspirations require the renovation of the building envelope, replacement of inefficient, fossil fuel-driven heaters with efficient, renewable-based heating systems, increasing energy efficiency of appliances, the installation of decentralised energy generation technologies and discouraging fossil fuel consumption through the introduction of a carbon tax (BMU 2019). However, achieving this roll-out poses a challenge since it depends on the co-investment by the private sector where a trend of decreasing willingness-to-pay is evident despite the overall consensus that environmental goals should be reached (Andor et al. 2017). It is estimated that the energy transition in Germany will require an annual investment of between 15–40 billion € annually for the next 30 years—although it should be noted that the full costs of the energy transition are unknown and estimates need to take into account the damage costs of not taking action as well as incorporate the savings (Agora Energiewende 2018). This highlights concerns about the economic impact of the energy transition in the debate and gives rise to the need to define what is meant by growth and include assurances for well-being (social and economic) within the limits of the environment.

At the heart of the energy transition, consumers are key to unlocking the potential to achieve energy and climate change targets in Germany. These renewable energy and energy efficiency targets of the energy transition will remain unachievable without the active participation of customers (households), as is ingrained in the European energy policy direction. Nearly, a third of Germany's final energy use is directly attributable to households with two-thirds of this consumption met with fossil fuels. As such, households have a significant part to play in transforming the energy system. To encourage households to shift from fossil fuels and to invest in renewables and energy efficiency (including building renovations), financial disincentives, such as a carbon tax are added to fossil fuel consumption. However, the majority of German households lack the financial or decision-making power to make the necessary investments in energy-efficient and renewable technologies. Policies and national-level energy planning are typically based on energy system modelling assessments, which assume averaged households. However, basing assessments on a homogenous household sector may result in the overestimation of the contributions from this sector towards achieving energy and emission targets, and are not capable of addressing the energy welfare concerns of households.

Energy poverty is on the rise across Europe—and is further impacted by geopolitical insecurity such as in the case of the Ukraine crisis resulting in supply constraints and energy price increases and the economic impact of the COVID-19 pandemic, which poses particular challenges for the resilience in lower income households and could impact the energy transition pathway taken to reduce emissions or move away from fossil fuels. Assessments that do not include consideration for the heterogeneity of the household sector within energy planning will likely result in estimates falling short of the energy and climate change targets, a lack of active participation and a reduction in the energy welfare in the vulnerable population. Understanding the significance of this is crucial to ensuring all households have the opportunity to participate in the energy transition and are not disproportionately disadvantaged.

The key challenges, therefore, are around the need to understand the differentiated needs and capabilities of households as well as the drivers influencing energy-related investment and consumption patterns and to incorporate these into a process, which will also allow a long-term assessment of the influences on the energy system with a view to achieving the energy transition targets. This characterisation of the household sector is essential to be able to assess the distributional impacts of energy-related policies on the energy welfare of specific types of households.

This chapter begins with outlining the significance of household energy vulnerability within the context of the energy transition in Sect. 2. This is followed by a characterisation of the household sector differentiated by socio-economic parameters and those related to the built environment in Sect. 3. Section 4 will summarise the discourse on carbon taxes and different redistribution approaches. Section 5 describes the methodology designed to assess investment and energy consumption patterns, emissions and the energy welfare of households. Section 6 discusses some results derived from the energy system optimisation model where scenarios explore alternative redistribution approaches, while Sect. 7 concludes with a short discussion.

2 Household Energy Vulnerability

Energy poverty is increasingly prevalent in the energy transition discourse. It is no longer a question of if the energy transition will benefit lower income households, but how to enable this (European Commission 2016; Sunderland et al. 2020; Ugarte et al. 2016). The lack of a common understanding across Europe on what energy poverty is results in fragmented approaches or discounting its significance entirely (Pye et al. 2015). This is a problem because there are indications of an increasing trend and current strategies risk leaving lower income households behind (Dobbins et al. 2019). Household energy vulnerability is commonly termed 'energy poverty' and understood as 'a situation where households are not able to adequately meet their energy needs at affordable cost, and is caused by a combination of overlapping factors including low income, high energy prices, poorly insulated buildings and inefficient technologies and sometimes limited access to clean and affordable energy sources' (Dobbins et al. 2019). The common policy approach to address household energy vulnerability is to provide financial support through the social welfare system. However, this does not allow for the possibility to address the cross-sectoral nature of the issue with policies directed towards alleviating the energy deficiencies related to the structural causes of household energy vulnerability.

While there is consensus that energy should be affordable and is outlined as a key pillar of the energy policy architecture, there is no consensus on how the inability to afford energy should be addressed in Germany. Although a formal definition of energy poverty does not exist in the German context, there has been a noticeable increase in the number of households who struggle to afford adequate energy services such that approximately 11–21% of German households are estimated to live in energy poverty (Bleckmann et al. 2016; Heindl 2014; Pye et al. 2015). Energy affordability is a key component in defining energy poverty, which can have an even greater impact on low-income households, who typically live in less efficient buildings and are often tenants. Affordability remains a central goal within the framework of the goals of the energy transition to decarbonise the energy system, to increase energy efficiency and the contribution of renewable energies (Bundesregierung 2010). Germany is among the countries with the highest electricity and gas prices in Europe, with an estimated 17.4% of the population spending twice the median on energy in 2015. According to European estimates, 3–18% of the population in Germany are affected or at risk of energy poverty (EPOV 2021). Missing repayments led to more than 230,000 electricity and 24,000 gas outages in 2020 (BNetzA 2021), putting households in a cycle of debt and outages that further increases the difficulty of meeting basic energy needs (Bouzarovski et al. 2021). Due to the COVID-19 pandemic and energy price increases related to the war in Ukraine, evidence shows that these aspects are exacerbated and will negatively affect households further. This has the potential to further affect household energy wealth (Dobbins et al. 2019; Schultz 2022) and give rise to a unique opportunity to take action to resolve the multiple inequalities exposed by these crises (European Commission 2020). Nonetheless, while a definition is important to gain agreement and clarity, it is still possible to undertake an evaluation of the energy welfare of households relative to other households.

There is a need to be able to assess energy poverty by classifying the differentiated needs and capabilities of households. The exclusion of the consideration of this inequality is further compacted by the fact that current policies determining strategies for the household sector are based on modelling assessments, which assume a homogenous population and monitoring benchmarks for policies are gauged according to average households (BMWi 2018). This oversimplifies the assumptions for the household sector and leads to one technology (and therefore policies, measures and targets) identified as the most cost-effective solution to meet a particular demand. An average household does not adequately capture the observed technological diversity and the differences in investment decisions and consumption behaviour across different types of households and does not account for barriers to actual investment behaviour on the part of this sector. Therefore, there is a need to differentiate between the financial and decision-making ability of different households to be able to better determine how to meet the required investment demands leading to the achievement of sector-specific renewable energy and energy efficiency targets, especially when aiming to stimulate an increase in the numbers of prosumers, which is contingent on the mobilisation of capital from the private sector. To be able to determine how policies such as carbon taxes affect households and influence household energy vulnerability, it is insufficient to use methods applied to averaged households. A holistic methodology will account for the differentiated situation of households within the context of the energy transition.

3 Characterisation of the Household Sector in Germany

The characterisation of the household sector in Germany within the context of the energy transition is based on an evaluation of the drivers of energy-related investment and consumption patterns. Households are responsible for a significant share of the final energy consumption with 27.5% of the total final energy domestic consumption (excluding mobility) and 10.1% of the total greenhouse gas emissions (AGEB 2019; BMU 2018, 2019; BMWi 2021b). Households in Germany are expected to increase shares of renewable energy use in heating and self-generated electricity while also decreasing energy consumption (or increasing energy efficiency) in line with energy transition targets (BMWi 2019). The majority of household energy consumption goes towards end-uses for space heating and water heating met largely with gas and oil with the average household in Germany consuming 57 GJ annually, spending 1,644 € on consumption (direct household energy expenditure excluding mobility) and 564 € on investments (linked to indirect energy expenditure) in 2018 (BMWi 2021a; Destatis 2018). Expenditure is closely coupled to income and the analysis conducted will show that there is a mismatch between the expected financial capacity of the majority of households according to their income levels and that of the average household. Lower income households are disadvantaged on two fronts: lack of capital and lack of decision-making power. Income is a key factor for the ability to alter the household energy infrastructure and degree of reliance on fossil fuels. Key to ensuring the success of the energy transition's objectives is the mobilisation of capital from the private sector. However, investment behaviour is not linear and not always rational. The investment and consumption behaviour of different actors is defined along socio-economic characteristics, preferences, financial capacities, techno-economic aspects and is guided by policy. The influence of these policies and measures on the investment and consumption behaviour of particular low carbon, energy efficient and/or renewable technologies can be further attributed to individual ideals and limited by purchasing power. This Section will describe the disaggregation of the household sector into distinct socio-economic profiles according to differentiated investment and consumption profiles.

3.1 Socio-Economic Disaggregation of Households

In order to be able to analyse the impact of policies and the opportunities households have as actors in the energy system to reduce fossil fuel consumption and emissions, and increase renewables, households need to be characterised by different socio-economic parameters. The disaggregation of the heterogeneous actors within the household sector were categorised considering the major drivers of energy demand based on socio-economic characteristics beginning with building type (single-family and multi-family homes), tenure status (owner/tenant), location (urban/rural) and then income group (disposable income, savings). The basic demographic development of Germany is the main driver of energy consumption as this determines the number and size of homes as well as the associated energy service demands (BMU 2019; Möller-Ühlken and Kuckshinrichs 2007). In 2018, the population increased to 80.3 million living in 40.7 million households with an average household size of 1.97 people per household (Destatis 2013; EUROSTAT 2020). In 2018, which is used as the analysis year for the case study for reasons of data availability, 58% of households in Germany live in rented apartments. Over 88% of households in the lowest income group are tenants, while the home ownership rate in the highest income group is over 75%. A total of 35% of households live in single-family houses, with the highest income group accounting for 30% of all single-family houses. Within this income group, however, more than 68% of all households live in single-family houses. The number of people per household also increases with income: 1.1 people per household live in the lowest income group, and 3.1 people per household in the highest income group (Destatis 2018b).

Income and expenditure are a central component of the socio-economic characterisation of households and determinant of their energy consumption. The disaggregation of the residential sector by income groups for the integration into modelling assessments is not often undertaken, but income has been recognised as a key driver of energy consumption as well as a limit for households to achieve a certain level of energy services in the home (Cayla et al. 2011). Disposable income determines the availability of capital which enables (or restricts) a household to invest in technologies and consume energy (Alberini et al. 2011; Cayla et al. 2011; Kaza 2010; Longhi 2015; Vassileva et al. 2012). Figure 1 shows the average shares of direct (operating costs of consumption) and indirect (investments) monthly energy-related expenditures and shares of income by income groups per household in Germany in 2018 (Destatis 2018b). The income groups are categorised in the national statistics database by household monthly income.

The indirect investments include expenditure on appliances, energy-related home maintenance and renovations. On average, each person spends a total of about 100€ per month on direct and indirect energy expenditures (193€ per household). However, the population per household distribution varies within income groups. The average person spends around 74€ representing 2% of their monthly income on energy consumption (direct energy expenditures and 146€ per household), but while a person from the lowest income group would spend 82€ or just over 11% (82€ per household), a person from the highest income group would spend around 67€ and or under 1% of their income (193€ per household). On average, people from all income groups spend less than ~ 1% of their income on indirect energy expenditures (energy-related investments). These expenditure patterns reveal that the spending on the upgrading of appliances and the home (indirect expenditures) enable lower energy bills. This reflects that higher income households have more disposable income to spend on energy-efficient technologies, thereby translating into savings on current energy expenditures. Investments on indirect energy (i.e. investments in household appliances or housing maintenance and renovations), increase with income (Destatis 2018a). Household sizes (people per household) also increase with income, which

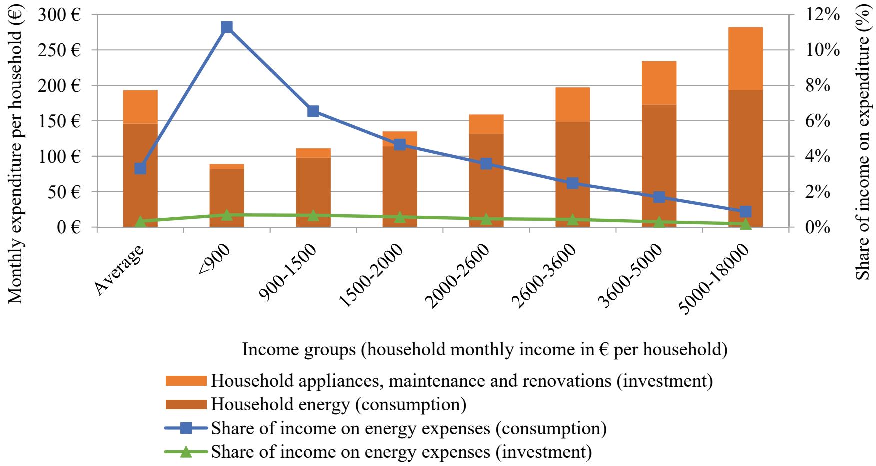

Fig. 1 Income and expenditure by income group per capita in Germany, 2018. *Source* own graph based on (Destatis 2018a) as given in (Dobbins 2022)

means that increased investments benefit a greater number of people. This is critical as the larger investment requirements do not scale proportionately with the number of people, so a single-person household requires one heating system, one building envelope renovation or one refrigerator much the same as a three-person household.

Energy efficiency is outlined as a fundamental step towards not only achieving the energy transition targets but also alleviating energy poverty in European legislation as this addresses some of the underlying causes of energy poverty (European Parliament 2018). Investments in energy efficiency increase with income, which underscores that the greatest energy efficiency potential often resides in the appliances used and buildings occupied by lower income households, who by default, often do not have the financial capital for the high-upfront costs of investments nor the decision-making power as tenants. The challenge will be to mobilise investment in the lower income and rental sector and this begins with the acknowledgement and inclusion of the variation in investment capabilities of households in energy system modelling leading to sector targets and policy measures.

The potential to afford the high upfront investment costs is examined by compiling the potential monthly financial savings accumulated per income group. Less than a quarter (22.2%) of all households save more than the average household with approximately 22.2% and 539€ per month in 2018, which could be considered theoretically available for investments in renewable energy and energy-efficient technologies or building upgrades. While the share of homeowners in the upper income groups has increased over time, the households which both have higher than average savings and are homeowners represents just 16.7% of all households, which underscores the limitations in the potential of these actors to be able to carry the burden of achieving the household energy transition targets.

3.2 Household Energy-Related Investment and Consumption Patterns

As income increases so does the size of the dwelling and the number of people per household. The socio-economic parameters and the living situation determine the energy consumption profile of a household and this correlates directly with the financing and decision-making ability of a household to make the necessary investments to reduce its dependence on CO_2-emitting energy sources and thus to a CO_2 price to be able to react.

Based on the population distribution into the actor groups, an energy balance was developed for 56 distinct profiles that took into account the differentiation of various actors or groups within the household sector where it was first necessary to characterise the drivers of energy consumption. While some of the drivers of household energy consumption are interlinked and cannot be distinguished which influence on energy consumption they have from one another, they can nonetheless be summarised into the following key categories: (i) demographics, (ii) income and expenditure, (iii) dwelling characteristics (including tenure, location, building type and heating structure), (iv) access and use of self-generation technologies, (v) appliance stock and use, and (vi) energy efficiency—current status and potential. Decisive to all of these demand categories is also the access to infrastructure for specific fuel types and the capability to react to price signals that may shift households to alternate between different options.

Level of urbanisation influences the energy demand and the types of technology investments made in residential buildings due in large part to the access to different energy sources, such as grid-based energy sources like district heating and gas, or some renewable energy carriers (Druckman and Jackson 2008; Kramer 2010; Satterthwaite 2009). The level of access, determined through the level of urbanisation, drives the dependency on specific fuel types to fulfil energy service demands, such as space heating and will, therefore, result in different consumption patterns (Arbabi and Mayfield 2016; Kleinhückelkotten et al. 2016; Kramer 2010). Home ownership is a significant determinant of energy consumption, which is typically characterised by greater living space and appliance ownership (Destatis 2014; Frondel and Kussel 2018; Li and Just 2018; Schlomann et al. 2004). The greatest potential for energy savings in the household sector lies in buildings, but one obstacle to increased uptake of decentralised energy supply systems and energy efficiency of the building envelope could be the ownership structure (Bird and Hernández 2012; Frondel et al. 2015; Kockat and Rohde 2012; Scott 1997). The building stock is the main determinant of the overall energy consumption in the household sector due to the significance of space heating consumption in overall household consumption. The energy consumption of the residential building stock is mainly characterised through the number of units per building (building type), the age and floor area. The building typology is commonly confined to two main building types: single-family homes (SFH) and multi-family homes (MFH) (Cischinsky and Diefenbach 2018;

Diefenbach and Clausnitzer 2010; IWU 2012; Kockat and Rohde 2012; TABULA 2015).

Applying these energy drivers results in energy-related investment and consumption patterns by the socio-economic profiles. The energy consumption and CO_2 emission profiles of the different households form the basis for the assessment of the effects of CO_2 pricing and the possible relief through redistribution of the revenue. A significant share of fossil fuel consumption also comes from transport fuel consumption, which increases per capita as income increases, as shown in Fig. 2. The profiles for household-related transport are based on the German Mobility Panel (Ahanchian et al. 2020) and are calibrated according to (BMWi 2021b). Lower income households rely to a greater extent on fossil-based fuels, such as oil and gas, than higher income households and since lower income household sizes are smaller, the cost burden is condensed. This shows that the share of energy sources used for heating purposes in the energy consumption profile of low-income households is larger per person, while the share of energy used for transport is lower. This trend is reversed as income increases, which also leads to lower CO_2 emissions per person, however since the number of occupants per household increases as income increases, the total household consumption and CO_2 emissions increase with income. Compared to the average household, households with low incomes have higher per capita energy consumption overall and twice the energy consumption for heating. In contrast, the CO_2 emissions per household in households with higher incomes are well above the German average. These differentiated energy consumption patterns need to be considered when implementing carbon tax policies because of the impact on specific households and their ability to take action.

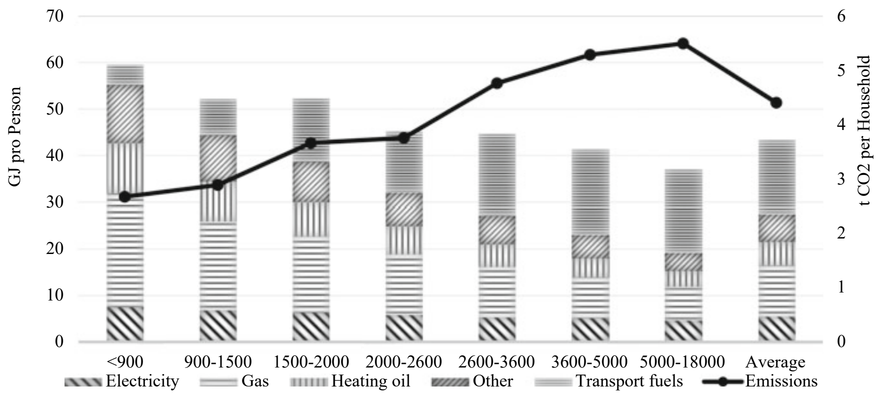

Fig. 2 Energy consumption for heating and transport per person and CO_2 emissions per household by income group, 2018. *Source* Own calculations based on (Dobbins 2022) according to (Destatis 2018b; BMWi 2021)

4 Carbon Taxes and Redistribution Policies

Since the climate crisis requires measures to reduce greenhouse gas emissions, CO_2 taxes and emissions trading systems have also established themselves as important measures to reduce emissions (Agora Verkehrswende und Agora Energiewende 2019; Vermittlungsausschuss 2019). Carbon pricing has the crucial steering function of signalling to consumers that using the environment as a carbon sink comes at a clear price. These can be applied to the supply sector to encourage electricity generation towards alternative-based energy sources, e.g. renewables. Similarly, the tax can be applied to the demand side where the consumer pays a tax per consumption of carbon-emitting fuels thereby leveraging a financial incentive for consumers to invest into more efficient technologies based on renewable fuels. While the theory is straightforward, the tax can have unintended distributional impacts (Bach et al. 2020). The carbon tax may disproportionately impact lower income households and tenants who lack the financial capacity or decision-making power to alter the structure designating the types of fuels and amount of energy necessary to meet household energy service demands. This relates particularly to the lower income and rental sector without the capital or decision-making abilities to make these required investments. This Section reviews the policies and discourse around the implementation of the carbon tax in Germany as well as approaches to redistribute the carbon revenue.

As concerns grow about the potentially regressive nature of carbon pricing for low-income households, there is an intense debate in Germany on how best to use the funds generated by carbon pricing to counteract this. The redistribution of revenues from carbon pricing is seen as a tool to achieve several goals. It should be ensured that the selected redistribution model mitigates the negative distribution effects, promotes investments in the energy infrastructure in the private sector and increases social acceptance of the CO2 pricing policy (Thomas et al. 2019; Vermittlungsausschuss 2019). In pursuit of balancing out social inequities experienced by some households as a result of the carbon tax, revenues derived from the carbon tax should fund the reduction of the EEG levy on electricity as a means to dampen these distributional impacts (BMF 2019; Harthan et al. 2020), or alternatively to redistribute to the population through a climate bonus (Bundestag 2022). General acceptance of the climate bonus is at risk if there is no steering mechanism in place to ensure that the funds go towards decreasing emissions (Barckhausen et al. 2022). Lower income households are prone to rebound when households invest in energy efficiency, or similarly, consumption may increase by increasing income because households are now able to afford previously unmet household service demands (suppressed demand) (Sorrell 2007). Therefore, it is critical to understand the impacts policies aimed at discouraging fossil fuel consumption and the progressivity of redistribution policies have on different households to better estimate the energy welfare of households in addition to the overall energy and emissions.

In Germany, in terms of CO_2 pricing, all combustibles and motor fuels that are not integrated into the European emissions trading system (EU ETS) (especially for use in heat generation for buildings and in transport) are regulated within the framework of the National Fuel Emissions Trading Act (BEHG). (Vermittlungsausschuss 2019). The entry-level price in 2021 was 25€/t CO_2. The price is set to rise to 55€/t CO_2 by 2025. Subsequently, the fixed CO_2 price system is to become a certificate trading system, in which the CO_2 price is formed freely on the market. A price corridor of at least 55€/t CO_2 and at most 65€/t CO_2 is planned for this in 2026. Based on a field report that will be presented to the federal government in 2024, a decision will be made on the further design of price corridors or fixed prices (Deutscher Bundestag 2019).

Germany is intensively discussing how the revenue generated can best be redistributed in the interests of revenue neutrality in the case of CO_2 pricing. Options include various measures such as funding for electricity price cuts, subsidies for low-income households, renters, heating systems and building renovations, and commuters, or even redistribution to the entire population or specific sections of the population. The government plans to increase the heating cost quota for social welfare beneficiaries in order to compensate for the addition of the carbon tax, and at the same time to evaluate the best way to implement the carbon tax for the rental sector such that tenants are encouraged to conserve energy while landlords are incentivised to invest in energy efficient or renewable heating systems as well as building renovations (Harthan et al. 2020). Finally, it was decided that the additional financial burden of CO_2 pricing should be cushioned, in particular by financing the commuter allowance and reducing the EEG surcharge on electricity (Vermittlungsausschuss 2019). With the coalition agreement of the new federal government (SPD/BÜNDNIS 90/DIE GRÜNEN/FDP 2021), it was also announced that a social compensation mechanism would be developed beyond the abolition of the EEG surcharge in the form of a climate bonus.

Several studies in Germany assess the potential impact of redistribution schemes on different household types and their fairness in terms of offsetting the cost burden of carbon pricing, with each study assessing a different focus, assumptions and redistribution options (Thomas et al. 2019). Here, the overview focusses only on the redistribution options assessed and the assessed impact on low-income households, as some studies also focus on alternative taxation options and other consumer groups. The most common types of redistribution are either general or targeted. An administratively simple option is to distribute the income equally among all people (Kalkuhl et al. 2021; Lange et al. 2019), the so-called per capita redistribution. Another possibility is to only give the income back to low-income households (Frondel 2020). A third option is to redistribute the income to households with particularly high energy costs or a significant burden from CO_2 pricing (Frondel 2020; Kalkuhl et al. 2021; Thomas et al. 2019; Thöne et al. 2019; Venjakob and Wägner 2021).

Each of these options has advantages and disadvantages, with similar trends seen across studies. The expected cost burden and relief by income group varies somewhat across studies, depending on available revenue, population and household distribution, and associated energy use and emission profiles. Sample household profiles are evaluated to show the impact of various parameters such as tenure, commuter status, building type, urbanisation, household composition or combinations thereof (Agora Verkehrswende und Agora Energiewende 2019; Bach et al. 2019; Bach et al. 2020;

Frondel 2020; Kalkuhl et al. 2021; Lange et al. 2019; Thöne et al. 2019; Venjakob and Wägner 2021). In general, it is intuitively understandable that larger households with more people could benefit more from a per capita redistribution, since energy costs do not increase proportionally with the number of people per household, with particularly large households with children benefiting (Agora Verkehrswende und Agora Energiewende 2019; Frondel 2020). Higher income households would benefit less, since overall energy consumption increases with income—mainly due to the associated increase in energy consumption in transport—and the cost burden could exceed the redistribution amount (Frondel 2020). Households that do not rely on fossil fuels for heating energy would also benefit disproportionately as they would pay less CO_2 tax and get more back (Frondel 2020).

With a per capita redistribution, households with high energy costs could be more heavily burdened, such as households with low incomes and high consumption, but also, for example, commuters with high energy bills who depend on motorised private transport and often have no opportunity to use public transport to change (Venjakob and Wägner 2021). But low-income households that are unable to reduce their emissions could also be disproportionately affected (Frondel et al. 2018). According to these studies, the expected burden from the additional CO_2 pricing alone is higher for households with low incomes in absolute figures and in relation to income or consumer spending than in other income groups, especially those with high incomes. Accordingly, the notion of a regressive effect of CO_2 pricing is confirmed. However, the results of the studies vary with regard to the benefit of a per capita redistribution of the revenue from CO_2 pricing. Lower income households could benefit from an overall lower consumption of CO_2-emitting fuels (Agora Verkehrswende und Agora Energiewende 2019; Bach et al. 2020), unless they cannot invest to reduce their dependence on technology based on fossil fuels (Frondel 2020). In certain cases (e.g. long-distance commuters, one-person households, tenants, households with oil heating), households with low incomes may need additional, targeted financial support in addition to redistribution per person (Agora Verkehrswende und Agora Energiewende 2019; Bach et al. 2020; Frondel 2020; Kalkuhl et al. 2021; Thomas et al. 2019).

These approaches usually assess the effects of redistributing funds based on a per capita redistribution, measured using quintiles or deciles of the income distribution. However, such an approach distorts the effects of such relief measures, since the parameters relevant to the energy transition are not taken into account. The distribution of the population and households according to income is a key component for determining CO_2 emissions as a function of socio-economic parameters. When evaluating CO_2 pricing variants by income group in relation to the population, the lowest income group contains 2.6% of the population and 4.9% of households, while the highest income group represents 30.1% of the population and 22.2% of the households. As described in Chapter 3.1, the distribution of the population and households by income groups has implications for the investment and consumption requirements. The aggregation of the statistical income groups into income deciles in relation to the population means that the differences in financial possibilities (income) and energy consumption (based on factors such as the number of people per household or the type of building) are combined in one decile from different income groups, so that these are merged into profiles that do not adequately take into account the heterogeneity, particularly in the case of lower income households. Breaking down the population into income brackets instead of deciles provides a more detailed insight into household energy use and financial capacity, as the heterogeneous determinants of energy use, such as regional, technological, access and building factors, and financial capacity are directly accounted for, as well as the household size. Every household, regardless of the number of people living there, needs a heating system. With an increasing number of people in the household, the installation and consumption costs are also spread over more people.

The per capita redistribution may be a simpler solution from an administrative point of view, but a redistribution per household, which seems similarly easy to implement, can better reflect the needs of the households. The question of how the revenues are to be distributed and whether this increases the social acceptance of carbon pricing depends on an analysis of the population and their living situation and how this correlates with the energy transition in terms of the financial burden of carbon pricing. Therefore, an overarching energy system optimisation model is a tool ideally placed to assess the long-term effects of policies on energy and emissions and should be developed to also incorporate the differentiated socio-economic disaggregation of the household sector.

5 Energy Welfare of Households within the Context of the Energy Transition

Typically, the household sector in Germany is represented in energy system optimisation modelling exercises as one homogeneously defined average household representing all households, disaggregated only by building type or location (BMWi 2018), which oversimplifies the situation and leads to one technology identified as the most cost-effective solution to meet a particular demand. The expected contribution from the household sector towards achieving the targets hinges on energy system analyses performed based on the profile of average households. Despite increased granularity of various attributes in the building sector (e.g. such as investor-specific barriers, ambience heat distribution and uptake of policies and measures), recent assessments have found that the building sector does not now nor will it meet the expected targets for 2030 (Repenning et al. 2020). These additions still do not allow an assessment of the energy welfare of households and so may still underestimate the impact on lower income households and overestimate the possible contributions from the household sector towards achieving the overall objectives of the energy transition. The TIMES (The Integrated MARKAL-EFOM System) model generator is a least-cost optimisation, bottom-up, technology-rich, linear-programming energy system model that can be applied to analyse the implications of a range of pathways for long-term energy investments and to identify least-cost measures to realise the climate and energy objectives of a particular region through the integration of relevant energy policies and technologies under a detailed technical and socio-economic framework (Loulou et al. 2016; Loulou et al. 2016). The TIMES modelling framework has a detailed representation of energy technologies and their linkages across sectors (or actors) and considers the interdependencies of the energy system. This enables the analysis of the competition and substitution effects between technologies and provides detailed results of the energy flows, capacity investments, emissions and costs. The TIMES framework is applied towards the development of a household sector model (the TIMES-Actors-Model (TAM) Households) with high actor resolution to enable the analysis of parameters around access and affordability, which are key to account for the differentiated needs and capabilities of energy-related investment decisions households make for building-related investments within an energy system model.

5.1 Disaggregation

Disaggregating a model to more specific user profiles is very data-intensive, especially in the case of this bottom-up energy system model, where each actor will need to be defined in terms of demands, technologies, buildings and the associated socio-economic projections. Disaggregation is also the cornerstone for integrating consumer investment and consumption behaviour, particularly with regard to developing policies to improve the electricity consumption of households through energy efficiency measures (Gouveia et al. 2015; Jones et al. 2015; Sütterlin et al. 2011) or to account for other socio-economic factors, location, consumer or occupant-related behaviour (Druckman and Jackson 2008; Jaccard 2015; Leroy and Yannou 2018; Li and Just 2018; Reveiu et al. 2015; Tomaschek et al. 2012). The basis for modelling households as actors is the statistical investment and consumption behaviour by end-use for households in order to adequately capture and assess the socio-economic parameters (Destatis 2013).

As shown in Fig. 3, the final model disaggregation includes income group, tenure status and building type-specific profiles, energy service demands and technologies. The energy service demands are determined exogenously for each profile-defined building and are based on techno-economic assumptions for the development of technologies and the political and socio-economic framework as the key drivers for demand. This model is dynamic in that the population can shift into other income groups and buildings over time, thereby allowing a better representation of the shifts in energy demands precisely because the demands are directly related to the defined socio-economic profile.

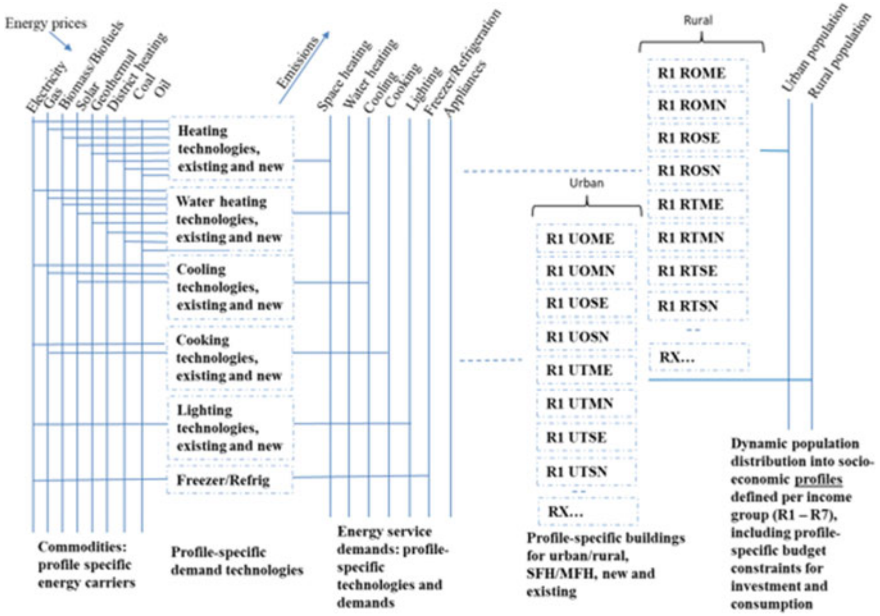

Fig. 3 Reference Energy System for the household sector in TAM-Households.[1] *Source* Own calculations as given in (Dobbins 2022; Dobbins and Fahl 2022b)

5.2 *Budget Constraints*

Income, expenditure patterns and available savings are key factors in affordability of household energy services (Alberini et al. 2011; Cayla et al. 2011; Kaza 2010; Longhi 2015; Vassileva et al. 2012). Available capital is essential to cover the costs of consumption as well as the investment costs of new or alternative technologies and measures. Modelling affordability is about: (i) understanding and incorporating the dynamics within income groups and within the profiles, (ii) reflecting the affordability of each profile according to the budget constraints, (iii) reflecting the present value of future cash flows through the application of appropriate discount rates and iv) incorporating the applicable coping mechanisms to meet needs with limited budget, such as extending the technical lifetime of technologies and/or buying second-hand appliances—which have lower upfront, but higher operating costs. The model restricts the financial ability of households to invest in the high upfront cost of appliances to better reflect the actual potential in overall capital investments by determining the overall available budget per profile based on statistical analysis of the disposable

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[1] Income groups are disaggregated by monthly income per household R1: < 900€, R2: 900–1500€, R3: 1500–2000€, R4: 2000–2600€, R5: 2600–3600€, R6: 3600–5000€, R6: > 5000€; Location by U = Urban, R = Rural; Tenure by O = Owner, T = Tenant, Building type by M = Multi-family home, S = Single-family home, Building age by E = Existing, N = New.

income, savings, GDP and typical investment patterns (Destatis 2018b; IMF 2019a, 2019b).

Based on (IMF 2019a), the GDP per capita in Germany is projected to increase by 81.4% between 2013 and 2060 from 36,948 €2015/cap to 67,0715 €2015/cap. With a total available capital (actual investment and consumption expenditure plus available savings) of 179 billion € in 2013, the distribution across income groups is projected to increase to 631 billion € in 2060 (Dobbins 2022). The majority of the wealth in the household sector resides in the upper two income groups. This available capital is further distributed per defined profile within each income group according to projections of the shares of households and population. These figures are used to define the budget restrictions for each actor group in the model described in the next section. The overall household energy budget is considered by including this into the assessment for households service needs. This additional disaggregation better reflects the holistic financial and decision-making power of specific actors in the household sector and is previously not reflected in modelling assessments for long-term energy planning in Germany. The investment limitations are represented with household budget constraints for each defined profile based on the available savings for each income group. This budget constraint represents the statistically available savings for each income group and is considered as the potentially available budget that households could invest in more efficient or renewable-based end-use technologies (heating, water heating, lighting and other appliances), retrofit the building and small-scale PV rooftop power generation (playing a role as prosumer).

The model takes into account the limitations in the available budget for each actor group through the implementation of profile-specific budget constraints. The budget constraints for each profile are calculated based on available statistics on income-specific typical investments in energy appliances, energy improvement investments and savings (Destatis 2013). The budget restriction is applied to each actor group through a user constraint on the investment and consumption costs (Ahanchian et al. 2020). This budget constraint is applied to all investments in owner-occupied households. Similarly, the budget constraint is included for tenants, but applies only to technologies which they have the decision-making power to replace and therefore excludes heating, water heating and PV technologies as well as building renovations. Instead, these investments include a higher discount rate to represent the apprehension of landlords to make costly investments in properties from which they may not derive a benefit, as outlined by the landlord/tenant dilemma (Bouzarovski et al. 2018; Griffiths and Causse 2010).

5.3 *Incorporation of Policies and Measures*

Policies and measures can be modelled as constraints according to particular targets (Senkpiel et al. 2020) and were modelled in TAM-Households in line with the policies and measures influencing energy use in the household sector, such as targeted greenhouse gas emissions. Methods to model energy-related policies and measures are largely adapted from TIMES-D (Fais 2015; Haasz 2017) and further developed within the Decentral project (Ahanchian et al. 2020). In TAM-Households, it was necessary to apply constraints (e.g. renovation rates, market shares for specific technologies or energy carriers) to achieve these targets for the whole sector or according to the profiles defined (e.g. homeowners, building type, location, income group). Measures, such as subsidies, grants (financial incentives) and taxes can be included through a price reduction on the fuels or technologies for specific actor groups (e.g. income group, homeowners). Specific policies and measures modelled include the decarbonisation targets and carbon taxes implemented in the scenarios. The decarbonisation target applies a zero emissions target in 2050 whereupon the model finds the least-cost pathway to achieving this target given other variables and constraints in the model, such as the budget constraints. Environmental taxes, such as carbon taxes, are added to carbon-emitting fuels and related to the consumption by each specific actor groups represented in TAM-Households.

6 Results

The majority of investments to achieve the goals of the energy transition in households will have to flow into increasing energy efficiency and into a higher contribution, directly or indirectly via secondary energy sources such as electricity, district heating or hydrogen, to renewable energies through building renovation, heating replacement and new means of transport. Low-income households are unable to meet these demands and risk being left behind in the energy transition. The majority of households lack financial capital or the decision-making power to make the necessary investments. Providing additional financial support to low-income households would enable them to pay their energy bills and provide a platform for infrastructure investment. The TAM-Households model was applied to analyse the impacts of financial support provided through the redistribution of carbon revenue. The method of including disaggregation and the budget constraints means that it is possible for a rich analysis of the impacts on energy and emissions for different household types. The results in this section explore the impacts of the carbon tax in general on different households according to their socio-economic parameters, followed by an analysis of the distributional impacts of various approaches to applying redistribution schemes.

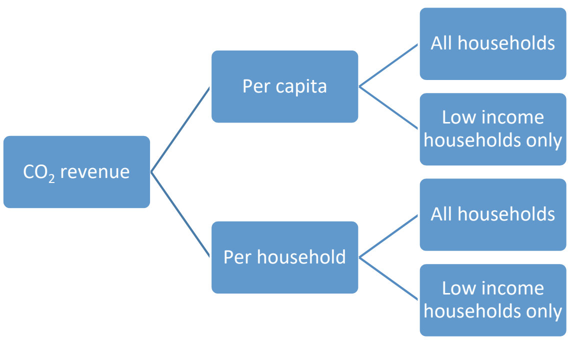
6.1 Scenario Descriptions

Several scenarios are defined in the TAM-Households model and compared against a reference scenario. The reference scenario includes the TAM-Households methodology with the disaggregation and the budget constraints as well as all expected policies implemented underpinned by the same socio-economic development and price assumptions. In order to compare the effects arising through different redistribution approaches, four variations are contrasted with the reference scenario. While the current method to be deployed is to collect a carbon tax according to the consumption of fossil fuels and then, to redistribute this through a tax relief per kWh electricity consumed (Vermittlungsausschuss 2019), other options discussed include reallocating the funds through a ‘climate bonus’ at 100€ per capita annually (CB scenario) as explored in other studies (Kalkuhl et al. 2021). Another approach is explored in the CBLI scenario where the climate bonus is provided to the lower half of the population only but increased to 200€ per capita annually. However, as described previously the capital-intensive investments are bound to the household infrastructure, which must be implemented irrespective of the number of occupants. Therefore, two further approaches for redistribution are also explored. In the CBHH scenario, each household irrespective of occupants or income are provided the same subsidisation amount related to the equivalent of 100€ per capita and equals 193€ per household annually. One further scenario (CBLIHH) provides the per household subsidy but again only to the lower half of the population, which increases the allocation to 383€ per household annually. These scenarios are summarised in Table 1 and Fig. 4.

Table 1 Scenario description: Improving the energy welfare of households

Socio-economic framework (GDP, population growth, energy prices, etc.)	
TAM-HHs/ REF	Disaggregated, all expected policies implemented, budget constraints
CB	Annual climate bonus; 100€ per capita; carbon tax; EEG surcharge without levy relief
CBLI	Annual climate bonus only for half the population (lower incomes); €200 per capita; carbon tax; EEG surcharge without levy relief
CBHH	Annual climate bonus; 193€ per household; carbon tax; EEG surcharge without levy relief
CBLIHH	Annual climate bonus only for half the population (lower incomes); 383€ per household; carbon tax; EEG surcharge without levy relief

Fig. 4 Overview of approaches to carbon redistribution schemes analysed



The effect that can be compared is the compensation of the carbon tax with a reduction in the electricity levy in the reference scenario (REF), or applying a carbon tax without the electricity levy reduction while redistributing the carbon revenue to the population as a means to compensate the impact and the means of defining the allocation (i.e. per capita or per household). The redistribution simulates a fixed amount of carbon revenue with alternative reallocation amounts so as to compare the impacts. It should be noted that as households invest in renewable energy and energy efficiency, the fossil fuel dependency will decrease and so will the carbon revenue.

6.2 *Impact of Carbon Tax*

The reference scenario details the impact of the carbon tax policy with a tax on the consumption of fossil-based fuels including funding a reduction on the renewable energy levy on electricity consumption. This levy relief should, in part, act as a compensation for any unfair effects on specific households. The carbon tax should incentivise households to invest in renewables and energy efficiency, while electricity levy relief incentivises a shift to renewable and electricity-based consumption (e.g. in heat pumps). These will impact households differently according to socio-economic parameters in 2025 and the annual financial expenditure and compensation per household is shown in Fig. 5. Lower income households consume more fossil fuels and less electricity and therefore pay more on carbon taxes than they receive in levy compensation. The carbon tax burden increases with income up to medium-income households, but decreases in the highest income groups. Higher income households are greater consumers of electricity and therefore benefit from a reduction in the electricity price since fossil fuels make up a smaller share of the total consumption resulting in lower carbon tax contributions. These trends indicate that the policy results in a disproportionate burden on lower income households.

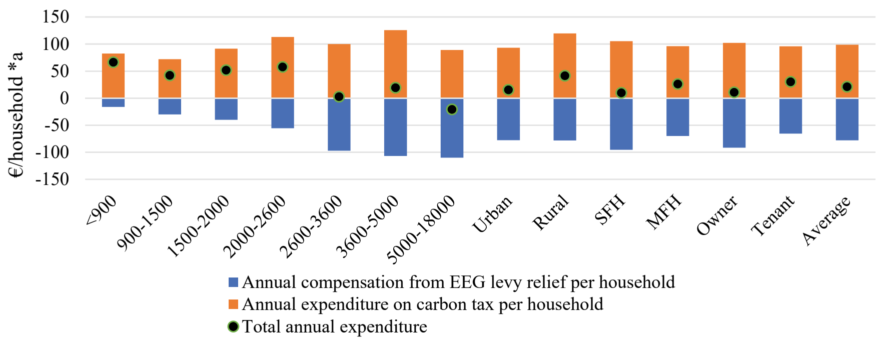


Fig. 5 Comparison of annual expenditure on carbon tax and EGG levy relief per household by socio-economic parameters, 2025. *Source* Own graph as given in (Dobbins 2022)

Some studies point to different trends. Lower income households are assumed to consume greater shares of electricity which would mean households are compensated overall (Kalkuhl et al. 2021). Bach et al. (2020) agree lower income households would be disproportionately impacted by the carbon tax, but find that the electricity levy reduction compensates the financial loss. The difference lies in the input data for the assessments. Both studies assume constant electricity consumption per capita regardless of income level, while the energy balance in the present study developed a bottom-up calculation of all fuels according to socio-economic parameters thereby accounting for household size, appliance ownership, building type and access to technologies and resources. Lower income households typically have fewer occupants per household than higher income households, but some electricity-based appliances will consume the same amount of electricity without regard for the number of occupants. This consumption is distributed per capita, which reduces per-person consumption as the number of occupants in the household increase.

The disaggregation of the household sector also allows the analysis of the impacts for occupants by location (urban or rural), specific building types (SFH and MFH) and ownership (owners or tenants). A just allocation of the cost burden between landlords and tenants has been debated in parliament with various proposals discussed to ensure that landlords are incentivised to make investments. Given the share of households as tenants, this sector has a significant potential and role towards achieving emissions targets (Schultz 2021). While owners and tenants have similar levels of expenditure for the carbon tax, owners receive more compensation for the electricity levy reduction. Given the diversity of how the carbon tax impacts different household types, it is necessary to understand these discrepancies and as they relate to socio-economic parameters and the selected approach to redistributing carbon revenues.

6.3 Redistribution per Person

An administratively simple way to redistribute the carbon tax is to simply provide each person with an allocation. This first scenario considers this approach for an annual redistribution of the carbon revenue collected into a climate bonus given to all households at 100€ per person (CB) or 200€ only to the lower income half of the population (CBLI). The climate bonus is added in the model as additional available capital per household in the budget constraint, as shown in Table 2, which illustrates that with a per capita distribution the allocation per household increases with income as the number of occupants increases.

The final energy consumption does not change significantly across scenarios with the final energy consumption in the CB scenario resulting in 1,781 PJ (52 Mt CO_2-eq) and the CBLI scenario resulting in 1788 PJ (54 Mt CO_2-eq), compared to the Reference scenario with 1,736 PJ (54 Mt CO_2-eq) in 2030, as shown in Fig. 6. The REF scenario exhibits greater shares of electricity consumption compared to either Climate Bonus scenarios since the electricity levy relief is not provided and therefore disincentivises electricity consumption. The addition of the carbon tax without the

Table 2 Average annual additional budget per household by income group and redistribution scheme based on a per capita redistribution (€$_{2015}$)

Scenario	< 900€	900–1500€	1500–2000€	2000–2600€	2600–3600€	3600–5000€	5000–18,000€	Average
CB	101	128	152	183	228	217	202	193
CBLI	203	257	303	367	456	11	–	182

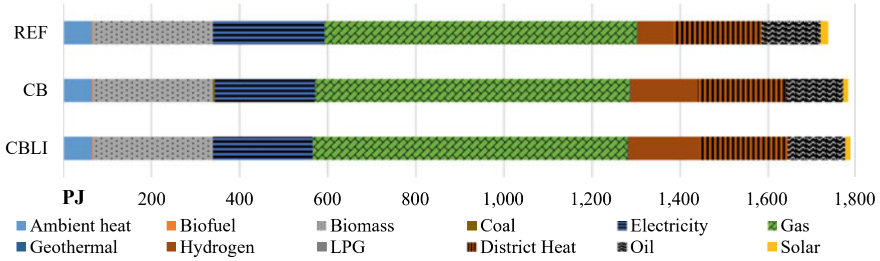


Fig. 6 Final energy consumption in all households by energy carrier and scenario, 2030. *Source* Own graph as given in (Dobbins 2022)

EEG levy relief on electricity, however, results in higher demand to use the existing gas infrastructure together with a hydrogen or biofuel blend in favour of replacing existing technologies with alternatives in both Climate Bonus scenarios since households are unable to afford the high upfront investment costs for technologies. The shares of renewables shift only slightly from 20.6% in the REF scenario to 19.8% in both climate scenarios, while the share of fossil fuels reduces only slightly from 48.5% in the REF scenario to 47.6% and 47.2% in the CB and CBLI scenarios, respectively. Biomass continues to play a significant role in the fuel mix because the pricing is competitive in relation to the increasing carbon tax on fossil fuels.

In typical modelling assessments, it is not possible to assess the distribution of energy, emissions and costs on different household types and the added capital injection to households as provided through the redistribution scheme results in little differences to the overall emissions. Through the disaggregated assessment, it is possible to analyse the impacts according to the defined socio-economic parameters. Examining the energy consumption profiles of the lower four income households reveals significant differences in consumption across the scenarios, as shown in Fig. 7. The equal annual allocation of 100€ per capita in the CB scenario increases the average consumption to 34 GJ per household from 31 GJ per household in the Reference scenario. When the allocation is doubled and provided only to the lower income groups in the CBLI scenario, the consumption increases to 35 GJ per household. Fossil fuel shares reduce from 63% in the Reference scenario to 62% in the CB scenario and 59% in the CBLI scenario. While renewables make up 7.2% in the Reference scenario, these decrease to 5.6% in the CB scenario and increase to 7.9% in the CBLI scenario. This indicates a greater shift for the lower income households in the CBLI scenario towards renewables and away from fossil fuels compared to both other scenarios. In 2030, the end of the technological lifetime of the majority of space heaters is reached and requires replacing. Since insufficient budget has been accumulated in the lower four income groups to this date to afford infrastructural changes, the key bridging solution is to blend fuels, for example, with hydrogen or biofuels. In subsequent modelling periods, sufficient budget is accumulated for alternative investments and the use of hydrogen and biofuels disappears again. While the CBLI scenario shifts a greater extent of the demand to network supply, such as

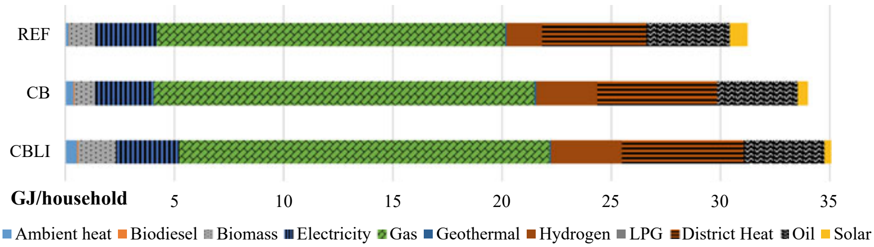


Fig. 7 Average energy consumption per household for the lower four income groups, 2030. *Source* Own graph as given in (Dobbins 2022)

district heating and gas, and higher input fuels, such as biomass, the CB scenario reduces carbon-intensive fuels, including gas and oil, to a greater extent than in the other scenarios. None of the scenarios exhibit substantial investments into energy efficiency measures where the REF scenario incorporates an energy efficiency equivalent of an average of 0.07 GJ per household and each of the climate bonus scenarios an average of 0.1 GJ per household. However, an analysis of energy consumption alone does not render sufficient information about the energy welfare of households.

The addition of the budget constraints related to the disaggregation in the methodology allows an analysis of the budget deficit experienced by households in meeting energy-related investment and consumption patterns. The budget deficit is translated into a quantification of the suppressed demand and provides an insight into the energy welfare of households. Suppressed demand is experienced extensively by lower income households in the REF and CB scenarios, and is reduced significantly in the CBLI scenario, as shown in Fig. 8. In 2030, 11.4 million people require an additional 84€ each in the REF scenario, with a redistribution of 100€ per capita in the CB scenario, suppressed demand reduces to 5.7 million people requiring an additional 52€ each. This shows that the additional budget supports the additional consumption of energy for previously unmet needs, but still remains insufficient to eliminate it. By increasing the redistribution to 200€ and targeting it to the lower income households only, the suppressed demand diminishes the number of households suppressing demand to 131,000 people requiring an additional 118€ each.

The trends in investment and consumption patterns highlight how additional capital influences suppressed demand in Fig. 9. The investment profiles in the REF and CB scenarios follow similar trends to 2040. While households in the REF scenario can only make investments once a sufficient budget has been accumulated, households in the CB scenario have additional budget but opt to increase consumption expenditure while making steady investment expenditures. In the CBLI scenario, both investment and consumption expenditure increase, which results in a greater degree of suppressed demand than in the other two scenarios.

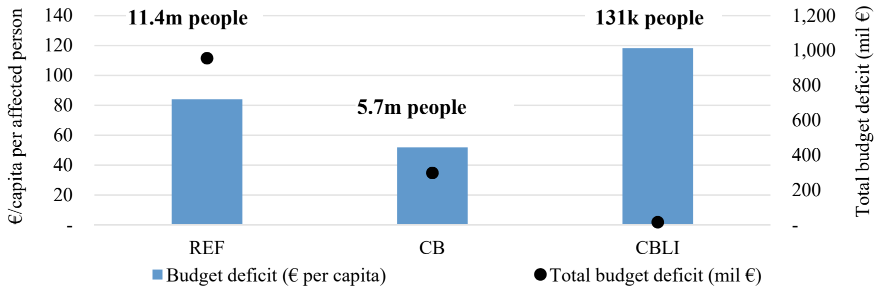


Fig. 8 Average suppressed demand per capita for the affected population by scenario, 2030. *Source* Own graph as given in (Dobbins 2022)

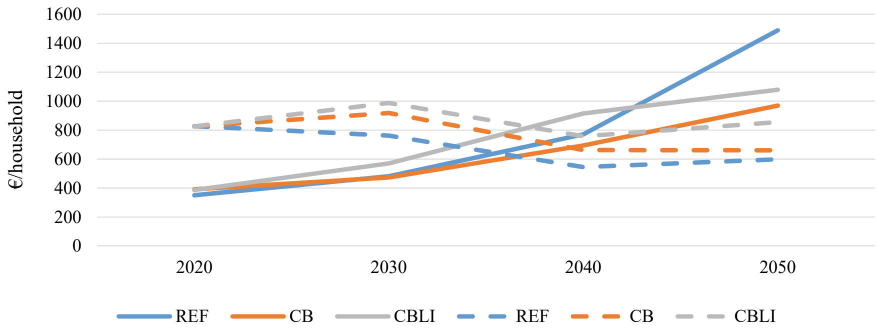


Fig. 9 Investment and consumption trends in the average lowest four income groups by scenario, 2020–2050. *Source* Own graph based on (Dobbins 2022)

6.4 *Redistribution per Household*

Investments in building infrastructure will require households to be able to afford the high upfront costs and the key driver for these investment are the home and not the number of people living there. As such, these next scenarios compare an annual redistribution of the carbon revenue to each household rather than to each person. In general, with a redistribution of the budget per household instead of per capita, each household receives an additional annual budget of 193€ each (CBHH scenario). When these funds are redistributed to the lower income half of the population only, these households receive an additional annual budget of 383€ each (CBHHLI scenario). As highlighted in Fig. 8, the total budget deficit in the REF scenario totals 955 million Euros annually. A redistribution of 193€ per household surpasses this deficit, such that the suppressed demand is eliminated with an administratively more simple distribution across each household. With a redistribution across lower income households only, the model does not produce different results compared to the redistribution across all households, therefore, the analysis focusses on the redistribution across all households only. Compared to the REF scenario, the

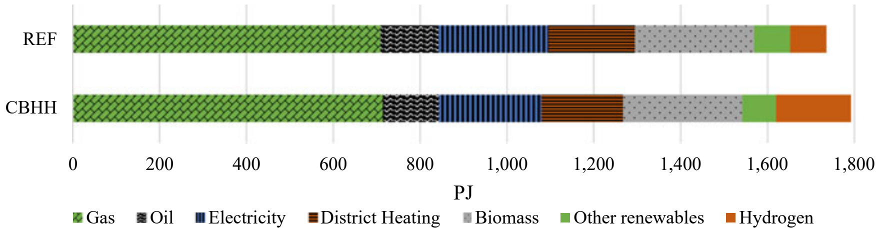


Fig. 10 Total final energy consumption across all households by fuel type, 2030. Source Own graph as given in (Dobbins 2022)

CBHH scenario results in overall shares of 47.1% fossil fuels and 29.3% renewables and 2.6% less emissions, as shown in Fig. 10.

A closer examination of the total energy consumption profiles by socio-economic parameters and fuel type is explored in Fig. 11. The overall shares of fossil fuels and renewables indicate that the share of fossil fuels decrease with income while the share of renewables increase with income, while owners (typically with higher incomes) consumer more renewables and less fossil fuels.

The results are analysed further to compare the cost burden from the carbon tax paid on gas and oil fossil fuel consumption and the compensation received from the climate bonus and are presented in Fig. 12 as a percentage of net household income. In the CB and CBLI scenarios, the climate bonus is redistributed per person,

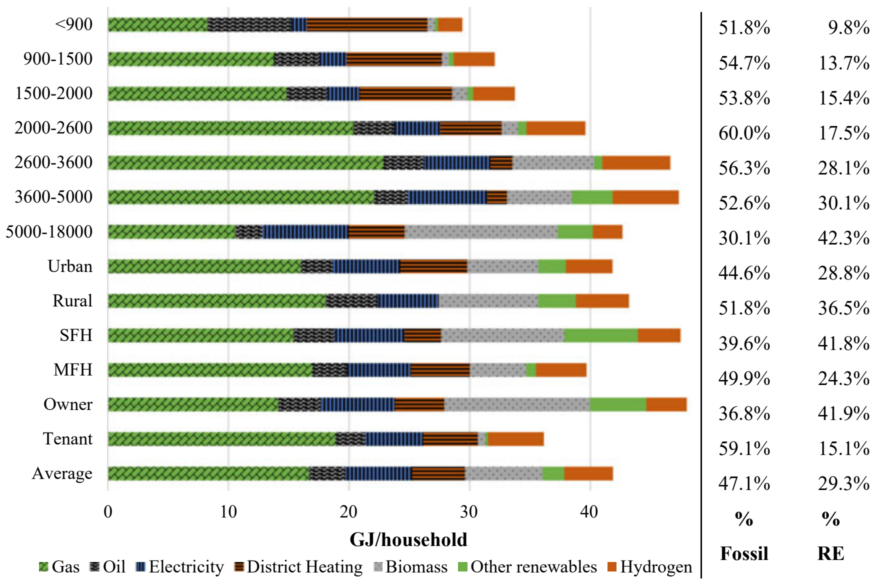


Fig. 11 Final energy consumption per household by fuel type and socio-economic parameter, 2030. Source Own graph as given in (Dobbins 2022)

while the CBHH scenario redistributed the carbon revenue per household and the reference scenario has no redistribution. The effect of CO_2 pricing remains regressive even with a per capita redistribution. The reference scenario indicates that the majority of households spend more on the carbon tax than received in compensation. In the CB scenarios, the carbon tax burden outweighs the compensation for lower income households while higher income households benefit. When the redistribution is targeted to compensate only lower income households, these households benefit substantially while higher income households receive less compensation than they pay. Redistributing the carbon revenue to all households benefits all households, with lower income households benefiting to a greater extent than higher income households. This better aligns the redistribution with the needs of the households, so that redistribution per household in the lowest income group achieves a net benefit of + 1.0% of the net household income (CBHH), compared to 0.2% with a per capita redistribution (CB). The average household benefits in the CB and CBHH scenarios and are negatively affected in the CBLI and REF scenarios.

These variations across income groups change with parameters such as the heating structure (oil and gas heating), tenants without decision-making power or residents of multi-family homes. The result is whether the climate bonus has a progressive or regressive effect. Linking the redistribution of carbon pricing revenues to the number of households irrespective of the number of people living in a building provides a better opportunity of involving low-income households in making investments.

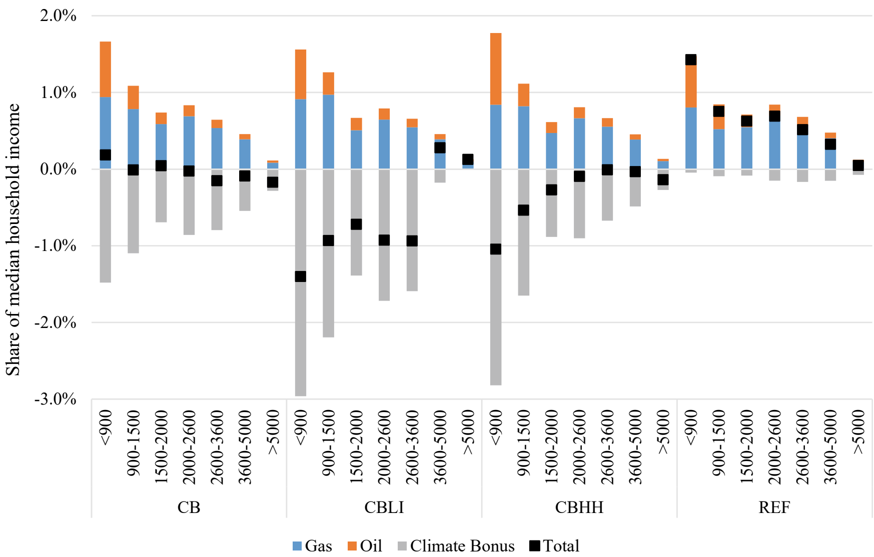


Fig. 12 Carbon tax cost burden (positive values) and redistribution compensation (negative values) for the scenarios by income group, 2030

6.5 Discussion

A key challenge in the energy transition, which demands action from the private sector is to ensure that emissions are reduced. Carbon pricing is a common policy to disincentivise fossil fuel consumption and incentivise investments for renewables and energy efficiency. Lower income households and tenants do not have the financial or decision-making capacity to make the necessary investments to shift their underlying household infrastructure. Carbon revenue redistribution schemes aim to compensate households that may be disproportionately affected by carbon pricing policies. This study compared four approaches to redistributing carbon revenue to a reference scenario with no compensation scheme. This additional capital to the available budget[2] per household in each income group, which increases with income due to the larger household sizes. The lower income groups remain below the average additional budget in the CB scenario due to the amount of debt and inability to accumulate savings while the higher income households have greater incomes and savings at disposal.

The common methodology to assess the effects of CO_2 pricing and the redistribution of income based on the population, underestimates the social consequences. Higher income households receive net benefits with a per capita redistribution while lower income households pay more in carbon taxes than they receive in compensation. Targeting the redistribution to lower income households only provides the necessary support these households require to shift the underlying household energy infrastructure. This relates to the types of investments required to achieve the household sector energy transition targets. Regardless of the number of people living in a house, each home will need only one building-related investment, such as for renovation or a heating system. Therefore, progress towards achieving the goals and supporting low-income households can be better achieved through a redistribution program per household. This also increases the social acceptability of CO_2 pricing in contrast to a per capita redistribution, in which households with low incomes are disadvantaged on average.

This study showed that the focus is specifically on the effects of carbon pricing and the redistribution of the revenues generated to low-income households. For this purpose, the usual, purely arithmetic redistributions, which concentrate on a per capita redistribution, are being switched to a needs-based approach that would better reflect the financial and decision-making abilities of the households. This would ensure that the assessment of the impact of carbon pricing options on low-income households is more in line with their needs and requirements for participation in the energy transition and that they are not disproportionately affected without the possibility of mitigation measures to benefit.

[2] The available budget is calculated based on a statistical regression analysis of actual spending and savings (or debt) according to Destatis (2013a) and projected according to GDP and population prognoses based on (IMF 2019a).

7 Conclusions

This chapter described a methodology developed to better assess the heterogeneous needs and capabilities of households with a view of supporting lower income households within the energy transition process in Germany. The method presented here incorporates disaggregation and budget constraints to better represent the heterogeneity of the household sector in relation to their needs and capabilities around energy-related investment and consumption. The method was applied to evaluate the impact of policies on household energy and emissions as well as the energy welfare of households.

Carbon taxes have long been implemented as a means to reflect the environmental damage incurred through the combustion of fossil fuels, but these can disproportionately impact lower income households and tenants who lack the financial capacity or decision-making power to alter the structure designating the types of fuels and amount of energy necessary to meet household energy service demands. CO_2 pricing is an important measure to support the energy transition in order to be able to reduce CO_2 emissions efficiently and effectively. However, it can have negative affordability and social impacts on low-income households, particularly those who are already struggling to meet their basic energy needs. The redistribution of the revenue from CO_2 pricing should cushion the effects of the resulting increase in energy costs and provide financial support for investments in energy efficiency and renewable energies in households. Because the household sector is so diverse, it is important to consider the different needs and capabilities when assessing the effects of revenue redistribution.

The most common methods assess the impact of redistribution, particularly per capita redistribution, using income deciles based on population distribution. The crucial problem is that income deciles based on population distribution aggregate the heterogeneity of household income groups and thus do not correctly reflect and overestimate the financial possibilities of households in the lower income categories. A redistribution of funds per person benefits higher income households more, since higher income households also have more people per household. On the other hand, an alternative redistribution of income per household or per household living in buildings would benefit households with lower incomes more, which is of crucial importance since investments have to be made in the building. However, low-income households often struggle to meet their basic needs, and additional funds from the redistribution of carbon pricing revenues could accordingly lead to higher consumption rather than investment in the building. By linking redistribution to investment in the building, low-income households would be better able to absorb the long-term impact of energy and carbon price increases. Overall, this analysis of CO_2 pricing variants shows that a redistribution based on households and not population recognises the important role of the building as a target for investments in the energy transition. Social acceptance of carbon revenue redistribution schemes can better be guaranteed when investments are channelled into investments that will reduce carbon emissions.

While this study has provided a methodology that vastly improves the overall understanding of investment and consumption patterns in different household types cased on their socio-economic parameters, there are some caveats that should be noted. The geopolitical energy security challenges have shaped consumer energy prices that affect lower income households to a greater extent. The role and influence of prices in energy-economic modelling exercises should be considered. The prices in this study represent pre-pandemic and pre-war energy prices as long-term energy models reflect megatrends as opposed to (hopefully) short-term disruptions. However, under these price assumptions, it is already possible to establish the trade-off investment decisions households make. Higher fossil energy base prices would further justify investments into renewable energy and energy efficiency. To better reflect holistic household budgets, this household model could be coupled with a transport model since transportation is a significant contributor to greenhouse gas emissions and vary considerably.

Designing carbon revenue redistribution schemes must take into consideration not only the impact they have on the energy-related investment and consumption patterns of households but also on energy welfare. This will require methods that take consideration of the differentiated needs and capabilities of households to better ensure that households are able to undertake investments that will shift the underlying household energy infrastructure.

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Households' Energy Demand and Carbon Taxation in Italy

Ivan Faiella and Luciano Lavecchia

1 Introduction

Energy is a fundamental requirement for human welfare: households depend on energy services for heating, cooling, cooking, lighting, food conservation and transportation. The demand for these services changes according to consumer preferences, their spending capacity and to exogenous factors (e.g. technology, climate, etc.). In general, we can expect that in the near future energy demand in Italy will change because of climate change (Campagnolo e De Cian 2022) and demographics (Faiella 2011).

Climate change is expected to increase the frequency and the intensity of extreme weather events, such as heatwaves; this, in turn, will put pressure on vulnerable people (e.g. the elderly), requiring sizable investments for adaptation (Carleton et al. 2020) and an increase in energy expenditure to achieve a standard thermal comfort. Indeed, climate change is already affecting energy demand; IEA (2019) estimates that one-fifth of the growth in global energy use in 2018 was due to hotter summers, pushing up demand for cooling and cold snaps leading to higher heating needs, i.e. climate change will likely shift (and maybe increase) energy consumption from space heating to space cooling. The IEA (2018) estimates that energy demand for cooling services will drive future electricity demand, while Randazzo et al. (2020) find that households adapt to hotter spells installing AC systems and spending between 35 and 42% more on electricity. However, AC adoption is unevenly distributed across income levels (Pavanello et al. 2021) therefore potentially unavailable for poorer households. An ageing population can also alter the patterns of energy demand (Bardazzi and Pazienza 2020).

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In Italy, where life expectancy is one of the highest in the world, almost one-quarter of the population is aged 65 + ; in 2050 it will be more than one-third (ISTAT 2020). This change can influence energy demand in two opposite directions: elderly people spend more time at home, demanding more energy while using less energy for private transport (Faiella, 2011). This pattern is similar to what is expected in a post-COVID scenario where teleworking becomes more frequent (Hook et al. 2020).

In terms of household budgets, the share of energy purchases is typically higher for less affluent households, private transport being an exception (e.g. Faiella 2011). These households will probably see a larger part of their budgets being eroded because of the energy transition, as it happened during the 2021–22 energy crises (Faiella and Lavecchia, 2022). They have less options when energy prices increase and the climate policies needed to achieve the ambitious target of the European Green Deal (a 55% cut in greenhouse gas emissions by 2030 compared with 1990) will put further pressure on prices (because of the support of low carbon sources or because of carbon pricing).

Understanding how households demand and spend on energy services requires granular information: do they reside in areas subject to extreme weather? Are they living in the countryside or big cities? Which are their household characteristics? What about their dwelling type? And, more importantly, will they cope with a progressive increase in energy prices without compressing other basic needs or eroding their income? These questions are more relevant while analysing the impact of climate policies to deploy to curb GHG emissions. In particular, as global carbon price is the economists' recommended choice for tackling climate change (Tirole 2017) but, at the same time, also poorly adopted on grounds of equity concerns, it's fundamental to carefully appraise its distributive impacts and devise compensatory measures (Burke 2020).

In order to try to answer some of these questions, we build a household-level dataset covering the last twenty years to impute the monthly energy demand of Italian households for electricity, heating and private transport. We merge this data with the corresponding prices in order to estimate a set of price elasticities that differs according to households' characteristics and economic conditions. In particular, we model energy demand through a quasi-panel (Deaton 1985), focusing on conditional demand (i.e. taking the choice of appliances as given; Dubin and McFadden 1984; Rehdanz 2007). We use the model for simulating the introduction of a one-off carbon tax on electricity, heating and transport fuels prices; our strategy allows us to estimate the effect of the tax on expenditure and quantities along the expenditure distribution. In all simulations considered the price increase triggered by the carbon tax is regressive: poorer households suffer a greater drop in energy use and a bigger increase in energy expenditure.

The structure of the chapter is the following. After having presented the literature on estimating energy demand (Sect. 2), we describe households' energy expenditure in our dataset (Sect. 3). Section 4 introduces the model for estimating the elasticities that are then used in Sect. 5 to assess how different households would react to a one-off introduction of a carbon tax. Section 6 draws the main conclusions and sets the future research agenda.

2 Literature Review

Households' energy demand—There is a significant amount of research on households' energy demand, the first work dating back to Houthakker (1951). The number of studies increased considerably in the 1970s, after the "oil shocks" (Dahl 1993), with results far from being conclusive. Labandeira et al. (2017) carry out a meta-analysis for a dozen surveys on energy demand while Espey and Espey (2004) report a meta-analysis of 36 papers, with more than 123 short-run and 96 long-run price elasticities estimates of residential electricity demand.

Surveying the estimates of price and income elasticities for electricity, Taylor (1975) observes that price elasticity is larger in the long run. Dubin and McFadden (1984) propose a discrete choice to model the propensity to purchase home appliances and a linear model to estimate the electricity demand (a sequential discrete–continuous model).

Dahl (1993) reviews the energy demand for different fuels (natural gas, oil, carbon, electricity), showing a great uncertainty in the estimates,[1] especially for long-run price elasticity. Only residential energy and gasoline demand studies exhibit some consistency.

Rehdanz (2007), focusing on heating oil and natural gas demand for space heating in Germany, finds a larger price elasticity for oil than for natural gas while Schulte and Heindl (2017) find a weaker response for low-income households (and a higher one for top-income ones).

For Italy, Faiella (2011), by analysing the shares of expenditures for energy purchases, finds that the effect of price changes on the shares is negative for heating and positive for private transport. For electricity, the effect is negative for the 1997–2004 period and positive for the 2005–2007 subsample. Bigerna (2012) observes that the price effect on electricity demand depends on the time of the day (due to the tariffs system in place up to 2016, encouraging off-peak use) and on the geographical zones, ranging between −0.03 and −0.10. Bardazzi and Pazienza (2020) observe that, with respect to the age of the head of the household, electricity demand is hump-shaped, reaching a peak when the head of a household is 50 years old, while natural gas demand keeps increasing with age, as the time spent at home increases. They also show that elasticities for electricity and natural gas (at the national level equal to −0.7 and −0.6 respectively) are higher in the Centre and in the Southern regions.

[1] Dahl (1993) states that "yet despite our attempts, it appears that demand elasticities are like snowflakes, no two are alike.".

3 Data

According to the National Accounts, in 2019 Italian households' energy purchases amounted to €77 billion (€37 billion for electricity and heating and €40 billion for liquid fuels for private transport).[2] In the last 20 years, purchases (in EUR billion) for electricity and heating have decreased by 16% while the expenditure for liquid fuels has dropped by a resounding 37%, taking the corresponding share of total expenditure to roughly 3.5 and 3.8% respectively (from 4.1 and 6.0% in 2000). To understand the drivers of these dynamics (e.g. the demographics, the economic situation and so on), one can analyse the microdata on energy demand. However, only a handful of countries, such as the United States and the United Kingdom[3] collects data on households' energy demand.

Italy, as many countries, unfortunately, does not. As an alternative, we leverage on the expenditure microdata from the Italian Household Budget Survey (HBS), conducted yearly by Istat.[4] The HBS collects information from about 23.000 households interviewed in different periods of the survey year. The HBS data collection is very accurate[5] and it involves a combination of personal and telephone interviews with weekly diaries or logs compiled by households.[6]

We define the energy expenditure of household i at time t as the resources the household earmarks for electricity ($E^{E}{}_{i,t}$), heating ($E^{H}{}_{i,t}$) and private transportation ($E^{T}{}_{i,t}$). Heating includes all heating fuels, such as natural gas (either from a pipeline or tanks), coal, kerosene or wood,[7] while private transport includes gasoline, diesel and LPG (which is used by almost 9% of cars in Italy). Let $Exp_{i,t}$ be the total expenditure.

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[2] In real terms, euros for 2015.

[3] In the United States, for example, the Energy information administration (EIA) collects every five years data on households energy demand, through its Residential Energy Consumption Survey (RECS—latest report in 2015), and on commercial buildings, through its Commercial Buildings Energy Consumption Survey (CBECS—latest report in 2018). In France, the INSEE carries on every year an Annual survey on industrial energy consumption (EACEI) at a very granular level (establishment) for 8.500 establishments. Most of the other western countries, instead, focus on expenditure instead of energy demand. In the UK, since 2008 there has been the Living Costs and Food Survey (LCFS) which replaced the previous Expenditure and Food Survey (EFS), which collects the spending patterns and the cost of living of British households, with 6.000 households surveyed every year. Most of the EU member states carry on Household Budget Survey (HBS) including detailed data on energy expenditure. Eurostat collects data on a harmonised level unfortunately every five years (latest available: 2010). In 2012 the Australian bureau of statistics collected information on household energy expenditure, consumption and behaviours in the Household Energy Consumption Survey (HECS) while some information on energy and water use for firms in the Business Longitudinal Analysis Data Environment (BLADE).

[4] In this work, we use the *Indagine sui consumi delle famiglie* for the years between 1997 and 2013 and the *Indagine sulla spesa delle famiglie* from 2014 to 2018.

[5] The survey reports monthly expenditure for electricity, natural gas, coke, heating oil, district heating, wood…, disaggregated by main and any additional dwelling.

[6] Some information on energy expenditure is also available in the EU Survey on Household Income and Living (EU-SILC), but with far fewer details and for a shorter period (IT-SILC started in 2004).

[7] Between 1996 and 2018, natural gas accounted for 83.4% of total heating expenditure, followed by district heating (8.6%), wood and coal (4.8%) and kerosene and gasoil (3%).

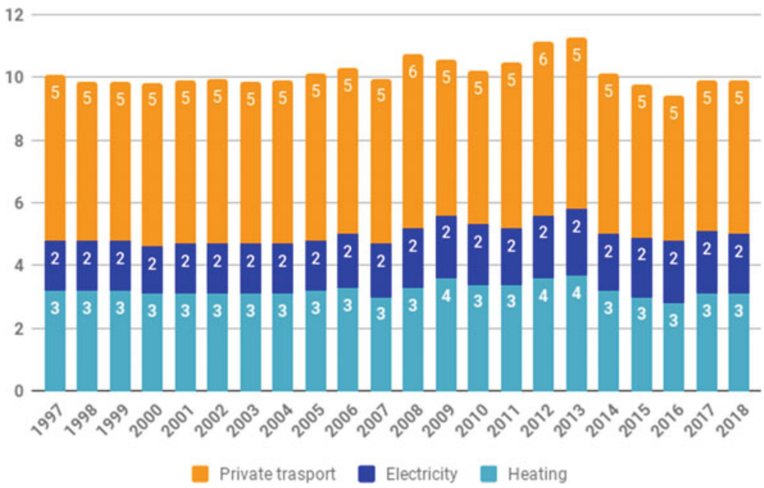

Fig. 1 Share of expenditure by energy use *Source* Authors' on HBS data

The household-level share of energy expenditure, $S^E{}_{i,t}$, is:

$$S^E_{i,t} = \frac{E^E_{i,t} + E^H_{i,t} + E^T_{i,t}}{Exp_{i,t}} \tag{1}$$

Between 1997 and 2018 the average Italian household spent around 10% of its budget on energy, a roughly constant fraction, with the notable exception of 2012–13, when energy prices peaked (Fig. 1) and the share of energy consumption reached 12%. In 2018, the purchase of fuels for private transport represented half of households' energy expenditure, followed by heating (30%) and electricity (17%).

In order to evaluate how this share changes with households' welfare, as there is no data on income in the HBS, we look how the share of energy expenditure is different across the tenth of the expenditure distribution (computing for each *i-th* household the equivalised expenditure as $Exp^{*}i,t = Exp_{i,t}/\gamma_{i,t}$ where $\gamma_{i,t}$ is the household equivalence coefficient).[8] In 2018 the share of energy is just below 10% for the average household, for the bottom tenth showed 13 and 7 for the top tenth (Fig. 2).

With respect to the previous decade—when oil prices were record-high and the share of energy was 10.8%—the situation improved almost uniformly, with a reduction of 1 p.p. for all the tenth of the distribution, except for the extremes. The share of electricity decreases steeply across the expenditure distribution, while the share of liquid fuels appears fairly stable; the share of heating stays between the two (Fig. 3).

[8] We use the"Carbonaro" scale, which assigns a weight equal to 0.6 for a single person household, 1 for a couple, 1.33 for a household with 3 members, 1.63 with 4 members and up to 2.4 for a household with 7 or more members. This is the scale used by ISTAT for its analysis regarding poverty.

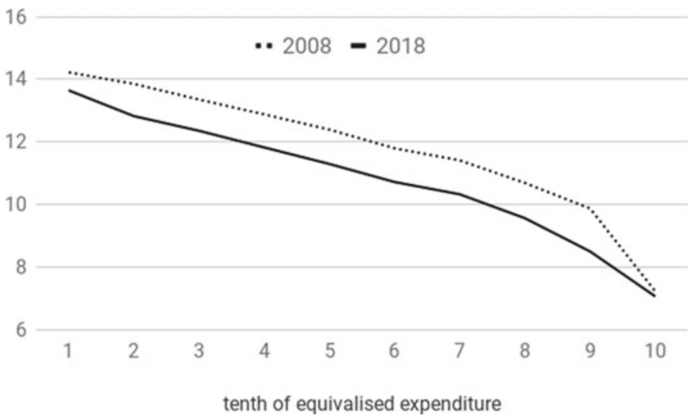

Fig. 2 Energy share by tenth of expenditure: 2008 vs 2018 *Source* Authors' on HBS data

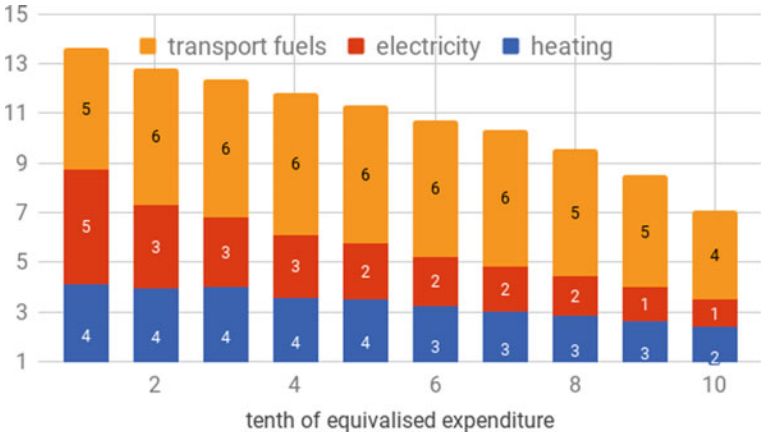

Fig. 3 Energy share by tenth of equiv. expenditure in 2018 *Source* Authors' on HBS data

Following the estimation process described in Appendix A, we are able to analyse energy demand. We estimate energy demand for every year in the sample. For the sake of simplicity, in 2018, an average Italian household consumed 2.500 kWh of electricity, 43 Gj of natural gas and 814 L of fuels for private transportation (see Table 1).

Overall, energy demand decreases over time while it increases with household welfare (Fig. 4, left panel). As a consistency check, we compared the overall energy demand with the Physical energy flow accounts (PEFA) from Eurostat. Results in Table 2 suggest that our estimation process performs fairly well (95% of all energy demand predicted), with a little overestimation for heating and other energy services and a larger underestimation for transport fuels.

Table 1 Energy demand in 2018

	baseline	Carbon taxes (€ per tonCO2eq)			
		50	100	200	800
Electricity (kWh)	2.512	2.469	2.428	2.353	2.020
Heating (Gj)	43	41	39	35	22
Transport fuels (lt)	814	793	773	737	584

Source Authors' on HBS data

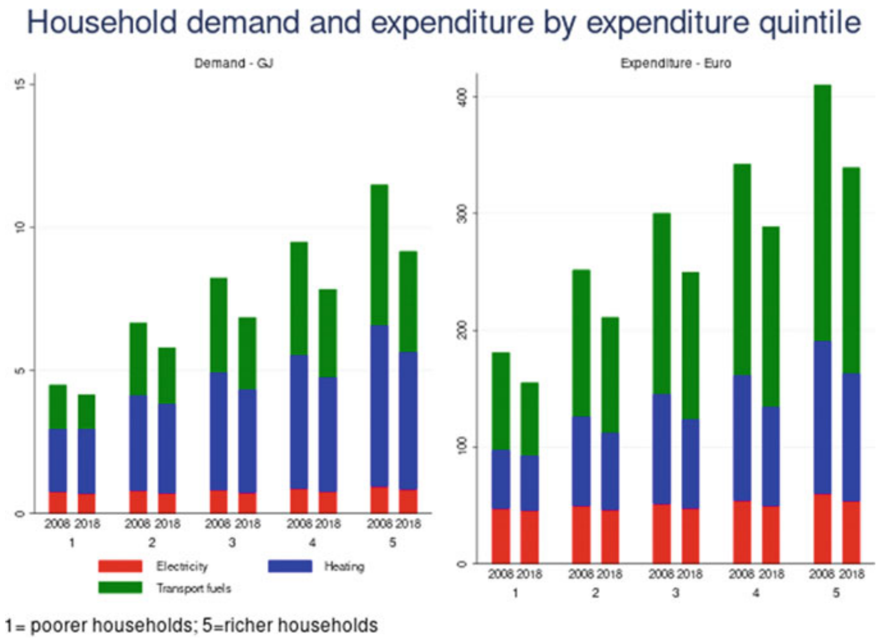

Fig. 4 Household demand and expenditure by fifth *Source* Authors' on HBS data

Table 2 Households energy demand: micro vs macro consistency check

Households energy demand in 2018 (Terajoule)			
	Heating and other	Transportation	Total
This chapter	1.342.097	765.173	2.107.270
PEFA	1.317.732	894.358	2.212.090
ratio	1.02	0.86	0.95

Source Authors'

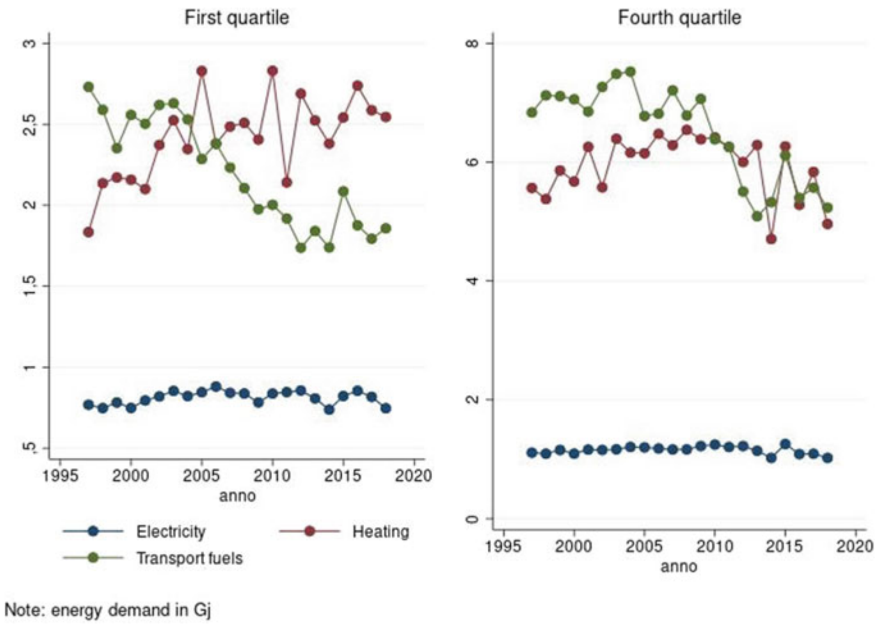

Fig. 5 Energy demand of a couple with 1 child by expenditure fifth *Source* Authors' on HBS data

Our approach emphasises the different heterogeneity of energy demand across households. As an example, Fig. 5 plots the energy demand for a specific type of household (a couple with 1 child) over time and the equivalent expenditure distribution. We observe that the same type of household but at the two extremes of the distribution exhibits radically different consumption patterns: the poorer household consumes less (as a share of their budget) than the richer one while the electricity demand profile of the richer household is smoother. Moreover, the heating demand for the poorer household increases over time, while it is stable for the richer. Finally, demand for transportation fuels decreases faster for poorer households.

4 Estimating Elasticities

With the energy demanded for each energy use $z = E, H, T$ by each $i - th$ household at time t, we can estimate the price elasticity, ϵ_z as:

$$\epsilon_z = \frac{\partial Q_i^z}{\partial P_i^z} * \frac{P_i^z}{Q_i^z} \tag{2}$$

In an ideal setting, we would observe the quantity demanded and the price for the same household over time. However, the HBS is a cross-sectional survey without

Table 3 Strata considered in the pseudo panel

Stratum ID*	Households' type
× 01	Single person under the age of 35
× 02	Single person aged 35–64
× 03	Single person aged 65 and over
× 04	Childless couple with contact person under the age of 35 years old
× 05	Childless couple with contact person aged 35–64
× 06	Childless couple with contact person aged 65 and over
× 07	Couple with 1 child
× 08	Couple with 2 children
× 09	Couple with 3 or more children
× 10	Single parent
× 11	Other types

* Stratum = Fourth of expenditure distribution (x = 1,2,3,4)* 100 + Household type. In the estimates, strata × 01 and × 04 are collapsed into × 02 and × 05 to preserve a minimum sample size
Source Authors'

a panel component. Following Faiella and Cingano (2015) we adopt a *quasi*-panel approach (Deaton 1985), which compares the values of population subgroups (so-called *strata*), and estimates the demand elasticity for each group exploiting the change in time of energy demanded at stratum-level. In this approach, the unit of observation is no longer a *single* household but a *cluster* of similar households, aggregated in a stratum according to specific characteristics (constant over time—see Table 3).

In order to define each stratum, we consider the joint information on household types[9] and their position in the expenditure distribution (split into fourths). Therefore, we identify 36 subgroups of households for each month of our time series, spanning 22 years (1997 to 2018), roughly 9,500 observations. Our model uses the following log–log specification where the s subscript indicates stratum, t the month and z, as before, the different energy services:

$$log Q^z_{s,t} = \lambda_s log Q^z_{s,t-1} + \beta_s log P^z_t + \gamma_s log E_{s,t} + w + s + t + t^2 + \epsilon_{s,t} \quad (3)$$

The log of the quantity of energy demanded, $log Q^z_{s,t}$, depends on:

- a lagged term, $log Q^z_{s,t-1}$, which captures the fact that households demand tends to be fairly stable in the short term;
- the price of energy use ($log P^z_t$)[10];

[9] In the HBS, households are already classified by ISTAT into 11 types, depending on their size, composition and age (see Table 3). We further collapse this classification into nine groups to have a reasonable number of observations in each cell.

[10] Prices are expressed in 2015 values using the consumer price index.

- households' total expenditure ($log E_{s,t}$), as a proxy of households' overall welfare;
- a set of trend (t and t^2) and seasonal dummies (w for autumn and winter months and s for summer);

The parameter of interest is β_s,, the stratum-level short-run price elasticity, which should be read as the percentage change in energy demand due to a 1% change in the energy price. This setting is a special case of the autoregressive distributed lag (ARDL) model of order 1, also known as partial adjustment model. A special (and convenient) feature of this model is that the long-run elasticity is equal to $\frac{\beta_s}{1-\lambda_s}$ (see Greene 2008 for a discussion). We estimate this model using least square (LS) for the total sample for each stratum. The results for the total sample are summarised in Table 4 and Fig. 6.

According to the LS estimates the demand for heating and electricity is more responsive to price changes: on average, a 1% rise in prices reduces the electricity (heating) demanded by 0.36 (0.40)%. The average LS estimated elasticity for liquid fuels is lower (−0.17) and less precise. The LS price elasticities at the stratum level, which are used to estimate the energy demand, are presented in Tables 5 and 6.

Table 4 Price elasticities

	Short-run price elasticities			
	LS	stratum-level LS	2SLS	long run
Electricity	−0.36***	−0.29*	−0.40***	−1.17***
Heating	−0.40***	−0.44**	−0.44***	−1.23***
Transport	−0.17**	−0.45**	−0.66***	−1.46***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
Source Authors' on HBS data

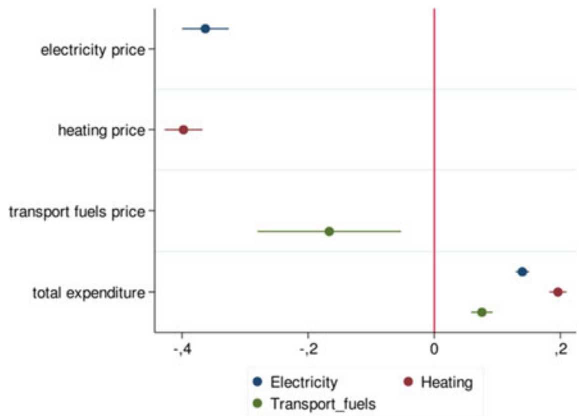

Fig. 6 Short-run price elasticities (95% confidence interval) *Source* Authors' on HBS data

Table 5 LS stratum-level coefficients ($\widehat{\beta}_s$) and robust standard errors ($\widehat{\sigma}_\beta$)

Strata	Share	Electricity		Heating		Transport	
		$\widehat{\beta}_s$	$\widehat{\sigma}_\beta$	$\widehat{\beta}_s$	$\widehat{\sigma}_\beta$	$\widehat{\beta}_s$	$\widehat{\sigma}_\beta$
102	1.41	−0.493	0.317	−0.605	0.223	−0.843	0.467
103	3.51	−0.447	0.160	−0.403	0.163	−1.263	0.797
105	1.34	−0.665	0.260	−0.672	0.219	−0.472	0.193
106	3.13	−0.439	0.162	−0.538	0.151	−0.953	0.233
107	4.07	−0.305	0.161	−0.263	0.127	−0.315	0.113
108	5.37	−0.481	0.129	−0.294	0.130	−0.551	0.102
109	1.94	−0.489	0.189	−0.551	0.184	−0.535	0.154
110	2.37	−0.460	0.181	−0.487	0.148	−0.733	0.214
111	1.86	−0.167	0.207	−0.669	0.166	−0.313	0.188
202	2.28	−0.072	0.257	−.536	0.195	−0.895	0.211
203	3.82	0.083	0.179	−0.524	0.178	−0.980	0.412
205	2.04	−0.541	0.195	−0.446	0.198	−0.204	0.147
206	2.94	−0.248	0.156	−0.490	0.155	−0.543	0.142
207	4.55	−0.286	0.127	−0.224	0.137	−0.303	0.092
208	4.74	−0.227	0.135	−0.212	0.120	−0.254	0.117
209	1.13	−0.840	0.260	−0.632	0.216	−0.525	0.143
210	2.14	−0.310	0.178	−0.610	0.186	−0.490	0.161
211	1.34	−0.587	0.258	−0.675	0.205	−0.250	0.186
302	2.92	−0.153	0.215	−0.428	0.192	−0.478	0.173
303	3.75	−0.221	0.169	−0.498	0.147	−0.654	0.290
305	2.12	−0.103	0.171	−0.663	0.165	−0.100	0.130
306	2.75	−0.109	0.170	−0.577	0.160	−0.072	0.133
307	4.50	−0.172	0.140	−0.389	0.141	−0.067	0.074
308	3.81	−0.269	0.136	−0.351	0.144	−0.138	0.091
309	0.72	−0.015	0.246	−0.790	0.401	0.100	0.219
310	1.96	−0.281	0.251	−0.445	0.181	−0.348	0.160
311	1.09	0.246	0.257	−0.657	0.208	−0.517	0.188
402	7.28	−0.381	0.150	−0.370	0.121	−0.253	0.083
403	3.69	−0.119	0.204	−0.459	0.148	−0.390	0.209
405	3.79	−0.155	0.148	−0.219	0.131	−0.238	0.122
406	2.50	−0.017	0.188	−0.583	0.171	−0.364	0.140
407	3.74	−0.358	0.159	−0.223	0.116	−0.537	0.110
408	2.50	−0.407	0.175	−0.384	0.156	−0.247	0.141
409	0.41	−1.198	0.349	−0.891	0.287	−0.716	0.297
410	1.66	−0.526	0.206	−0.726	0.178	−0.385	0.188
411	0.79	−0.140	0.259	−0.822	0.259	−0.624	0.251

(continued)

Table 5 (continued)

Strata	Share	Electricity		Heating		Transport	
		$\widehat{\beta}_s$	$\widehat{\sigma}_\beta$	$\widehat{\beta}_s$	$\widehat{\sigma}_\beta$	$\widehat{\beta}_s$	$\widehat{\sigma}_\beta$
Average		**−0.287**	**0.175**	**−0.436**	**0.157**	**−0.446**	**0.183**

* Strata × 01 and × 04 are collapsed into × 02 and × 05 to preserve a minimum sample size
Source Authors' on HBS data

Because we observe price and quantity at equilibrium, there might be an issue of endogeneity (price can be influenced both by supply and demand changes). We therefore also employ an Instrumental Variable (IV) estimator using wholesale prices[11] as instruments, under the assumption that they are marginally influenced by households' demand. This is obvious for international oil markets and it does not seem unreasonable for domestic electricity and gas markets (the share of households' demand on the total is a fifth for electricity and a quarter for gas). As we have one instrumental variable for each equation, ours is a *just identified* model.

As a further control we check for a possible non-stationarity of the time series component of our pseudo-panel. We test the residuals of our regressions on the total sample with the Im-Pesaran-Shin test (Im et al. 2003), a specific test for unbalanced panels (not all strata are present in each period considered); the null hypothesis of non-stationarity (H0: each panel has a unit root) is never accepted. IV estimates are comparable with LS except for liquid fuels, for which the instrumented coefficient is almost four times the LS estimate. The results are coherent with a robust version of the Hausman (1978) test developed by Wooldridge (1995), testing for exogeneity: the null is strongly rejected only in the case of fuels for private transportation. We also tested whether our IVs are sufficiently correlated with the endogenous variable, i.e. testing for "weak instruments". Because the strategy proposed by Stock and Yogo (2010) is unfeasible (it only works under the assumption of i.i.d. errors), we look at the (robust) first stage F-statistic, taking into account the suggestion by Lee et al. (2020) of looking for a value above 104. This is exactly our case: we have values of 851, 2,306 and 12,031 for, respectively, the IVs for electricity, heating and transport fuels. Moreover, as pointed out by Andrews and Stock (2018), in the case with one endogenous variable ($k = 1$), the robust F-statistics is equal to the F-statistic by Montiel Olea and Pflueger (2013).

In the long run energy demand is more reactive, as expected: all elasticities are greater than 1 and the use of transport fuels is the most responsive to price changes.

Our method allows us to compute stratum-level price and expenditure elasticity, running the model described in Eq. 3 separately for each stratum *s*. IV and LS estimates are closer when one considers the weighted average of stratum-level LS

[11] For electricity we use the day-ahead price ("Prezzo unico nazionale" or PUN), for heating the natural gas price set at the Virtual Trading Point ("Punto di scambio virtuale" or PSV) and for liquid fuels the Brent dated price (free on board). All prices considered are in euros for 2015. When prices of electricity or gas are not available (before 2004 and 2013 respectively) we use oil prices (in euros for 2015 per MWh).

Table 6 LS stratum-level coefficients ($\gamma\hat{}_s$) and robust standard errors ($\sigma\hat{}_\gamma$)

Strata	Share	Electricity		Heating		Transport	
		$\gamma\hat{}_s$	$\sigma\hat{}_\gamma$	$\gamma\hat{}_s$	$\sigma\hat{}_\gamma$	$\gamma\hat{}_s$	$\sigma\hat{}_\gamma$
102	1.41	0.614	0.102	0.277	0.105	0.421	0.039
103	3.51	0.663	0.050	0.194	0.077	0.132	0.043
105	1.34	0.594	0.082	0.320	0.095	0.635	0.040
106	3.13	0.623	0.047	0.272	0.066	0.487	0.029
107	4.07	0.500	0.052	0.129	0.055	0.603	0.026
108	5.37	0.443	0.045	0.147	0.054	0.683	0.024
109	1.94	0.582	0.054	0.250	0.075	0.600	0.038
110	2.37	0.536	0.046	0.242	0.063	0.606	0.035
111	1.86	0.656	0.058	0.327	0.070	0.608	0.036
202	2.28	0.618	0.065	0.278	0.086	0.553	0.037
203	3.82	0.615	0.065	0.278	0.080	0.329	0.034
205	2.04	0.672	0.054	0.226	0.081	0.614	0.036
206	2.94	0.505	0.048	0.253	0.069	0.527	0.034
207	4.55	0.509	0.047	0.116	0.055	0.668	0.039
208	4.74	0.530	0.047	0.107	0.048	0.572	0.044
209	1.13	0.536	0.062	0.311	0.083	0.672	0.039
210	2.14	0.544	0.053	0.306	0.075	0.646	0.036
211	1.34	0.597	0.055	0.349	0.080	0.574	0.035
302	2.92	0.644	0.055	0.226	0.081	0.535	0.042
303	3.75	0.603	0.055	0.277	0.064	0.366	0.026
305	2.12	0.649	0.056	0.321	0.069	0.557	0.035
306	2.75	0.591	0.052	0.297	0.067	0.559	0.034
307	4.50	0.542	0.047	0.196	0.065	0.562	0.040
308	3.81	0.520	0.049	0.168	0.055	0.567	0.039
309	0.72	0.620	0.055	0.374	0.149	0.637	0.041
310	1.96	0.591	0.063	0.241	0.070	0.609	0.023
311	1.09	0.688	0.064	0.335	0.080	0.679	0.042
402	7.28	0.446	0.042	0.172	0.048	0.540	0.027
403	3.69	0.537	0.051	0.244	0.058	0.495	0.028
405	3.79	0.486	0.046	0.100	0.049	0.538	0.043
406	2.50	0.512	0.053	0.286	0.064	0.535	0.032
407	3.74	0.518	0.044	0.110	0.043	0.615	0.038
408	2.50	0.461	0.048	0.181	0.056	0.587	0.039
409	0.41	0.467	0.067	0.433	0.101	0.579	0.040
410	1.66	0.551	0.045	0.337	0.064	0.615	0.034
411	0.79	0.655	0.065	0.405	0.094	0.637	0.045

(continued)

Table 6 (continued)

Strata	Share	Electricity		Heating		Transport	
		$\hat{\gamma}_s$	$\hat{\sigma}_\gamma$	$\hat{\gamma}_s$	$\hat{\sigma}_\gamma$	$\hat{\gamma}_s$	$\hat{\sigma}_\gamma$
Average		**0.550**	**0.052**	**0.217**	**0.065**	**0.547**	**0.035**

[*] Strata × 01 and × 04 are collapsed into × 02 and × 05 to preserve a minimum sample size
Source Authors' on HBS data

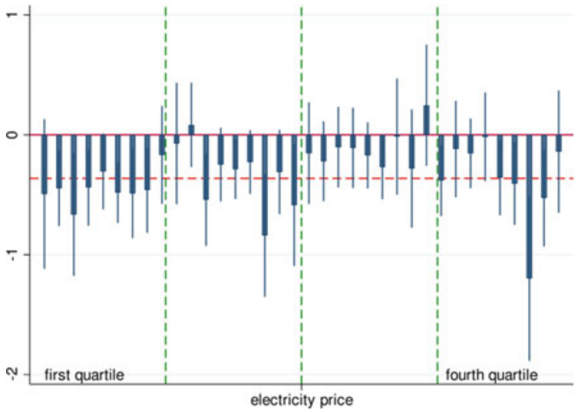

Fig. 7 Price elasticity of electricity by stratum (95% conf. interval) *Source* Authors' on HBS data

estimates (third column of Table 4 and last row of Table 5), the price elasticities of the three energy services become more uniform (ranging from −0.45 for transport fuels to −0.29 for electricity).

Table 5, Figures. 7, 8 and 9 report the LS price elasticities (and their standard errors/confidence intervals) for electricity, heating and transport per stratum (Table 6 reports the LS expenditure elasticities per stratum). In each graph, the red horizontal dotted line represents the corresponding price elasticity estimated for the total sample reported in Table 4 while the green vertical lines separate the estimates for each fourth of the equivalent expenditure distribution.[12]

Less affluent households are more reactive to price increases for electricity (Fig. 7), while for heating the demand responsiveness seems more uniform across the expenditure distribution, and more affluent households reduce their consumption more (Fig. 8). For transport fuels, less affluent households again react more, but confidence intervals within the first fourth are pretty large (Fig. 9). Having obtained a reaction function of energy demand to energy prices that differs according to households' characteristics, we can exploit this information to simulate the introduction of a one-off carbon tax.

[12] Therefore the strata belonging to the bottom fourth are on the left of each figure, while those belonging to the top fourth quarter are on the right; households' types are then reported within each fourth in the same order as in Table 3 within quarter and across energy use.

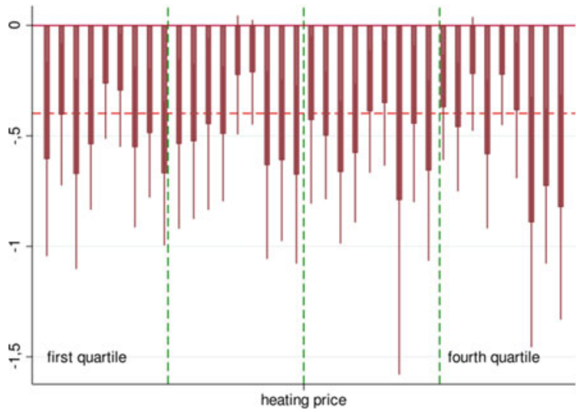

Fig. 8 Price elasticity of heating by stratum (95% conf. interval) *Source* Authors' on HBS data

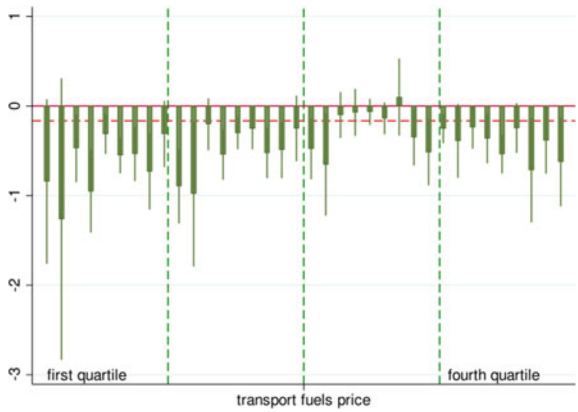

Fig. 9 Price elasticity of transport fuels by stratum (95% conf. interval) *Source* Authors' on HBS data

5 The Simulation of a Carbon Tax

5.1 The Rationale for a Carbon Tax

There is a significant amount of literature on carbon pricing, especially carbon taxation. A global carbon price is the economists' recommended choice[13] for tackling climate change (Tirole 2017). Indeed, carbon pricing mitigates the mispricing of climate risks and provides an incentive for firms to move away from fossil-fuel technologies and adopt (or develop) carbon-free technologies, fostering innovations (Nordhaus 2021).

[13] More than 3,800 economists, among which 28 Nobel Prize winners in Economics, support a bipartisan proposal for a carbon tax in the United States from the Climate Leadership Council which appeared in The Wall Street Journal, 17 January 2019.

In theory, carbon pricing should reflect the social cost of carbon (SCC), i.e. the monetary damage caused by an additional ton of greenhouse gas emitted[14] or be the price that guides the economy towards the 1.5°C or 2°C scenarios (Stern and Stiglitz 2021). Under perfect information, carbon pricing can be implemented either via a carbon tax—the price is set and the amount of emissions consequently adjusts—or an Emissions Trading System (ETS)— the supply of emissions permits is established according to a cap on total emissions and the price of the permits reacts according to their demand.

The effect of carbon pricing on the real economy is not conclusive: some empirical analyses find very small or nil negative effects on economic activity and job creation (Metcalf and Stock 2020); a recent meta-analysis points to firms' competitive and distributional impacts of carbon pricing are significantly negative (Penasco et al. 2021).

Despite the unanimous support from economists, there is a widespread scepticism towards carbon pricing. Indeed, in the world there are currently 68 carbon pricing initiatives in place (34 ETSs) and covering almost 23% of global GHG emissions (World Bank 2022). By 1 May 2022, 37 countries were running a carbon tax scheme, covering 5.7% of global emissions. In the United States, there are some local schemes, such as the Regional Greenhouse Gas Initiative or the California State cap and trade scheme, but there is no Federal scheme. Moreover, recent proposals to introduce a local carbon tax have been rejected.[15] As a consequence, the global average carbon price is too low ($2 per ton of CO2 according to the World Bank 2021).

In Europe, 30 countries (all EU-27 member states plus Iceland, Liechtenstein and Norway)[16] are part of the EU-ETS which covers 45% of all member states GHG emissions. Local carbon pricing initiatives exist in half of the EU member states (Batini et al. 2020), but various attempts to introduce or increase taxes on carbon emissions have faced stiff opposition (as happened in France with the *gilets jaunes* protests).[17]

A key point for increasing the social acceptance of this instrument is to carefully appraise its distributive impacts (Burke 2020) and devise compensatory measures. A policy of revenue recycling for the resources collected could increase the support for a carbon tax, even if set at $70 per ton of CO_2 (Beiser McGrath and Bernauer 2019). In a meta-analysis of 53 empirical studies referring to 39 countries Ohlendorf

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[14] There are several methodological issues behind the models used to estimate the SCC, as underlined by Pindyck (2013, 2017) and Hernandez-Cortes and Meng (2020): the choice of the damage function and the discount rate applied, on top of the uncertainty relating to the estimation of climate sensitivity.

[15] Voters in the State of Washington rejected two proposals (I-732 and I-1631) in 2016 and 2018.

[16] Following Brexit, the United Kingdom set up a UK-ETS which is of the same scope as the EU ETS it replaces.

[17] This hostility can be explained, in the US, by the increasing ideological polarization (Anderson et al. 2019) and the lack of adequate communication (for example on compensatory measures). Moreover, recent evidence from France point to a problem of distrust in Government which might lead households not to internalize the positive benefits from carbon tax even after redistribution (Douenne and Fabre 2022).

et al. (2021) find that carbon pricing is likely to have progressive distributional outcomes in lower income countries and for transport sector policies. Kanzig (2021), in a general equilibrium framework, (Kanzig 2021) shows that a carbon tax can be significantly regressive, especially given its indirect effect; indeed, the reduction in wages in the sectors most affected, would account up to 80% of the final impact on vulnerable households. For Italy, Faiella and Cingano (2015) show that a carbon tax could significantly reduce transportation emissions and its revenues could finance the deployment of renewable energy, replacing the existing charges on electricity consumption, thus alleviating the cost burden for less-affluent households.

However, household heterogeneity must be taken into account in the design of the redistribution scheme. van der Ploeg et al. (2022) show a trade-off between efficiency and equity, depending on the way revenues are recycled: a lump-sum transfer is more equitable but less efficient; lower taxes are more efficient but less equitable; a mixed approach, with no more than 60% of the revenues transferred as a lump sum, can result in a more balance between efficiency and equity, spurring enough support for the carbon pricing. In a similar analysis for the United Kingdom, Paoli and van der Ploeg (2021) find that targeted transfers lead to the largest fall in inequality while income tax reduction leads to an increase.

A similar point is made by Eisner et al. (2021) which shows the importance of targeted support based on household size or vulnerability. Studying the effects of carbon tax is also paramount to understand the effects on the financial system. Carattini et al. (2021) model the relationship between macroprudential and environmental policies. In particular, they calibrate an environmental DSGE where the unexpected introduction of a $30.5 carbon tax creates a recession in a setup with financial frictions, leading to a credit crunch that also affects green activities. Faiella et al. (2022) find that a carbon tax could increase the share of financially vulnerable households and firms (and their associated debts).

5.2 A Carbon Tax in Practice

The ambitious EU target of achieving carbon neutrality by mid-century requires a sharp reduction in the carbon content of our activities, and an unprecedented change in the way we transform and use energy. In the decade 2008–2019 EU greenhouse gas (GHG) emissions decreased by 2.1% per year; a 55% cut in emissions by 2030 (compared with 1990) requires this rate to more than double (around 5% per year in the next decade).

Although in Italy emissions are only priced under the ETS system (that covered 43% of domestic fuel combustion's emissions in 2018), the implicit tax rate on energy (the average amount of taxes per unit of final energy) is among the highest in Europe. In 2018, according to Eurostat data, the tax burden per one ton-of-oil equivalent (42 GJ) was €376 against a European average of €244, the second highest value after Denmark. This corresponds (grossly) to an implicit price of CO2 from energy uses of around €150 per ton (5 times the price of CO2 set on the EU-ETS by the end of 2020).

Nonetheless, the ambitious climate targets shared by Italy under the European Green Deal require a steeper reduction than the one planned in its latest National Energy and Climate Plans (a reduction of 34.6% in the "effort sharing" sectors' emissions by 2030 compared with 2005). Expanding the perimeter of carbon pricing, extending the coverage of EU-ETS or introducing a carbon tax on energy use, are key policies to achieve these targets. Our dataset and the elasticities previously estimated could help the policymakers to assess to what extent a carbon tax on household final energy use could: (1) reduce energy demand and GHG emissions, (2) increase revenues and (3) impact vulnerable households (proxied by the location in the bottom part of the expenditure distribution).

We simulate the effects of a carbon tax on households' energy expenditure, focusing on four possible levies (in real euros for 2015): €50, €100, €200 and €800 per ton of CO2. In practice, carbon taxes are set in a specific year and then progressively increased according to predetermined steps. For the sake of simplicity, we assume a one-off introduction on final energy use on top of existing taxes on energy (and costs levied as part of the EU-ETS).

A carbon tax of €50 is the 2021 average of the emissions price on the EU-ETS, close to the value of the French carbon tax in 2018 (€44) and almost double the recently introduced German tax scheme (€30). This value might be not enough to meet the Paris targets: the IMF (2019) suggests a global carbon tax of €62 ($ 75) by 2030 to meet the 2C target while The Carbon Pricing Leadership Coalition (2017) suggests a carbon price level ranging between €35 and €70 ($ 40–80) by 2020. Similar figures are provided by the International Energy Agency (IEA 2020): under the Sustainable Development Scenario, carbon pricing in advanced countries should be around $63 per ton of CO2 in 2025 increasing to $140 in 2040. Other simulations point to higher carbon prices ranging from $20 to $360 in 2030, and from $85 to $1,000 in 2050, depending on the stringency of the target, the smoothness of the transition and the availability of carbon removal technologies (Guivarch and Rogeljb 2017). In order to reach the new EU targets (a cut of 55% in emissions by 2030 and carbon neutrality by 2050), higher levels of carbon pricing are needed: some observers[18] suggest introducing a carbon tax of up to €200 by 2050 while McKinsey (2020) forecasts that a carbon tax of €100 would only make 80% of the required investments profitable. In the short term, a hypothesis of introducing a carbon tax ranging between €50 and €100 is therefore not unreasonable.

In order to grasp the long-term profile of carbon pricing, one should look at the Social Cost of Carbon (SSC) that results from different climate scenarios. The SCC is the welfare cost of future global climate change impacts that are caused by emitting one extra tonne of CO2 in a given year compared with a reference scenario.

In 2020, the Network for Greening the Financial System (NGFS) released a first set of representative scenarios (NGFS 2020) that describe the possible paths for keeping the temperatures within the Paris targets (1.5°C–2°C), depending on the

[18] *A Climate-Neutral EU by 2050*, Shell Climate Change, a blog by David Hone, 5 May 2020.

timing of mitigation actions—i.e. if the transition is orderly or disorderly—and on the availability and costs of carbon dioxide removal technologies (CDRs). These scenarios can be compared with a situation where no mitigation is undertaken (*Hot house world*)[19] and are designed to provide central banks with basic information to carry out climate-stress test exercises. With an *orderly transition*, i.e. a situation where there is an early and ambitious strategy to achieve carbon neutrality, the price of carbon reaches $100 by 2020 and $300 by 2050 (all values are expressed in real $ 2010 per ton of CO2). In the event of a *disorderly transition*, i.e. where climate mitigation is delayed, the carbon price is lower in the first years but it skyrockets thereafter, reaching up to $800–1,200 by 2050. For these reasons, we will discuss the effects of a carbon price of €200 and €800 separately in our simulations, as a way to gauge the difference between an *orderly* versus a *disorderly* scenario.

5.3 The Simulation Design

To estimate the impact of each carbon tax on final energy prices, we apply the specific carbon emission factors for each fuel considered. All prices are in euros for the year 2015. For electricity, we use the time series of the carbon emission factors of electricity demand estimated by ISPRA (2019).[20] For heating, we use the emission factor for natural gas provided by the Italian Ministry for the Environment (Ministero dell'Ambiente 2019), which reports a carbon emission factor of 0.055820 ton CO2 per GJ. As previously mentioned, we assume that the whole of the heating demand is satisfied by natural gas. Finally, for transport fuels, we calculate the emission factors considering the energy content and the specific emission factors of petrol and diesel.[21]

Using 2018 prices as baseline, the introduction of a carbon tax of €50 per ton, is equivalent to add: €0.014 to each kWh of electricity (+6%); €2.8 to each GJ of gas (+12%) and €0.12 to each litre of gasoline or gasoil (+8%). Overall, heating prices increase more, between 12 and 48% under a CT of €50–€200, and almost triple in the event of a carbon tax of €800, followed by transport fuels (8–32% for a CT of €50–€200) and electricity (6–25%) (see Table 7).

Similarly to Faiella and Cingano (2015), our empirical strategy is the following: first, we combine the estimated stratum-elasticities (see Sect. 4) and the price increases described in the previous section to obtain the quantities that would have been demanded in a given year for each household if these different carbon taxes

[19] Among the NGFS set of scenarios there is the *Too little too late* scenario where physical and transition risks are greatest; this scenario has still not been modelled.

[20] Between 2010 and 2018, this average carbon emission factor amounted to 332 gCO2 per kWh, 388 gCO2 per kWh in 2010 down to 281 in 2018 as the result of the decarbonization process in the Italian power sector. As a conversion we use 1 kWh = 0.0036 GJ.

[21] For 1 GJ: 29.8 L of petrol, 26.1 of gasoil. Specific weights: 0.725 kg/dm3 petrol, 0.825 for gasoil. Carbon emissions: 3.14 kg of CO2 for 1 kg of petrol, 3.17 for gasoil. Carbon emission, 0.067903 tonnes of CO2 per 1 GJ for petrol and 0.068301 for gasoil.

were in place; we use original data for 2018 (the latest year for which HBS microdata are available) as a baseline. For each household i in stratum s, the energy demand for fuel z coherent with the price change τ_{CT}^{z} induced by the introduction of a carbon tax ($CT = €50, €100, €200, €800$) is given by the following equation:

$$\widehat{Q}_{is|(\tau=CT)}^{z} = \widehat{\beta}_{s}^{z} * \left[log\left(P_{t}^{z}+\tau_{CT}^{z}\right)\right] + \widehat{\epsilon}_{s}^{z} \tag{4}$$

where $\widehat{\epsilon}_{s}^{z} \sim N\left(0, \widehat{RMSE_{s}^{z}}\right)$ and $\widehat{\beta}_{s}^{z}$ are the estimated elasticities of energy vector z for each stratum s.

The estimated elasticities $\widehat{\beta}_{s}^{z}$ are assigned to each household of the sample according to its stratum. In some strata the estimated parameters explain a fair share of the actual variance while in others the explaining power is lower (see for example Fig. 9). For this reason, in addition to the estimated coefficient, each family belonging to a given stratum is assigned a stochastic component, ϵ_{s}^{z}, , with a zero mean and a variability equal to the residual variance of the stratum-level regression ($RMSE_{s}^{z}$) for each fuel z, so that both the mean and the variance of the original distributions are preserved. Then we multiply this counterfactual demand by the new prices and we aggregate across different energy fuels in order to obtain an estimate of the energy expenditure under different levels of carbon taxation $E_{is|(\tau=CT)}$, where:

$$E_{is|(\tau=CT)} = \sum_{z=1}^{3} E_{is|(\tau=CT)}^{z} \tag{5}$$

and

$$E_{is|(\tau=CT)} = E_{i,s} * \frac{\widehat{Q}_{is|(\tau=CT)}^{z} * \left(P^{z} + \tau_{CT}^{z}\right)}{\widehat{Q}_{is|(\tau=0)}^{z} * P^{z}} \tag{6}$$

Finally, an estimate of the overall expenditure is derived under the assumption that the new level of energy expenditure affects total household expenditure proportionally. Therefore, the total expenditure after the introduction of the carbon tax is equal to the difference between the new energy expenditure and the baseline:

$$Exp_{is|(\tau=CT)} = Exp_{is} + \left(Exp_{is|(\tau=CT)} - Exp_{is|(\tau=0)}\right) \tag{7}$$

5.4 Simulation Results

The main results of our simulations are reported in Table 7: the baseline values are the original values of 2018. We will first discuss the results of the introduction of a one-off carbon tax of €50 or €100 per ton of CO2, followed by a discussion on the two options related to the level compatible with the NGFS (2020) scenarios (€200 and €800 per ton of CO2). Under a carbon tax of €50 or €100, electricity prices will increase by between 6 and 13%, heating between 12 and 24%, and transport fuels between 8 and 16%. Given that energy expenditure accounts for one-tenth of the households' total budget, overall inflation would increase by between 0.7 and 1.4%.

The increase in energy prices would decrease the quantity demanded for all energy use (see Fig. 10). Heating demand will decrease more, with a cut of between 5 and 10% of the original demand, followed by transport fuels (between 3 and 5%) and electricity (between 2 and 3%).

Energy expenditure would increase for all energy uses, and particularly for heating (7–13%), followed by transport fuels (5–10%) and electricity (5–9%) (see Fig. 11). Under the hypothesis that the energy share as a percentage of the overall budget remains stable, the total expenditure would increase by 0.5–1%.

Carbon taxation would decrease households' CO2 emissions by between 4 and 7% (a value similar to van der Ploeg et al. 2021), corresponding to a reduction of 5–9 MtCO2eq, a value in line with that obtained by Metcalf and Stock (2020). A carbon tax of €50 – €100 would raise between €4 and €8 billion, equivalent to 0.2–0.5 p.p. of GDP, which could be used to reduce the impact of the tax on vulnerable households, other taxes (e.g. on labour) or to support the deployment of low-carbon energy sources (as suggested in Faiella and Cingano 2015). As a matter of comparison, between 2012 and Q2-2021 the Italian Government raised €6.7 billion from the ETS auctions or

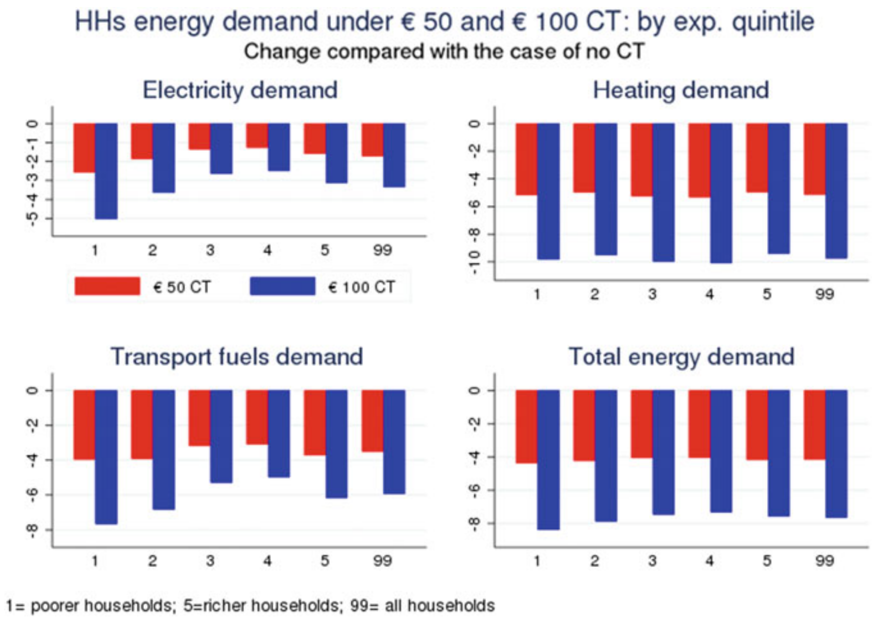

Fig. 10 Household energy demand under EUR 50 and 100 carbon taxes, by expenditure fifth *Source* Authors' on HBS data

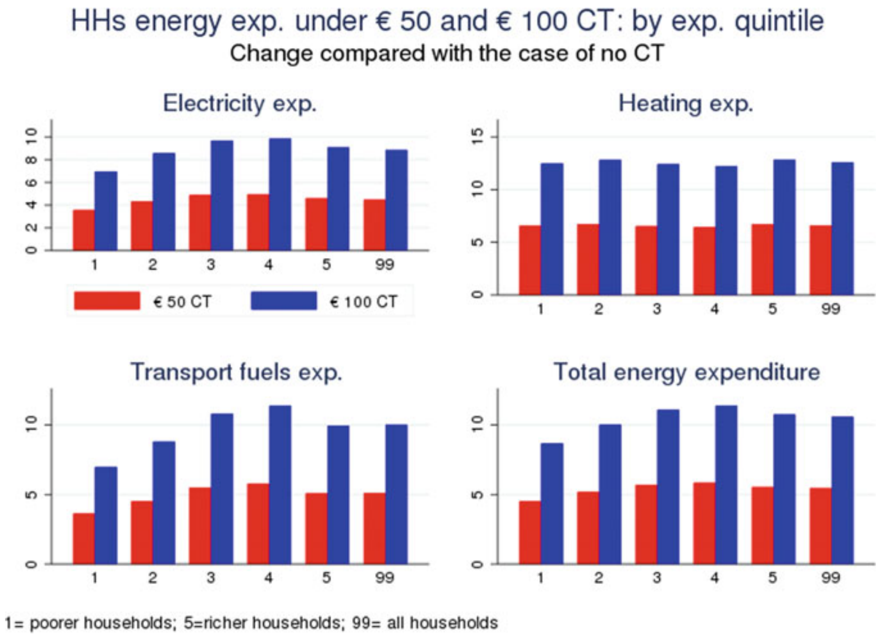

Fig. 11 Household energy expenditure under EUR 50 and 100 carbon taxes, by expenditure fifth
Source Authors' on HBS data

€670 million per year on average (GSE 2021). As for the distributive effects, our simulations suggest that carbon taxation in Italy would be regressive overall. Indeed, total expenditure would increase more for poorer households belonging to the bottom deciles of the expenditure distribution (Fig. 12 and Table 8), under all the levels of carbon pricing.

The effects measured on the expenditure are just a part of the story as poorer households would also further reduce their energy demand across all energy uses[22] (Fig. 10 and Table 9).

All in all, these results seem to suggest that the implementation of any carbon tax requires a careful design for the compensation measures. Indeed, without any revenue recycling mechanisms, a carbon tax would make vulnerable households worse off, thereby decreasing its social acceptability. To avoid this, the revenues of the carbon taxes might be used to compensate poor households, either via targeted direct payments or using indirect schemes (e.g. increasing the energy efficiency of their dwellings) (Burke 2020).

Finally, we also test the effects of applying a set of carbon taxes consistent with the NGFS (2020) scenarios: €200 for an *Orderly* transition *vis-'a-vis* an €800 carbon tax consistent with a *Disorderly* scenario. Energy prices will increase between 25

[22] One-fourth of all households belonging to the bottom fifth of the distribution owns no vehicles, therefore an increase in transport fuel prices might affect them less.

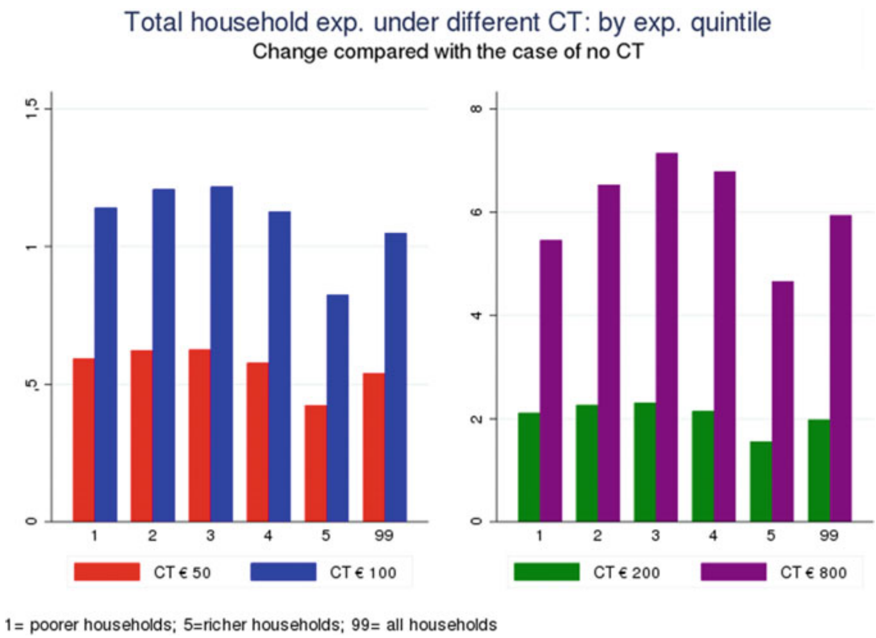

Fig. 12 Total household expenditure under different carbon taxes, by expenditure fifth *Source* Authors' on HBS data

and 47% under a €200 CT and more than double under a €800 CT. Energy demand would be cut by 14–38%, while total energy expenditure would increase between 20 and 60%. Emissions would drop significantly, with a cut of 17–48 MtCO2eq, or between 15 and 42% of all household emissions in 2018. The carbon taxes would raise between 0.9 and 2.4 p.p. of GDP and, without any compensating mechanisms, would be highly regressive (Fig. 12).

6 Conclusions

This work explored households' energy demand and expenditure using survey-based microdata covering all Italian households in the period 1997–2018. The details available in the HBS, with the external information on prices and aggregate quantities used in the exercise, allowed us to analyse three different energy services (electricity, heating and private transport) correlating energy quantities with households' socio-economic traits.

We present a novel methodology for estimating the price elasticities of these energy services for each stratum of households, which differs according to their characteristics and economic vulnerability.

Table 7 Main results: effects of carbon taxation on prices, demand and expenditure

Carbon Taxes				
€ per ton of CO2	50	100	200	800
Price variation				
Electricity	+6.3	+12.6	+25.2	+100.8
Heating	+11.8	+23.6	+47.2	+188.7
Transport fuels	+7.9	+15.9	+31.8	+127.2
Effect on inflation (2018)*	+0.7	+1.4	+2.8	+11.3
% change compared with the baseline year (2018) Energy demanded				
Electricity	−1.7	−3.4	−6.3	−19.6
Heating	−5.1	−9.7	−17.7	−48.1
Transport fuels	−2.6	−5.1	−9.5	−28.3
Effect on inflation (2018)*	−4.2	−7.7	−13.8	−38.0
Expenditure				
Electricity	+4.5	+8.9	+17.3	+61.6
Heating	+6.6	+12.6	+22.9	+54.1
Transport fuels	+5.1	+10.0	+19.2	+62.6
Effect on inflation (2018)*	+5.4	+10.6	+20.0	+59.8
CO2 Emissions and revenues				
% var	−3.7	−7.0	−12.9	−36.4
Emissions (ΔMtCO2e)	−4.8	−9.3	−17.0	−48.-0
Revenues (billion of €)	+4.2	+8.2	+15.5	+42.1

* Additional percentage points to the Italian consumer price index (NIC)
Source Authors' on HBS data

We then use these estimates to assess the effects of four levels of carbon taxation corresponding to €50, €100, €200 and €800 per ton of CO2.

According to our simulations, the increase in energy prices of a €50-€100 carbon tax would decrease the energy demanded and CO2 emissions ($-4/-8\%$) and increase energy expenditure ($+5/+11\%$), raising between €4 and €8 billion, which could be used to mitigate the impact on vulnerable households, to reduce other taxes (e.g. on labour) or to support low-carbon energy sources.

In all simulations the price increase triggered by the carbon tax is regressive: poorer households' expenditure increases more while they also suffer a greater drop in their energy use.

The results of introducing higher taxes (€200 and €800, consistent with NGFS 2020 scenarios), are in line with these general outcomes although considerably bigger.

Table 8 Total energy expenditure and total expenditure as % change compared with the baseline under 4 carbon taxes

	Total energy expenditure				Total expenditure			
Tenth of equiv	€/ton CO2				€/ton CO2			
expenditure	50	100	200	800	50	100	200	800
1	4.5	8.6	15.9	41.4	0.6	1.2	2.2	5.7
2	4.5	8.7	16.1	41.4	0.6	1.1	2.1	5.3
3	5.0	9.6	17.9	49.8	0.6	1.2	2.2	6.2
4	5.4	10.4	19.6	58.1	0.6	1.2	2.3	6.9
5	5.3	10.3	19.4	57.1	0.6	1.2	2.2	6.5
6	6.0	11.8	22.5	72.1	0.6	1.3	2.4	7.7
7	6.0	11.6	22.2	71.1	0.6	1.2	2.3	7.4
8	5.7	11.1	21.1	65.7	0.5	1.1	2.0	6.3
9	5.5	10.6	20.1	60.2	0.5	0.9	1.7	5.1
10	5.6	10.8	20.5	61.1	0.4	0.8	1.4	4.3
Total	5.4	10.6	20.0	59.8	0.5	1.0	2.0	5.9

Source Authors' on HBS data

Table 9 Energy demand as % change compared with the baseline under 4 carbon taxes

decile	Electricity (€ / ton CO2)				Heating (€ / ton CO2)				Transport fuels (€ / ton CO2)			
	50	10	200	800	50	10	200	800	50	10	200	800
1	−2.6	−5.1	−9.6	−29.6	−5.2	−9.8	−17.9	−48.2	−4.0	−7.7	−14.3	−42.1
2	−2.6	−5.0	− 9.4	−28.7	−5.2	−9.8	−17.8	−48.1	−4.0	−7.7	−14.3	−42.4
3	−2.1	−4.2	−7.9	−24.2	−5.0	−9.5	−17.4	−46.9	−3.5	−6.7	−12.5	−36.8
4	−1.6	−3.2	−6.0	−18.6	−5.0	−9.5	−17.4	−47.3	−2.9	−5.6	−10.5	−31.0
5	−1.6	−3.1	−5.9	−18.4	−5.0	−9.5	−17.2	−46.5	−3.0	−5.9	− 10.9	−32.6
6	−1.1	−2.2	−4.2	−13.0	−5.5	−10.4	−19.0	−51.4	−1.6	−3.1	− 5.9	−17.7
7	−1.1	−2.2	−4.2	−13.0	−5.5	−10.5	−19.0	−51.5	−1.7	−3.3	−6.2	−18.6
8	−1.4	−2.7	−5.1	−15.8	−5.1	−9.8	−17.7	−48.0	−2.3	−4.5	− 8.5	−25.0
9	−1.7	−3.3	−6.2	−19.2	−4.9	−9.4	−17.0	−46.2	−2.7	−5.3	−9.9	−29.6
10	−1.5	−3.0	−5.7	−18.0	−5.0	−9.5	−17.2	−47.1	−2.6	−5.0	−9.4	−28.0
Total	−1.7	−3.4	−6.3	−19.6	−5.1	−9.7	−17.7	−48.1	−2.6	−5.1	−9.5	−28.3

Source Authors' on HBS data

From a political economy point of view, the successful introduction of a carbon tax requires a commitment to keep the scheme in place; the price should gradually increase over time following a clear path (disclosure) which would reduce uncertainty, helping firms to adjust their investments and achieving an orderly transition.

An important point to explore is to evaluate whether the tax should be levied on final use and if it should be added on top of the existing energy taxation (which in Italy, per unit of energy use, is one of the highest in Europe). As an alternative, it could be imposed on upstream activities, as suggested by The Carbon Pricing Leadership Coalition (2017).

We confirm the literature results showing that the introduction of a carbon tax would be regressive. In order to increase its political acceptability, the effects of the tax should be compensated by transferring the accrued resources to vulnerable households (and firms), for example with lump-sum transfers or by funding low-carbon energy solutions.

Appendix A: Estimating Households Energy Demand

Modelling Energy Demand

Following Faiella (2011), we define $Q^E_{i,t}$ as the energy demand of households i for fuel z (where $z = 1$ with fuels for heating, $z = 2$ with electricity and $z = 3$ with gasoline, diesel and other fuels for private transportation). For each i th household this quantity (expressed in energy units, such as joules or ton of oil equivalent) can be represented as a function of other variables (time subscript are omitted for clarity):

$$Q^E_{i,z} = f(P_z, C_i, B_i, T) \tag{12}$$

where P_z is a vector of prices, C_i a set of characteristics of the $i - th$ household, B_i are consumer preferences and T some exogenous variables relating to climatic conditions. In the short term, energy demand might be rather inelastic, showing a low degree of substitution, while in the medium term, the rise of energy prices (P_z) could push a household to either invest in energy-efficient appliances or switch to different fuels. Energy demand also varies according to individual preferences (B_i). Some consumers are more environmentally aware (for example improving the energy efficiency of their dwelling), while others prefer higher indoor temperatures. In general, more affluent households, with a larger number of appliances and living in bigger dwellings, use more energy.

Climatic conditions (T) also matter and they will become increasingly important in the future because of climate change: the increase in surface temperatures reduces heating demand but increases cooling services. Cooling is expected to become the top driver of global electricity demand in the near future (IEA 2018). This is also true for Italy: according to HBS data, the share of households owning an AC appliance increased from 6% in 1997 to 41% in 2018.

Bearing in mind these determinants, in the following sections, we present our strategy for deriving the energy demand (in energy units) for electricity, heating and liquid fuels for private transport in Italy. Because we have only data on expenditure, we need to merge the HBS dataset with information on the energy prices for the three energy services considered in the analysis.

Estimation of Electricity Demand

In Italy, power retail prices are structured as an efficient two-part scheme (Feldstein 1972): a variable volumetric price, covering the marginal cost of each additional kWh consumed, and a fixed monthly fee, covering the fixed costs such as transmission and distribution.[23] Poor households (i.e. those with an indicator of the economic condition of the family below a certain threshold) are supported through a discount applied by the local distribution system operator (DSO), known as"*bonus elettrico*" (electricity bonus). Only one third of the price paid by the average Italian household[24] is linked to energy costs; one fourth is for remunerating the transmission, distribution and metering services while the remaining part finances the subsidies to renewable energy sources and other costs (26%, the"*oneri generali di sistema*" or general system charges)[25] and taxes 14%. Therefore, taxes and other levies stifle competition by hampering the price signal (Stagnaro et al. 2020). From the HBS, we observe the monthly electricity expenditure of the *i-th* household at a time (month) t, $E_{i,t}^{E}$:

$$E_{i,t}^{E} = \left(P_{i,t}^{vE} Q_{i,t}^{E} + P_{i,t}^{fE}\right)(1 + T_t) \tag{8}$$

where $P_{i,t}^{vE}$ is the variable price in euros per kWh, $Q_{i,t}^{E}$ is the quantity of electricity demanded (unknown), $P_{i,t}^{fE}$ is a fixed price component and $1 + T_t$ are taxes. Solving for $Q_{i,t}^{E}$, if follows

$$Q_{i,t}^{E} = \left(\frac{E_{i,t}^{E}}{1 + T_t} - P_{i,t}^{fE}\right) * \frac{1}{P_{i,t}^{vE}} \tag{9}$$

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[23] Up to 2016, the variable part increased with consumption, a common, albeit inefficient, scheme (Levinson and Silva 2022). This scheme was abolished by the end of 2016, with a progressive transition towards a volumetric system completed by 1 January 2019.

[24] Power load of 3.3 kW and annual consumption of 2,700 kWh as defined by the Italian energy regulator, ARERA.

[25] Since 2010, both the variable and the fixed part have included the funding of renewable energy sources which peaked in 2016 at €14.4 billion or 0.9 p.p. of GDP. According to the energy agency in charge of managing the RES incentives, the average household paid €75 to support this policy, i.e. one eighth of the average electricity bill (GSE 2018). These levies have been suspended since Q2-2021.

As previously mentioned, from the HBS we observe $E_{i,t}^{E}$, while T_t is the VAT rate, equal to 0.1 in the case of electricity.[26] Unfortunately, we do not observe either $P_{i,t}^{vE}$ or $P_{i,t}^{fE}$ and, we will therefore have to estimate them. As for $P_{i,t}^{vE}$, the variable price, we use the average, semi-annual, prices released by Eurostat from 2008 onwards assuming that these prices does not include the fixed component of the electricity bill. These data are available for three consumption bands: we take a weighted average of these prices, using the share of domestic consumption per band provided by the Italian energy authority (ARERA), obtaining a unique, semi-annual, average price for electricity. The data between 1996 and 2007 are imputed by regressing the price for the period 2008–2018 on the monthly electricity price index (from ISTAT) and on a set of time dummies (year and semester). The same index is used to derive monthly prices from semi-annual data. The part of the bill that does not change with consumption ($P_{i,t}^{fE}$) includes a fixed instalment and a component depending on the power load,[27] whose parameters have been updated quarterly by ARERA since 2007. We first estimate the amount paid by a representative Italian house—hold (domestic contract, power load of 3.3 kW); as these pieces of information are only available for each quarter from 2007 onwards, we compute the share of the electricity expenditure due to the fixed component, α_t, in the period 2007–2018. Then, we regress it over total electricity expenditure, prices and a year dummy, to estimate α_t for the period 1997–2007. This range stood at 8% in 1997 and increased to 27% in 2018, following the 2016 reform of the electricity tariff. We multiply this coefficient by the electricity expenditure in order to obtain an estimate of the fixed price component for each household or,

$$P_{i,t}^{fE} = \alpha_t * E_{i,t}^{E} \tag{10}$$

and then we substitute it back into the formula for $Q_{i,t}^{E}$. Finally, we winsorize the extremes and calibrate $Q_{i,t}^{E}$ to align our microdata with the annual information on households' electricity consumption from the National Energy Balance. The calibration increases average households' consumption by roughly one third.

Estimation of Heating Demand

We consider all heating-related fuel expenditure: natural gas, which is the main fuel used by Italian Households (ISTAT, 2014), district and central heating, wood, coal and kerosene. We thus obtain a comprehensive heating expenditure for household i at month t, $E_{i,t}^{H}$. Unfortunately, as for electricity, only semi- annual prices for natural

[26] There are other levies which are small in size. Moreover, VAT is applied to the levies as well. Therefore, for the sake of simplicity, we omit these levies and focus on the VAT.

[27] 92% of domestic customers in Italy had a 3.3 kW power load installed at the end of 2018 (ARERA 2019).

gas, published by Eurostat, are available.[28] However, prices for natural gas can be considered a reasonably good proxy for other fuels (such as wood and pellets).[29] Therefore, we model heating demand as a function of natural gas prices.[30] As for electricity, households heating expenditure is equal to

$$E_{i,t}^{H} = \left(P_{i,t}^{vH} Q_{i,t}^{H} + P_{i,t}^{fH}\right)(1 + T_t) \tag{11}$$

where $P_{i,t}^{vH}$ is the variable price (€ per gigajoule), $Q_{i,t}^{H}$ is the quantity of heating demanded (unknown), $P_{i,t}^{fH}$ is a fixed price component and $1 + T_t$ is the VAT rate, which changed three times between 1997 and 2018.[31] As before, we estimate the share of fixed costs as part of the total expenditure, β_t, depending on where the household lives, for the period 2010–2018.[32] For the period 1996–2009, we regress β_t on total heating expenditure, natural gas prices and the year dummy and then forecast the values. The same index is used to derive monthly prices from semi-annual data. We solve for $Q_{i,t}^{H}$ and calibrate the results with the total heating demand from the to align our microdata with the annual information on households' heating consumption from the National Energy Balance.

Estimation of Private Transport Demand

From the HBS, we observe each households' expenditure for transport fuels in Italy.[33] The share of expenditure on private transport is sizable, almost equal to the sum of the share of heating and electricity (Fig. 1). However, this share has its own specificity compared with other energy use; in fact the share of vehicle' owners is scant in the bottom part of the expenditure distribution. In the bottom tenth, less than two thirds of households own a car while in the top tenth this share is 9 out of 10.

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[28] As for electricity, we take a weighted average of these prices, using the share of domestic consumption per each band. Moreover, we assume that these prices does not include the fixed component of the gas bill.

[29] According to the Survey on households energy use, a one-time sample survey carried out in 2013, the price for wood and pellets in 2013, in energy equivalent terms, was very similar to that of natural gas.

[30] The share of heating costs due to natural gas from the pipeline has increased from 54% in 1997 to 70% in 2017.

[31] The VAT rate was 19% up to 1 October 1997 then 20% up to 17 September 2011, and then 22% since 1 October 2013).

[32] ARERA has been providing fixed costs for six different macro-regions, known as *Ambito territoriale*. Sardinia, which is not included in the price regulation because it is not on the gas grid, has been assigned to the macro-region of Sicily and Calabria, which is the most expensive.

[33] At the end of 2019, according to the *Automobile club d'Italia*, some 46% of cars used petrol and 44% diesel. There is also a 9% share of dual-fuel vehicles, using petrol with methane (CNG) or LPG.

The price of liquid fuels in Italy is fully liberalised, but taxes and levies weigh for more than two thirds of the final price. There is a reasonable level of price competition among the 15.000 petrol stations around the country.[34] We took the average national monthly price for petrol and diesel, as published by the Italian Ministry of economic development (MISE) to estimate the quantity of fuel demanded. We consider the joint demand for liquid fuels for private transportation,

$$Q_{i,t}^{T} = \frac{E_{i,t}^{G}}{P_{t}^{G}} + \frac{E_{i,t}^{D}}{P_{t}^{D}}$$

and a unique price for liquid fuels, as a weighted average (with w as the weight) of petrol and diesel prices,[35] using their respective share of total expenditure as weights. Finally, we calibrate the results with the total demand for liquid fuels published yearly by the business association of oil and gas companies (*Unione Energie per la Mobilità*).

Estimation of Total Energy Demand

We are then able to derive the monthly energy demand at the household level for the entire period considered (1997–2018) and we compare our estimates with the official data from the Physical Energy Flow Accounts (PEFA) from Eurostat. For 2018, our estimates for heating and electricity mimic the aggregate data pretty closely, while transport demand is slightly underestimated (our data are about 14% lower compared with transport demand in the official statistics). Overall, our micro data covers the 95% of the official household energy demand in 2018 as measured by the PEFA. Knowing the energy demand at the micro level allows us to analyse the pattern of energy demand according to household characteristics (age of the head, household size, location, and so on,). Considering a measure of their welfare (proxied with their position in distribution of the equivalent expenditure) we find, not surprisingly, that energy demand (and energy expenditure) increases with households welfare (Fig. 4). On average, households at the top of the expenditure distribution use more than twice the amount of energy demanded by poorer households (less than 5 GJ per month). In terms of fuel, the demand for electricity is pretty much uniform across the expenditure distribution, while heating and transport fuels demand is higher for more affluent households. Over the years, energy demand and expenditure has decreased across all fifths. After having merged our data with energy prices and having derived

[34] The difference between the highest and lowest price for petrol (self-service) on 31 March 2020, at national level was almost 11%—The price is available every day, for every petrol station, on the website of the *Osservatorio Prezzi carburanti* of the Italian Ministry of economic development (MISE).

[35] In the period 1996-2013 the expenditure for liquid fuels was collected jointly with that for diesel.

energy demand, we can proceed and estimate the elasticity of energy demand for each energy service.

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Assessing Ecobonus as Energy Poverty Mitigation Policy: Is Energy Efficiency for All?

C. Martini

1 Introduction

About 35 million EU citizens (approximately 8% of the EU population) were unable to keep their homes adequately warm in 2020, representing a critical issue with health, social, economic and environmental implications. This problem is likely to become more significant with the current crisis and surge in energy prices, with different effects according to the country energy dependence. In European Member States strategies to tackle with energy poverty, energy efficiency measures are more and more recognised as a long-term solution, to accompany and complement social security policies. The long-term objectives in clean energy transition could imply an increase in energy prices and then such a process could have consequences on energy poverty.

At European level, while there is common agreement on the main drivers of energy poverty (among which poor energy performance of buildings), there is not a shared definition of the phenomenon. In the directives adopted after the Winter Package, energy poverty has assumed a key role, which is also reflected in national policy strategies, such as the Integrated National Climate and Energy Plans (NECPs) and Long-Term Renovation Strategies of the Building Stock (LTRS). The role of energy poverty is becoming even more relevant with the Energy Efficiency Directive and Energy Performance of Buildings Directive recast. The phenomenon is relevant for the European governance and policy strategy at several levels (Papada and Kaliampakos 2018). The EU building stock needs, in the long term, to be renovated, converted to Nearly Zero Energy Buildings (NZEBs) as more as possible, and

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national renovation strategies should facilitate a cost-effective process, taking into account also that some households suffer an energy poverty condition.

An integrated approach could successfully deal with energy poverty, namely: choosing a comprehensive definition and to compare countries/regions; improving data availability and to integrate database; creating enabling conditions for energy efficiency potential to be exploited; implementing measures to address all relevant dimensions (split incentives, appliances, transport, etc.); recognising the role of non-technological actions; measuring energy poverty trend, to identify its main drivers and to elaborate sound projections.

The European Energy Network elaborated five recommendations for the European Commission (EnR 2019), which can be summarised as follows:

1. To introduce a unique EU energy poverty measure, which could be a Low-Income-High-Cost (LIHC) measure, and accompanying it by country-specific indicators, to be set according to country-specific characteristics;
2. To promote energy efficiency measures as key solutions to energy poverty, allowing for multiple benefits and structural change, and to act at local level;
3. To develop an integrated approach to tackle with energy poverty and to elaborate policy responses at country level;
4. To examine energy poverty implications in terms of cost distribution of the measures adopted to achieve the long-term energy and environmental objectives;
5. To recognise that training and information campaigns are essential to achieve a behavioural change and then boost the rate of energy renovation of dwellings of household in energy poverty.

This work is focused in different ways to the points above. It tries to highlight the linkage that definition and measurement have with policy action. It investigates MS strategies for energy poverty mitigation and provides a contribution in assessing if the policies in force are effective. In particular, most energy efficiency policies have been conceived with a wider scope than energy poverty mitigation: they are targeted also to energy-poor households, namely to households facing difficulties in satisfying their energy needs, but not specific to them. A crucial aspect is to check if they have differentiated impacts on different income groups, in terms of who is using the financial incentives or who is paying their cost. In this vein, a case study will be provided concentrating on the main energy efficiency policy for residential sector in Italy, namely the tax relief scheme for energy renovation of existing building stock (Ecobonus). This policy is mentioned in the Italian NECP as a key policy to achieve the 2030 energy-saving target. In the case study the regional differentiation in access to the tax relief scheme for energy efficiency is investigated, as a proxy of the effectiveness of Ecobonus in tackling energy poverty.

The chapter is structured as follows: first, the indicators available in the EU and the strategies adopted for energy poverty definition are briefly described, focusing on Italy for the latter; second, the trend in EU legislation is described as well as the different policy approaches for mitigation, providing an overview at MS level and a more detailed description of Italian policy mix; third the investigation method is described and its results provided; last two sections are devoted to discussion and conclusions.

2 Energy Poverty Measurement and Definition

In order to understand the incidence of the energy poverty phenomenon and effectively deal with it at policy level, the availability of proper data and measurement options is certainly a key issue. It is widely acknowledged in the literature that there are three main components at the basis of energy poverty (Ntaintasis et al. 2019; IEA 2011; BPIE 2014; Papada and Kaliampakos 2018; Bouzarovski and Petrova 2015; Pye et al. 2015; Ugarte et al. 2016; J. Schleich 2019): low household income; high/growing energy prices; inefficient energy performance of buildings concerning thermal insulation, heating systems and equipment.

These three components can be measured by different types of indicators and reflected in the definitions adopted by MS. There is a twofold link, since the definition is associated with the indicators available in the different countries but also to the adopted political strategies. According to the NECP, seven EU countries have an official definition of energy poverty and they are represented by Austria, France, Spain, Ireland, Cyprus and Italy. Also in the United Kingdom an official definition exists. In Italy a definition has been adopted in official documents as the National Energy Strategy and National Integrated Energy and Climate Plan, but it has not been officially adopted. In most of the countries the definitions are expenditure based.

Despite the growing attention devoted to energy poverty at EU level, shown in Clean Energy for all Europeans and later on in Green New Deal and Next Generation EU, a shared methodology to identify energy poverty households has not yet been elaborated. There is a general consensus on the multi-dimensional character of energy poverty; at the same time, indicators to adequately represent this complexity are not always available.

In order to help Member States (MS) to fight energy poverty, through the improvement of measuring, monitoring and sharing of knowledge and best practices, in January 2018 the European Commission launched the Energy Poverty Observatory (EPOV), consistently with Regulation 2018/1999. In 2021, the Energy Poverty Advisory Hub (EPAH) was created, building upon the work of EPOV.

EPOV selected a set of consensual (subjective) and expenditure-based (objective) indicators that should be used in combination in order to measure energy poverty. Primary[1] and secondary indicators are defined, and primary indicators are represented by (EPOV 2020):

[1] In particular, four different primary indicators for energy poverty are identified, two of which based on self-reported experiences of limited access to energy services (based EU Statistics on Income and Living Conditions—EUSILC data) and other two calculated using household income and/or energy expenditure data (based on Household Budget Survey—HBS data).

1) Consensual-based indicators

- Ability to keep home adequately warm, based on self-reported thermal discomfort[2]
- Arrears on utility bills, based on households' self-reported inability to pay utility bills on time in the last 12 months[3]

2) Expenditure-based indicators

- M/2—Hidden energy poverty: absolute (equivalised) energy expenditure below half the national median
- 2 M—High share of energy expenditure in income: share of (equivalised) energy expenditure (compared to equivalised disposable income) above twice the national median

Using information on EPOV website, these four indicators can be displayed also by second-level disaggregating variables: income deciles, tenure type, urbanisation density and dwelling type. Additionally, a set of 19 secondary indicators are extracted from different data sources, mainly the Eurostat (ESTAT) website, SILC and the Building Stock Observatory (BSO). They are relevant in the context of energy poverty, but not directly indicators of energy poverty themselves (e.g. energy prices and housing-related data). Each indicator captures a different aspect of the phenomenon. These indicators should be seen as a means to provide a snapshot of energy poverty issues, which can then be investigated in more detail in research and projects on the ground, exploring if this phenomenon is more widespread than expected across the EU.

As shown in Table 1, the incidence of energy poverty in a country crucially depends on how it is measured: for example, in Portugal, Lithuania, Cyprus and Bulgaria the share of energy poor is relatively high with the consensual indicator "Ability to keep home adequately warm" and it becomes almost 1/3 lower with the expenditure based M/2 indicator ("Hidden energy poverty"). In Italy, estimates for 2 M indicator show that in 2015 energy poor are 15,5% of total population (ADL), implying a relative stability of the share except for the indicator "Arrears on utility bills". As clearly shown in the maps in Fig. 1, the different aspects of the phenomenon measured by the indicators overlap only partially. In other words, different indicators capture different segments of the population.

Table 2 provides an overview of indicators available at country level when a specific component of energy poverty is investigated, namely energy poverty in the rented sector. This sector is highly fragmented and targeted policies are scarce if

[2] The corresponding question in the EU SILC survey is "Can your household afford to keep its home adequately warm?".

[3] The corresponding question in the EU SILC survey is "In the past twelve months, has the household been in arrears, i.e. has been unable to pay the utility bills (heating, electricity, gas, water, etc.) of the main dwelling on time due to financial difficulties?".

Table 1 Comparison of EPOV primary indicators in EU member states (share of population, %)

	Arrears on utility bills (2018)	Ability to keep home adequately warm (2018)	Hidden energy poverty M/2 (2015)	High share of energy expenditure in income 2 M (2015)
Austria	2,4	1,6	15,0	16,0
Belgium	4,5	5,2	9,8	13,0
Bulgaria	30,1	33,7	9,4	11,5
Croatia	17,5	7,7	7,5	12,0
Cyprus	12,2	21,9	13,2	12,0
Czechia	2,1	2,7	9,2	10,8
Denmark	5,1	3	–	–
Estonia	6,5	2,3	18,9	18,7
Finland	7,7	1,7	29,9	22,3
France	6,4	5	19,5	15,0
Germany	3	2,7	17,4	17,4
Greece	35,6	22,7	12,8	16,3
Hungary	11,1	6,1	9,3	9,0
Ireland	8,6	4,4	14,8	17,6
Italy	4,5	14,1	13,6	–
Latvia	11,6	7,5	10,7	12,7
Lithuania	9,2	27,9	14,4	13,9
Luxembourg	3,6	2,1	8,9	11,3
Malta	6,9	7,6	16,7	20,1
Netherlands	1,5	2,2	4,4	10,7
Poland	6,3	5,1	19,5	16,3
Portugal	4,5	19,4	6,8	15,1
Romania	14,4	9,6	16,8	16,9
Slovakia	7,9	4,8	7,9	9,3
Spain	7,2	9,1	13,0	14,2
Slovenia	12,5	3,3	8,9	13,9
Sweden	2,2	2,3	24,3	28,7
European Union	6,6	7,3	14,6	16,2

Source EPOV

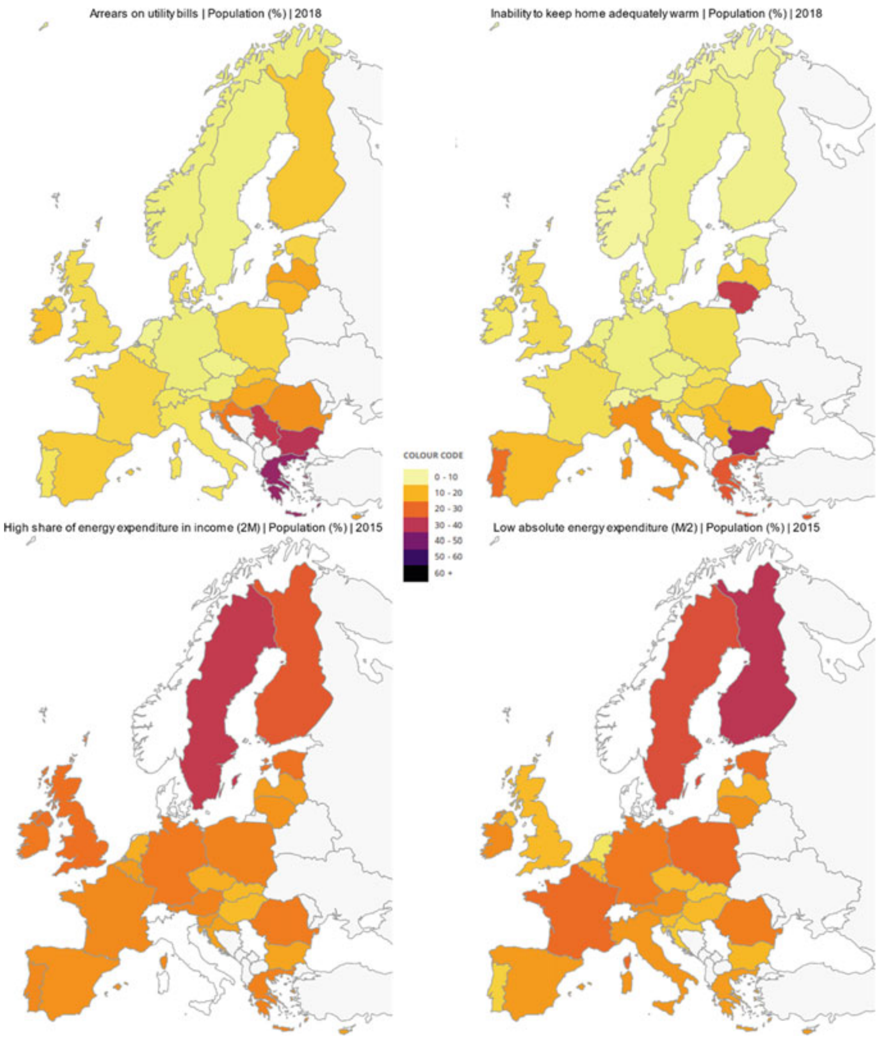

Fig. 1 Maps of EPOV primary indicators in EU Member States (*Source* Author' on EPOV data)

compared to social housing and homeowners' sectors. In addition, split incentives are a particularly relevant issue in delivering energy efficiency measures.[4]

As previously highlighted (Table 1, Fig. 1 and Table 2), each country made its own choices in measurement, given that no official EU-wide definition exists. Energy

[4] ENPOR projects investigates this specific aspect of the energy poverty phenomenon. Further information can be found in project deliverables such as D3.2 (https://www.enpor.eu/wp-content/uploads/2022/01/ENPOR-D3.2.pdf) and in analysis of national case studies, such as the German one (https://www.enpor.eu/27-05-22-enpor-submits-policy-recommendation-to-the-draft-law-on-sharing-co2-costs-between-tenants-and-landlords-in-germany/).

Table 2 Availability of indicators at different territorial levels

	National	NUTS1	NUTS2
Inability to keep home warm Arrears on utility bill Presence of leak, dump, rot Poverty risk	All MS	Austria—Belgium—Bulgaria—Croatia—Denmark—Estonia—Greece—Hungary—Ireland—Italy—Lithuania—Poland—Romania—Slovakia—Slovenia	Spain—Portugal—France— Czech Republic—Finland
Relative risk of asthma Size of the rental sector	All MS	–	–
Dwelling not comfortably cool High share of energy expenditure in income Low absolute energy expenditure Rented private housing energy poverty indicator	-	–	–

Source Author' on data from the energy poverty dashboard (https://www.enpor.eu/energy-poverty-dashboard/)

poverty measurement is controversial since the indicator choice is not neutral and the different pictures provided affect the adoption of mitigation policies. According to the non-binding requirements of the Integrated National Energy and Climate Progress Reports process, MS should measure and monitor energy poverty.

Italy anticipated this issue by using a new definition and measure in its 2017 National Energy Strategy, although this is not adopted as official definition. An ad hoc objective indicator was adopted, based on Faiella and Lavecchia (2015). The indicator combined three elements: the presence of a high level of energy expenditure, total expenditure below the relative poverty threshold, and a null value for the expenditure on heating. The measure is a Low Income-High Cost indicator, considering three dimensions: (1) a share of energy costs more than twice the average share of energy expenditure, (2) a household budget, after energy costs are deducted, below the national (relative) poverty line set by the National Statistical Institute (3) null heating purchases when total expenditure is below the median. Later on, the Integrated National Plan for Energy and Climate (NECP) adopted the same definition and in this work we refer to it.

According to this measure, in 2018 there were slightly more than 2 million of energy poor households (more than 5 million persons), equal to 8.8% of the total population. Energy poverty has a higher incidence in Southern Italy and in larger households.[5] According to the analysis in NECP, in 2007–2017 decade, the share

[5] More information can be found in 'Secondo Rapporto sullo stato della povertà energetica in Italia' (OIPE 2020).

of energy expenditure on the total has increased from 4.7% to 5.1%. This share is higher (around 8%) and it increased more (almost + 1%) for households in the first quintile of equivalent expenditure. When the official Italian indicator is computed by macro-region it is observed that North-East and North-West show lower shares of energy poverty, which instead are high adopting a hidden energy poverty indicator (OIPE 2020; ENEA, 2021).

NECP also developed energy poverty projections at 2030, using the following main drivers for energy poverty: the expected price trends for energy products, the trends in overall household expenditure, demographic changes and the trends in residential energy consumption and associated mix. Renovation rate of building stock is also relevant, as well as indirect benefits on sanitary system associated to a reduction in diseases related to living in apartments not adequately warm. According to the projections in NECP, in 2030 energy poverty incidence would remain in the range of 7–8%. This means that energy poverty would decrease by approximately one percentage point compared to 2016, corresponding to approximately 230,000 households; due, among others, to a number of people over the age of 65 equal to a quarter of the total in 2030, and to a fall by 15.5% of residential consumption in 2030 relative to 2016, with a growth in the electricity component against a reduction in natural gas. Clearly these projections are likely to be significantly affected by the recent geopolitical and energy prices developments.

Indeed, current energy prices are very likely to increase the number of energy poor household. Each household will experience a very significant surge in energy expenditure and thus, in some way, an increase in the risk to fall in energy poverty condition. Consumers' vulnerability can be considered connected with energy poverty (see next Section) and this confirms, once again, the interesting opportunities provided by energy efficiency technologies as well as behavioural solutions. Also the projections and targets for annual requalification rate developed in the Long-Term Building Renovation Strategies in 2021 are likely to affect the incidence of energy poverty at national level. An annual renovation rate in the range 0.6%-0.8% would be needed in residential sector to reach the 2030 NECP objective; clearly, apartments inhabited by energy poor household should be involved in such renovations and the financing of such interventions is a relevant challenge in the policy agenda.

3 Policy Strategies

Moderation of energy demand is one of the five dimensions of the Energy Union Strategy established in 2015. The vulnerability condition is mentioned for the first time in the second energy package (Directives 2003/54/EC and 2003/55/EC) and with the third energy package (Directive 2009/72/EC) energy poverty is explicitly indicated as one of the conditions determining vulnerability.

Over the past decade, the EU has increased its efforts to reduce and mitigate energy poverty, making it a key concept in the Clean Energy for All package adopted in 2019. Indeed, the package proposed a range of measures to address energy poverty through energy efficiency, safeguards against disconnection and a better definition and monitoring of the issue at MS level through the integrated National Energy and Climate Plans (NECPs). As a consequence, the EU legislative context for energy poverty underwent several changes. Energy poverty is currently mentioned in the Energy Efficiency Directive (2018/2002), the Energy Performance in Buildings Directive (2018/844), the Electricity Directive (944/2019) and the Governance Regulation (2018/1999).

As specified in the Directive 2018/2002, energy efficiency should be considered as complementary to social security policies when tackling energy poverty at MS level. Particular attention should be devoted to the accessibility to energy efficiency measures for consumers affected by energy poverty as well as to the cost-effectiveness and affordability of the measures for both property owners and tenants. Moreover, current building renovation rates are insufficient to meet the objectives of the Paris Agreement and buildings occupied by consumers affected by energy poverty are the hardest to reach. These are the reasons why the Directive states that, when designing the measures to fulfil energy saving objectives, MS should take into account the need to alleviate energy poverty in accordance with criteria established by them. To do this, they could require "a share of energy efficiency measures under their national energy efficiency obligation schemes, alternative policy measures or programmes or measures financed under an Energy Efficiency National Fund, to be implemented as a priority among vulnerable households, including those affected by energy poverty and, where appropriate, in social housing" (article 7).

The EU Regulation 2018/1999 on the Governance of the Energy Union and Climate Action sets out that MS in their NECPs "assess the number of households in energy poverty taking into account the necessary domestic energy services needed to guarantee basic standards of living in the relevant national context, existing social policy and other relevant policies, as well as indicative Commission guidance on relevant indicators for energy poverty" (article 3). If MS find a significant number of households in energy poverty, a national indicative objective to reduce energy poverty should be included in their plan. Integrated reporting on energy poverty is consequently required, in terms of quantitative information on the number of households in energy poverty and available information on policies and measures addressing the problem.

Furthermore, according to Directive 2018/844, MS could define their own criteria to take into account energy poverty and establish which are the relevant actions for its alleviation, to be outlined in their long-term renovation strategies. Each strategy should encompass an overview of policies and actions to target the worst performing segments of the national building stock, split-incentive dilemmas and market failures, and an outline of relevant national actions that contribute to the alleviation of energy poverty (article 2).

According to the Electricity Directive, MS shall ensure the protection of energy poor and vulnerable household customers and may apply public interventions in the price setting for the supply of electricity to energy poor or vulnerable household customers (art.5). According to art. 28, the concept of vulnerability may refer to energy poverty and in particular to income levels, the share of energy expenditure of disposable income and the energy efficiency of homes; the support for energy efficiency improvements is included among the actions to address energy poverty art. 29 states that MS shall define a set of criteria for the purposes of measuring energy poverty and that they shall report on its evolution to the Commission as part of their Integrated National Energy and Climate Progress Reports.

In 2020, as part of the Renovation wave strategy, the Commission published a Recommendation on energy poverty to support EU countries' efforts to tackle energy poverty. The recommendation provides guidance on adequate indicators to measure energy poverty and promotes sharing best practices between EU countries. Building on this recommendation, the Fit for 55 package, adopted in July 2021, proposed specific measures to identify key drivers of energy-poverty risks for consumers, such as too high energy prices, low household income and poor energy-efficient buildings and appliances, taking into account structural solutions to vulnerabilities and underlying inequalities. The Fit for 55 package also included a proposal for a revision of EED to put a stronger focus on alleviating energy poverty and empowering consumers. The recast proposal, which could be approved by the end of 2022, introduces an obligation for EU countries to implement energy efficiency improvement measures as a priority among vulnerable customers, people affected by energy poverty and, where applicable, people living in social housing. The criteria would take into account the different national contexts.

In autumn 2021, the Commission published the Communication "Tackling rising energy prices: a toolbox for action and support", where it lists a range of short- and medium-term initiatives that can be taken at national level to support and help the most vulnerable consumers. The EPBD recast also further stressed the importance of the mitigation of energy poverty in EU policies. According to recast, the alleviation of energy poverty is among the main considerations at the basis of the introduction of EU minimum energy performance standards to trigger the required transformation of the building sector. MS would need to provide adequate financial support and technical assistance, as well as to engage in the removal of barriers and the monitoring of social impacts, in particular on the most vulnerable. Connected to this, a wider new definition of "vulnerable households" is proposed, including also households with lower middle income that are particularly exposed to high energy costs and lack the means to renovate the building they occupy (new art.2).

In the vein of sharing best practices, the Commission Decision 2022/589 established in April 2022 the Commission Energy Poverty and Vulnerable Consumers Coordination Group, which aims to exchange best practices and increase coordination of policy measures to support vulnerable and energy poor households.

3.1 Energy Poverty Mitigation in EU Countries

The measurement of energy poverty is key to elaborate effective policy strategies. This is confirmed by comparing Table 2 in the previous section with Fig. 2. Indeed, MS having a high availability of indicators, not only at country level but also at NUTS

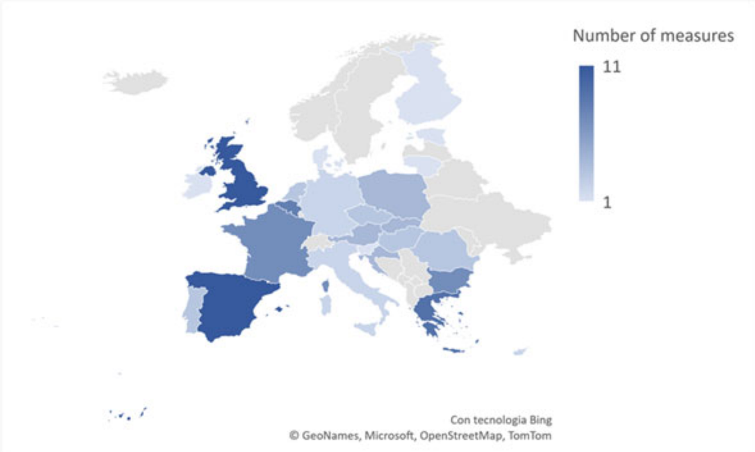

Fig. 2 Policy measures in different Member States (*Source* Author' on data from EPAH Atlas)

level 1 or 2 (Table 2), are likely to have a high number of policies, as depicted in Fig. 2, confirming the interlinkage between measurement and policy action (Faiella and Lavecchia 2021). It should be considered that Fig. 2 is based on the information available on EPAH Atlas, which is a database covering local, national and international projects and measures addressing energy poverty.[6] The list of local measures included there is not yet exhaustive, since the tool is continuously evolving and enriched by the uploading of new policy measures, as explained on the website. France and Spain represent countries having data at NUTS2 level and having also a significant number of policies in force.

Several policy approaches can be employed to fight and mitigate energy poverty. The approaches adopted by MS can be grouped in the following categories:

1. Support mechanisms to protect consumers, which lower energy cost by bill discounts or alternatively lower prices for specific customers;
2. Energy consultancies and information campaigns, aimed at promoting efficient energy use;
3. Financial tools to support energy efficiency, to sustain structural energy efficiency investments.

In addition to the three main components at the basis of energy poverty, namely household income, energy prices and building energy performance, a fourth one can be considered: it is represented by household behaviour. Behavioural economics could be helpful in this matter, suggesting two strategical actions (OIPE 2020). First one is related to improving the architecture of choices (nudging), for example, creating conditions to take better decisions relative to energy consumption, and second one to increasing competences (boosting).

[6] https://energy-poverty.ec.europa.eu/discover/epah-atlas_en.

The second category of measures above specifically deals with the behavioural component. Combining it with structural interventions, namely with the third category of measures, could prove to be particularly useful in order to effectively improve the living conditions of population segments affected by energy poverty. The most common approaches in MS are support mechanisms to protect consumers. They are followed by measures to improve energy performance of buildings targeted to energy poor households, which are becoming more frequent.

Support mechanisms to protect consumers are in force in Austria, France, Germany, Greece, Ireland, Italy Netherlands, Romania and United Kingdom. The discount is generally based on household component number and also, relative to gas bill, to expected temperature in the household territory. Some MS, among which Belgium, Greece, Portugal, Romania and Spain, have in force social tariff as alternative tools to support mechanisms.

The main schemes in the second category are EU-funded projects, such as ACHIEVE and ASSIST, as well as national schemes as those introduced in Czech Republic, Denmark, France, Germany, Spain and United Kingdom. They include: the analysis of energy bill, consumption and household behaviour; energy saving recommendations; assistance in identifying support mechanism that can be accessed (ENEA 2020). Information and training campaigns, conceived with wider scope and targets, can include specific activities devoted to energy poor households. This is the case of the ongoing campaign Italia in Classe A.

Financial tools include non-repayable fundings or subsidised loans, partially covering investment costs, and fiscal rebates, provided through tax reliefs in the years after the investment. Energy poor households can have difficulties in accessing financial tools due to several factors, such as: lack of competences to assess energy efficiency potential benefits and to access the incentive; lack of financial resources; insufficient fiscal capacity; decisional issues associated to living solutions in building blocks or rented apartments. In order to overcome such difficulties, some MS introduced targeted schemes to energy poor household: Belgium, France, Germany, Ireland, Poland and United Kingdom. They have common characteristics such as, for example, the presence of a promoting agent, different from the beneficiary; a higher intensity of the incentive; the exemption for the beneficiary to anticipate any funding for the investment (ENEA 2020).

A further categorisation can distinguish between protection and promotion measures. First type of measures are short term and they are aimed at ensuring a minimum level of energy services; bill discounts are included in this category. By contrast, protection measures have a long-term nature and they are able to introduce structural changes. This category covers the energy efficiency measures improving living conditions, as well as the measures improving awareness of household energy consumption.

3.2 Energy Poverty Mitigation in Italy

The Italian Integrated National Plan for Energy and Climate includes different measures to tackle with energy poverty, having different nature. In particular, they are categorised as follows:

- social measures, namely the electricity, gas and physical ailment bonuses;
- structural measures, the tax relief scheme for energy renovation of buildings;
- fiscal measures, namely the exemption from electricity and heating fuels excise duties respectively for households in the first consumption bracket and for households living in disadvantaged geographical areas.

Gas and electricity bonuses apply a discount on the final amount of the bill to customer having income lower than a specific threshold. The effectiveness of these measures had been hampered by their ability to reach only around one-third of the entitled households; for this reason they have become automatically granted since 2021.[7] Discounts are modulated according to the household size and the climate of the household location. Relative to the expenditure of a typical customer (annual consumption 2.700 kWh), in 2020 the electricity bonus was covered from a minimum of 24% (household with 1–2 components) of up to 33% (household with 4 or more components). The gas bonus represented from 3% up to 25% of the expenditure of a typical consumer (individual heating and annual consumption equal to 1.400 m^3).

NECP lists the tax relief scheme for energy renovation of existing building stock (Ecobonus) among the specific measures dedicated to energy poverty. Implemented as alternative measure under article 7 of EED (European Energy Efficiency Directive), Ecobonus allows the households in the no-tax area—which are likely to be energy poor—to transfer their tax credit to financial institutions, work suppliers or other private entities, reducing the investment cost for energy efficiency interventions.

ENEA collects the applications to access the incentive mechanism and is also charged of managing the monitoring system. Ecobonus incentive scheme has been in force since 2007: during the years, it was indeed confirmed by several Budget Laws, which introduced new features concerning, for some specific cases, tax credit rates, eligible actions and technical or performance requirements. In general, Ecobonus applies a tax relief on income tax paid by physical persons (or by companies), and the tax relief rate changes according to the eligible action considered.

According to 2018 Budget Law (Law dated 27 December 2017 no. 205) and 2019 Budget Law (Law dated 30 December 2018, no. 145), some examples of tax credit rates are:

- 50% for the expenses incurred for replacing windows and shutters, installing solar shading, replacing heating systems with at least class A energy-efficient condensation boilers;

[7] Decreto Fiscale 2019. Art 57 bis comma 5.

- 65% for replacing heating systems with at least class A energy-efficient condensation boilers and also installing an advanced thermoregulation system with efficiency classes V, VI or VIII as indicated in Commission Communication 2014/C 207/02;
- 65% for installing solar panels.

These tax credit rates are those relevant for the following analysis, evaluating Ecobonus incentive scheme based on 2018 data. The 2018 Budget Law also introduced a higher rate for energy efficiency actions on the building block and also for actions combined with anti-seismic interventions, for which the tax relief ranges from 70% up to 85% of the expense, depending on specific conditions. The Superbonus incentive scheme has been introduced in 2020 (Law Decree 34/2020, converted in Law 77, 17 July 2020), aimed to support deep renovation and at the same time to revitalise the economy during the covid pandemic. It incentivises energy efficiency and anti-seismic interventions on building blocks with a tax credit rate equal to 110%, reducing the number of payments from ten to five years and extending the tax credit transfer options. In this scheme, the tax credit rates for the expenses listed above change if the corresponding interventions are included in a deep renovation project. For example, the tax credit for windows and shutters becomes 110% if the intervention is associated to an intervention which improves building envelope and satisfies specific technical conditions.[8] These more recent legislative changes are not taken into account in the following analysis, since the evaluation is based on 2018 data.

The possibility of tax credit transfer for all eligible energy efficiency actions, for people in the no tax area and social housing institutes, was introduced by 2016 Budget Law (Law dated 28 December 2015, no. 209), and it was limited exclusively to suppliers who implemented works. For people in the no tax area, the tax credit transfer has been extended to other private entities, banks and financial institutions by 2017 Budget Law (Law dated 11 December 2016, no. 232). The tax credit transfer possibility is aimed to increase the access to Ecobonus scheme for households in difficult economic conditions, among which energy poor households are likely to be included. In the context of Superbonus incentive scheme the tax credit transfer has been extended to all taxpayers, not only those in the no tax area. After the first year of implementation, the tax credit transfer options have been restricted, with the aim of reducing the risk of carrousel frauds.

[8] More information on the Superbonus incentive scheme functioning can be found in Rapporto Annuale Detrazioni Fiscali 2021, https://www.pubblicazioni.enea.it/component/jdownloads/?task=download.send&id=459&catid=8&m=0&Itemid=101 as well as in the information leaflet available here https://www.efficienzaenergetica.enea.it/pubblicazioni/poster-riepilogativo-detrazioni-fiscali-2022.html

4 An Evaluation of the Ecobonus Incentive Scheme

The regional analyses developed in the last edition of Energy Efficiency Report (ENEA 2021) as well as those developed in the second report of the Italian Observatory on Energy Poverty (OIPE 2020) show a relatively higher incidence of energy poverty in Southern Italy. This result on energy poverty is in line with the incidence of relative poverty: high energy expenditures make critical situations even more problematic.

After having described the national definition of energy poverty and the overall mitigation strategy, in this section a methodological approach is defined to assess the effectiveness of a consolidated energy efficiency measure in mitigating energy poverty. In order to do so, a descriptive statistical analysis was applied and regional maps of the access to Ecobonus were elaborated. Italy offers an interesting case study because it combines a high climate diversity with heterogeneous socioeconomic conditions, as highlighted by recent studies on energy poverty in Italy (Besagni and Borgarello 2019).

4.1 Method

Based on information at regional level, namely ENEA microdata on Ecobonus, the possible relationship between household income and the access to Ecobonus is examined. Additionally, the method allows to investigate if this relationship changes for the different categories of interventions incentivised by the Ecobonus, such as the replacement of windows and shutters or of heating systems.

The hypothesis is that the incentive measure, in its current approach, has a regressive distributive effect on households, and it does not effectively support energy poverty eradication. To our knowledge, the relationship between income and interventions incentivised by Ecobonus has not been investigated before, neither at regional level nor in energy poverty framework.

The database of the Ecobonus incentive scheme includes data on investments in different types of interventions, based on different technologies, and on associated energy savings. Data on incentivised interventions are analysed in two different years, 2016 and 2018, namely before and post the introduction of the tax credit transfer.[9] To examine the results of Ecobonus incentive scheme at national level, a cost-effectiveness indicator can be computed, as the ratio between Euro spent per kWh saved. This indicator shows better values for interventions on envelope insulation, windows and shutters replacement and solar panels. Envelope insulation and windows and shutters replacement are also associated to a higher share of savings on the total; significant savings are also generated by replacing heating systems, in

[9] More recent data are available and can be found in the report on tax reliefs yearly published by ENEA, latest version available here https://www.efficienzaenergetica.enea.it/component/jdownloads/?task=download.send&id=559&catid=9&Itemid=101.

particular installing condensation boilers. The analysis of intervention distribution at national level also shows a relevant share of investment on buildings built before 1980 (77% of the total), which is consistent with a higher energy saving potential in these buildings. Finally, it is worth specifying that no information on households having transferred the tax credit is currently available in the database managed by ENEA.

The following analysis has its starting point by the higher incidence of energy poverty in Southern Italy shown by the adopted definition, and on this basis examines the regional distribution of investments activated by Ecobonus, considering different technologies. In particular, the ratio between regional investments, normalised (where relevant) to correct for climatic effects, and regional net available income will be shown in maps,[10] developed with a free online tool. This geographical representation is aimed at assessing the access to Ecobonus, showing evidence at qualitative and descriptive level. Some first insights on the effectiveness of Ecobonus in addressing energy poverty can be derived by connecting this evaluation with the available information on the geographical pattern of energy poverty incidence.

4.2 Results

At national level, 3.3 billion Euro of investments were activated by Ecobonus in 2016, among which 1.5 were associated to windows and shutters replacement and 950 million to envelope insulation. In 2018, total investment level was aligned and the replacement of windows and shutters was again the main component, with more than one billion of investments, followed by envelope insulation (900 million) and the replacement of heating system (slightly more than 870 million).

In 2018, regional total investments activated by Ecobonus incentive scheme range between a maximum equal to 785 million Euro and a minimum equal to 8 million Euro. Activated investments can be normalised by regional net available income, based on data provided by Italian National Statistical Institute.[11] After the normalisation, they show an asymmetric distribution. In fact, in 2016 only one region in Southern Italy was in the second quartile of the distribution, all the others being in the first one. The geographical incidence of energy poverty follows the opposite pattern, with a higher share of energy poor households in Southern Italy. The distribution of investments activated by Ecobonus slightly changed in 2018, with three regions in Southern Italy included in the second quartile (Fig. 3).

In terms of deviation from the average, Southern Italy regions are always below the national average, and this pattern has remained unchanged between 2016 and 2018.

[10] Maps are a tool more and more used to describe a wide range of phenomena, also thanks the availability of georeferenced data. Among others, it is interesting to mention the work by Hills (2012) devoted to map energy poverty in the United Kingdom and the work by Lelo et al. (2019), aimed at mapping a wide range of social phenomena in Rome.

[11] http://dati.istat.it/Index.aspx?DataSetCode=DCCN_SEQCONTIRFT, last accessed 2/12/2019.

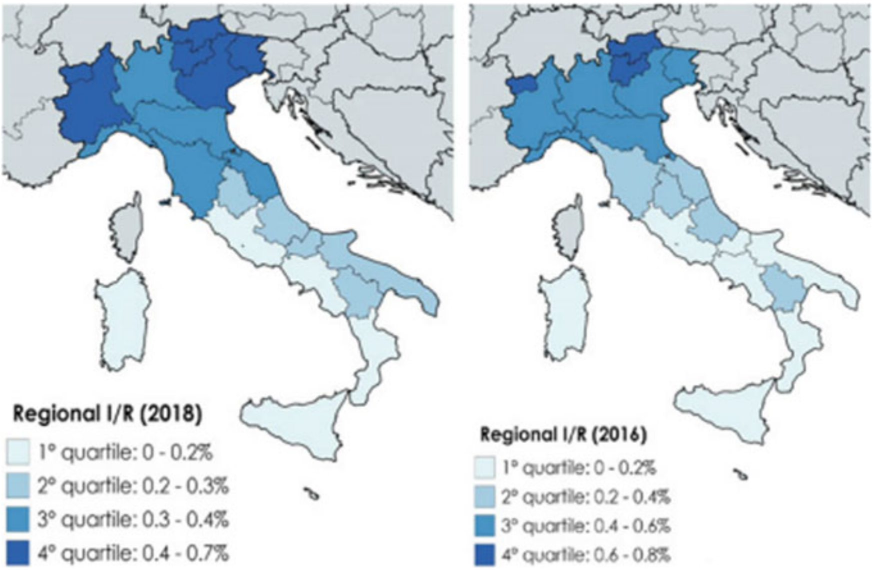

Fig. 3 Ratio between total investments activated by Ecobonus and net available income by region (I/R), 2018 and 2016 (*Source* Author' on ENEA data)

For example, Campania has the higher negative deviation from the average, followed by Sicilia and Sardegna, respectively in second and third position in 2018. By contrast, regions having higher positive deviation from the average are, in decreasing order, Trentino Alto-Adige, Valle d'Aosta and Piemonte.

The results can be mapped also relative to specific technologies, comparing 2016 and 2018: given their high share on total investment, windows and shutters, building envelope and heating system will be shown. For all these technologies, the investment activated by Ecobonus has been normalised by regional Heating Degree Days (HDD), available from Eurostat.[12]

In 2018, regional investments in the replacement of windows and shutters, normalised by HDD, range between 295 and 920 Euro per billion of net available income. The geographical asymmetry is less pronounced than for total investment, since already in 2016 three Southern regions are in the second quartile and another in the third one. An improvement in positioning of Southern regions is observed in 2018, with two regions in the third quartile and another in the fourth one (Fig. 4).

Regional investments in building envelope insulation, normalised by HDD, range between 120 and 965 Euro per billion of net available income in 2018. A pronounced geographical pattern is observed and a very slight improvement is observed, with a

[12] https://ec.europa.eu/eurostat/web/products-datasets/product?code=nrg_chddr2_m, last accessed 2/12/2019. In 2018, HDD in Italian regions ranged between a maximum value of 4,184 (Valle d'Aosta) and a minimum value of 946 (Sardegna). These two regions had the highest and lowest values also in 2016.

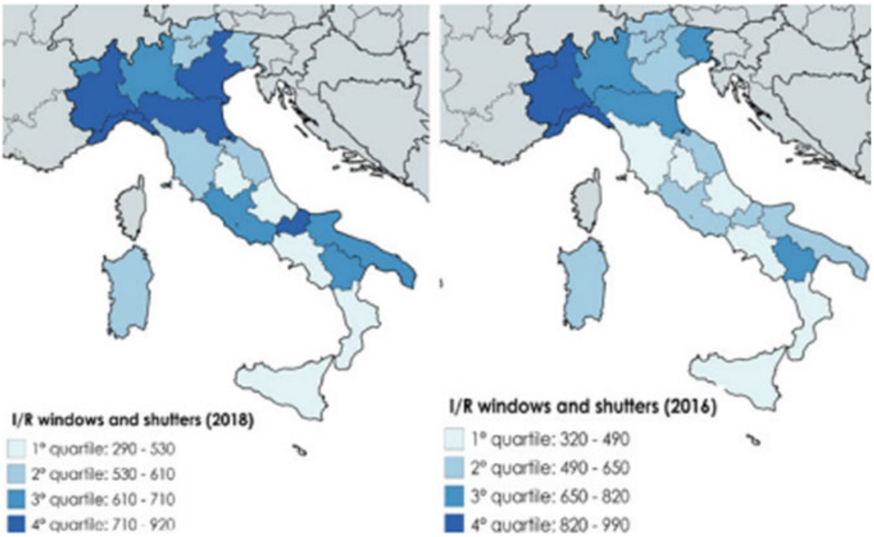

Fig. 4 Regional investments activated by Ecobonus normalised by regional HDD per billion of net available income (I/R), 2016 and 2018, windows and shutters (*Source* Author' on ENEA data)

Southern region moving to the third quartile and the number of regions in the second quartile of the investment distribution remaining unchanged (Fig. 5).

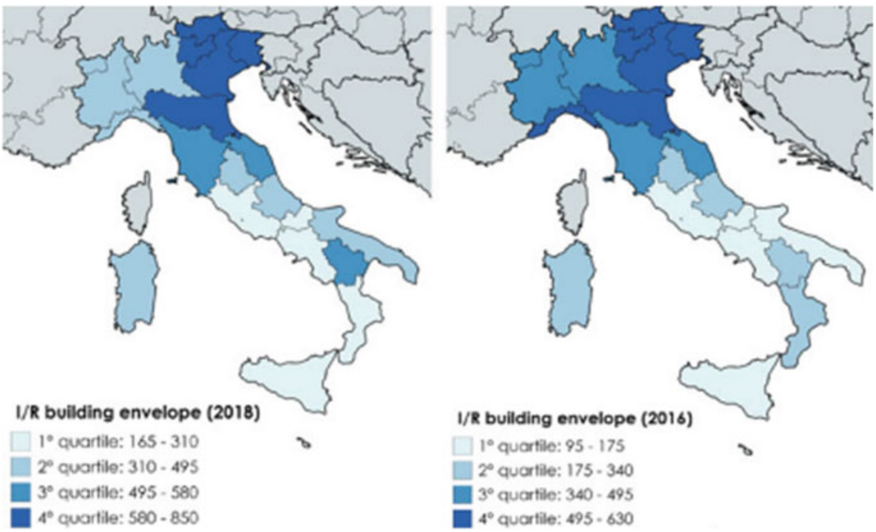

Fig. 5 Regional investments activated by Ecobonus normalised by regional HDD per billion of net available income (I/R), 2016 and 2018, building envelope (*Source* Author' on ENEA data)

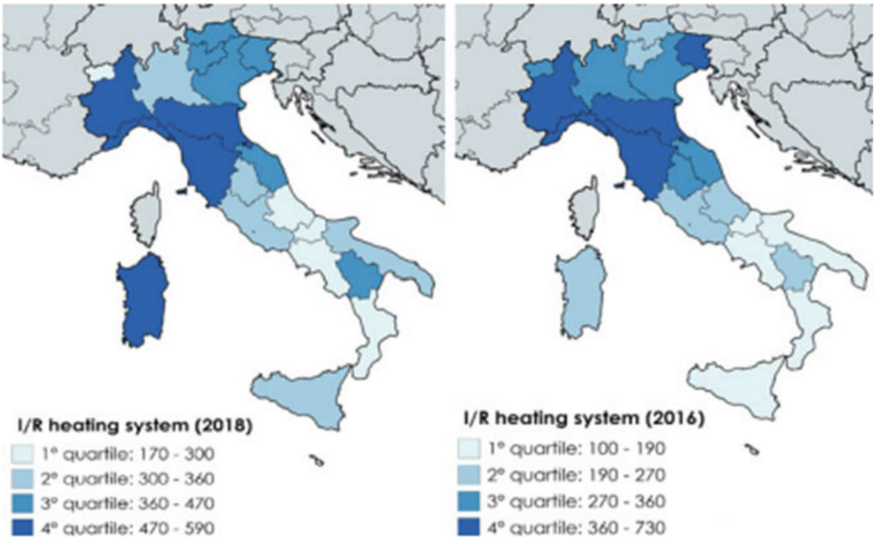

Fig. 6 Regional investments activated by Ecobonus normalised by regional HDD per billion of net available income (I/R), 2016 and 2018, heating system (*Source* Author' on ENEA data)

Looking at the replacement of heating system with a more efficient one, investments normalised by HDD range between 195 and 635 Euro per billion of net available income in 2018. The geographical asymmetry is again observed, as well as the improvement of Southern regions positioning in the quartiles. The number of Southern regions in the second quartile increases, and two regions pass in the third and fourth quartile (Fig. 6).

Finally, specific technologies which could theoretically have a larger potential in Southern than in Northern Italy, due to higher solar radiation, are investigated. This is the case, for example, of solar panel and solar shading; in 2018, total investments activated by Ecobonus in Italy amounted to 36 million Euro for solar panels and 128 million Euro for solar shading. For solar panels, regional investments range between zero and a maximum of 179 Euro per million of net available income; for solar shading, the range is between 10 and 223 Euro per million of net available income. The two maps shown in Fig. 7, relative to 2018 data, seem to suggest that a higher technology potential is not enough to support the access to Ecobonus incentive scheme in Southern regions. In other words, the higher potential in Southern Italy is not followed by a higher demand for tax reliefs at household level. This result is particularly relevant considering the fact that in energy poor household, renewable energy sources could represent a structural solution, similar to energy efficiency interventions.[13] The observed pattern could be due to, among others, the difficulties

[13] It is interesting to mention the local initiative "Reddito Energetico", financing small photovoltaic installations in buildings inhabited by energy poor households and also introducing a revolving

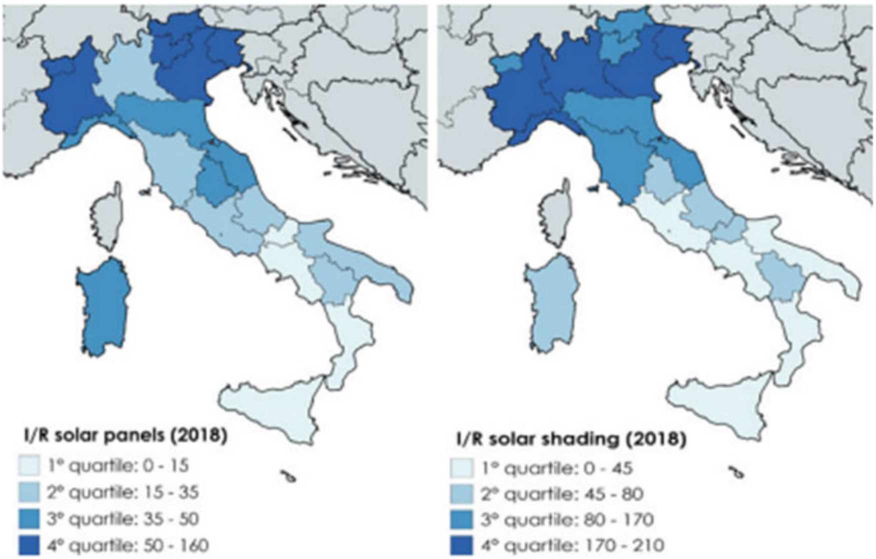

Fig. 7 Regional investments activated by Ecobonus normalised per million of net available income (I/R), 2018, solar panels and solar shading (*Source* Author' on ENEA data)

in accessing Ecobonus incentive scheme of household having a high potential but also a low-income level.

4.3 Discussion

According to the results shown in the previous section, Southern regions are very often in the lower distribution quintile of the ratio between investments activated by Ecobonus and household net available income. This is true at overall level (total investments activated) and also for specific technologies. In particular, this is true for both the technologies needing a correction for climate effects (interventions on windows and shutters, envelope insulation and heating system) and those having a higher potential in Southern Italy (solar panels and solar shading). The comparison between the first year in which tax credit transfer was made available (2016) and two years after its introduction (2018) shows small improvements in the access pattern at geographical level.

Italian NECP confirms that the results obtained through Ecobonus have been significant until now and that the incentive scheme will remain associated to a high saving potential in the next years. As described in Italian NECP, the overall cumulated contribution of tax reliefs to 2030 targets would be around 18.15 Mtoe of final

fund. This has been implemented by Gestore Servizi Energetici in Sardegna and more information can be found in Energy Efficiency Annual Report (ENEA 2019).

energy, which would cover almost all the saving target for residential sector.[14] Then, Ecobonus incentive scheme will certainly continue to play a key role to enhance energy efficiency in residential sector. The question is if the incentive would also contribute to energy poverty alleviation.

Indeed, some difficulties still remain for energy poor households to access Ecobonus, as already highlighted in general for the financial tools category. In particular, the beneficiary needs to anticipate the resources to finance the interventions, and until now the credit transfer has not been widely used. Moreover, limitations could also be linked to split incentives dilemma, in case of households renting their apartments.

Several development trends at policy level are envisaged in NECP to ensure and reinforce Ecobonus effectiveness in generating energy savings. Also in this case, it is worth to assess to what extent these interventions could contribute to increase the potential of the scheme in mitigating energy poverty. First of all, the tax relief schemes for energy renovation and for refurbishment of existing buildings would be optimised by integrating them into a single scheme. Additionally, this new scheme should provide a benefit scalable in relation to the expected saving, in order to reward those interventions with the best cost-efficiency ratio and to increase the trend towards deep renovation of buildings and seismic improvement. Finally, provisions aimed at promoting initial investments should be introduced, for example, extending the coverage and transferability of the tax credit and implementing a guarantee fund on green financing issued by credit institutions. This last intervention could modify the pattern in accessing Ecobonus incentive scheme for energy poor households.

Ensuring further adaptation of the Ecobonus incentive scheme to improve the access of energy poor households would be consistent also with the general approach proposed by EnR in its 2019 position paper. This analysis on the effectiveness of Ecobonus incentive scheme in tackling energy poverty and the eventual need to make it more suitable for energy poor households tries to comply with several EnR recommendations.

First, it is obviously in line with energy efficiency being a structural solution to energy poverty. Indeed, energy efficiency does not only alleviate energy poverty it acts on its causes, potentially allowing people to definitively exit their energy poverty condition. Supporting investments in building renovation would allow the strategies to contrast energy poverty to take into account that the energy needs change in an objective way according to technical building characteristics (Faiella et al. 2017). As widely known, energy efficiency is also associated to multiple benefits, such as social and health benefits, which are even more evident when energy efficiency interventions are implemented in energy poverty context (BPIE, 2014; Liddell and Guiney, 2015; Ntaintasis et al. 2019). If such benefits are opportunely translated into the investments' business plan, they may shorten the payback period and also

[14] Also the tax reliefs for refurbishment of existing buildings (Bonus Casa) would contribute to reach this overall figure. In 2018, interventions incentivised through Bonus Casa saved 0.225 Mtoe/year whereas those incentivised by Ecobnous 0.106 Mtoe/year. The contribution of Bonus Casa is calculated taking into account the energy savings generated by boiler substitution and not referring to other intervention in the renovation area.

increase the credit worthiness of low-income households. Besides, poorest deciles of the population are those where retrofit actions are usually more urgent, being more likely to live in non-refurbished homes with high fuel costs (Schleich, 2019). Ownership is another delicate issue to be taken into account: energy poverty condition could arise both in private residential sector, relative to households owning or renting their apartment, or in public residential sector, relative to social housing. Including renters among the eligible subjects of energy efficiency policies, as is the case in Ecobonus, could turn out not being fully effective due to the split incentive dilemma. Owners have no incentive to make investments whose benefits are mainly enjoyed by tenants and this problem could be especially acute in the energy poverty context. Sound solutions should provide incentives to both the owner and tenant, defining how multiple benefits due to energy efficiency could be split out among the two parties (Bird and Hernandez, 2012). Further research could extend this analysis to consider ownership information at regional level, to detect if relevant differences exist in accessing the Ecobonus incentive scheme. In Liguria region, Enershift project has promoted the use of Energy Performance Contract in social housing, according to an innovative financial mechanism that links energy efficiency incentives to the associated savings.[15] Finally, an innovative literature contribution (Vatikiotis, 2021) suggests that energy poverty could be an issue also in the context of micro-enterprises, which are managed at family level and very often share the company production and service sites with owners' living facilities.

Second, the regional figures shown in this work confirm the need of an integrated approach, where energy agencies work with regional and local institutions to promote and target the use of existing mechanism such as Ecobonus. As highlighted by Sanchez et al. (2020), in such a complex and multidimensional topic as energy poverty, governance should be a key element in promoting cooperation among different institutions. Additional resources can be provided by European structural funds, to be used both in private and public residential sectors, in particular in social housing. For example, several regional calls for tender have been published to finance energy renovation in social housing, and often these opportunities can also be associated with existing energy efficiency incentives such as Thermal Account.[16] Energy agencies could also contribute to the identification of consumers eligible for measures against energy poverty, for example, by looking at Energy Performance Certificates (EPCs) and to the associated integrated database at national level.[17] EPCs information could usefully complement the regional analysis developed here. Several studies use information from EPCs to investigate household vulnerability at municipal level: among others, Camboni et al. (2021) investigate energy poverty risk in Treviso, Fabbri and Gaspari (2021) use EPCs in mapping buildings that would imply

[15] Such a tool is perfectly in line with art.10 of Energy Performance of Building Directive (2018/844). More information can be found on the project website.

[16] More information on this incentive scheme for energy efficiency and renewable energy sources can be found in Ministerial Decree 16/02/2016.

[17] In Italy, an EPC integrated database exists and is managed by ENEA: it currently includes the EPCs from seven regions and two autonomous provinces.

risk of energy poverty in Bologna, Sanchez- Guevara et al. (2019) analyse summer energy poverty in London and Madrid and Yoon et al. (2019) study the water-energy nexus in low-income households in Barcelona. Although EPC certainly is a useful tool, it should be considered that referring to EPCs could provide partial information, since they are computed in simulated conditions and they do not refer to the effective energy use of a building. In general, the findings of different approaches in different countries confirm that low income and inefficient housing conditions interact to determine energy poverty: measurement and mapping of building conditions together with household in energy poverty would be very informative. This would also be of great importance to support the decision-making process in choosing the energy efficiency interventions to be adopted: despite the key role of insulation changing the overall building of thermal and energy performance, the replacement of windows, boiler and heating system is frequently preferred for they punctual nature, not requiring extensive and expensive works (Fabbri and Gaspari, 2021). Clearly, effective incentives may have a key boosting role in such a context.

Third, the analysis developed here is consistent with the need to deepen the knowledge on how existing energy policy measures could have differentiated impacts on income groups, in particular, in terms of who is paying their cost or who has better access to the financial incentives. If the distributive effects of energy policies are regressive, that is to say low-income households have a higher burden compared to richest ones, compensation should be envisaged or policy reforms should be implemented. Regressive effects of policy measures may worsen energy poverty incidence, as well as deteriorate indoor environmental conditions and, more in general, well-being of households (Berry 2019). This would be in deep contrast with the just transition principle, first used in the context of global employment movement (ETUC 2006) and then adopted in COP 21 and Paris Agreement (UNFCCC 2015). The principle is now one of the most prominent elements in the European Green Deal, to ensure that the transition towards a climate-neutral economy happens in a fair way, leaving no one behind (COM/2019/640 final). Campagnolo and De Cian (2022) examined the distributional implications of climate-induced changes to household energy expenditure in 2050, comparing the response of different Italian regions and income groups. They also calculated selected expenditure-based indicators of energy poverty in different scenarios. According to their results, a carbon tax would increase the regressivity of climate change impacts, inducing the poorest deciles to spend more on energy. Also in this study the regional dimension proves to be important: indeed, the overall impact on energy poverty is the result of the decrease in heating demand due to global warming, which would affect in a different way Southern and Northern Italian regions. To make the transition socially fair, climate impacts, adaptation and mitigation should all be considered when designing policy actions.

Fourth and last, the efforts to improve the access to Ecobonus incentive scheme by energy poor households could also include training, information, dissemination and awareness-raising activities. To date, little attention has been given to dissemination and public awareness of the energy poverty issue (Bartiaux et al. 2016), as well as the way the topic is dealt with by the media (Scarpellini et al. 2019).

5 Conclusions

The evolution of EU legislation clearly points out that energy poverty should be considered more than a simple component of poverty. For this reason, it is important to elaborate indicators assessing its evolution and policy measures aimed at contrasting it. This is even more true in the context of clean energy transition. The results of this study would contribute to existing literature with implications for policymakers, to better understand how adjusting energy efficiency measures to deal with energy poverty.

The maps suggest that there is room for manoeuvre in further modifying the possibility of tax credit transfer, introduced in 2016, in order to facilitate lower income households in accessing the Ecobonus incentive scheme. Indeed, the analysis shows that two years after the introduction of tax credit transfer, a lower access to Ecobonus is still observed in Southern Italy regions, where the incidence of energy poverty is higher. As suggested in EnR position paper, energy efficiency measures could represent a structural solution to energy poverty. The low access to the Ecobonus incentive scheme in Southern regions confirms the need to apply a distributive analysis on the policy measures adopted to achieve long-term objectives. Clearly, regional policy action, in particular, associated to a targeted use of European structural funds, could help in making energy efficiency existing measures more effective in tackling energy poverty. An integrated policy approach, as well as action at local level and information and training campaigns, could help in improving the access to Ecobonus incentive scheme for energy poor households. Further research should explore which compensation instruments could be adopted to reduce the distributive imbalances potentially associated to existing energy efficiency measures. This is a relevant issue in our country since several measures mentioned in the Italian NECP may have had adverse distributive effects in last years (OIPE, 2020). At EU level, the revenues from the EU Emissions Trading System (ETS) extension to buildings and transport will be used through the newly established Social Climate Fund to address possible negative distributional effects.

This case study, devoted to Ecobonus, suggests also some general policy considerations. First, the need of a multidisciplinary approach to the assessment of energy poverty and on related mitigation strategies. Behavioural issues could indeed play a role in the decision-making for the implementation of specific energy efficiency interventions. This is true, in particular, for split incentives between landlords and tenants and also for decision process for interventions in building blocks. Second, and connected to previous point, looking at the interactions of different policy instruments is very much needed: for example, the effectiveness of financial tools to support energy efficiency in energy poor household may be improved if they are combined with targeted consultancies or awareness raising campaigns. Third, the perspective in tackling energy poverty would need to be widened, by looking both at consolidated issues, such as the distributional consequences of long-term energy and environmental objectives, and at newer ones, such as energy poverty risk in family-owned micro-enterprises.

Finally, further research would need to address the implications of pandemic on the energy poverty phenomenon in developed countries but also in developing countries. Looking at the access to energy services on a wider scale, shows that a strong inequality still characterises living conditions at global level. According to the World Energy Outlook (2020), as a consequence of the pandemic, only in Africa 100 million people will lose access to electricity. This seems to suggest that in order to sustainable development become a reality there is still room for behavioural change and awareness in everyday life. Energy sufficiency would need to inspire our behaviour and become more and more our standard of living.

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Energy Poverty and Just Transformation in Greece

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1 Introduction

The European Union (EU) aims to become the world's first climate-neutral continent by 2050 (European Commission 2019). The EU climate and energy framework, shaped by the "EU green deal", the "Fit for 55 package" and the "Clean energy for all Europeans" initiatives, entails a 55% reduction of greenhouse gas (GHG) emissions compared to 1990 levels; a 32% share of renewable energy consumption and 32.5% energy savings compared to 2005 levels. Buildings, and consequently households, responsible for 40 and 36% of the total energy consumed and CO2 emissions produced in EU respectively, play a key role to achieve these goals (European Commission 2019). Energy poverty remains a major challenge to be further addressed in the EU. In the effort to tackle it, protect vulnerable consumers, and thus create a just energy transition to climate neutrality, policy efforts have increased, and energy poverty is a key topic in the "Clean energy for all Europeans" package (European Commission 2019). The reduction and mitigation of energy poverty has also been increasingly targeted in energy efficiency, decarbonisation and clean energy policies. Member States through the submission of their NECPs (National Energy and Climate Plans) indicate all the measures intended to alleviate energy poverty. In Greece, where energy poverty is a major social issue and the country scores some of the highest percentages in the EU, policy measures should be a strategic priority.

Despite the attention that the phenomenon of energy poverty has been getting the last years, and especially through the energy crisis of 2021–2022, there have

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been limited efforts to quantify the distributional and energy poverty implications of the transition to climate neutrality by 2050, especially for the most vulnerable households. Scientific literature is fragmented and focuses mostly on case studies. As a result, it lacks a comprehensive evaluation of distributional impacts across income deciles.

This is the first study where quantified results of the distributional impacts towards net zero energy transition in Greece are presented. In essence, we study, first, the most applicable and important policy targets with a specific focus on energy poverty and the just transition (i.e., Fit for 55 package for 2030 and Climate neutrality by 2050). Then, we simulate the distributional impacts by income decile. This simulation is performed and is fully integrated in the comprehensive, rigorous CGE modelling framework. Last, we also analyse the most relevant measures to tackle income inequality, energy poverty and create a just transition framework. These include, among others, the use of carbon revenues to reduce inequality.

This chapter is organised as follows: the strategic framework for energy poverty in Greece is described in Sect. 2, while Sect. 3 presents the indicators and methodologies used to measure energy poverty. Section 4, in turn, focuses on the poverty alleviation measures in Greece. Section 5 analyses the implications of the European Green Deal on energy poverty and equity in Greece, using a state-of-the-art macroeconomic model enhanced with a representation of income deciles. Last, Sect. 6 provides policy recommendations while it also describes planned future work, and concludes this chapter.

2 Strategic Framework for Energy Poverty in Greece

2.1 EU Policy Context

The European Commission has designed advanced and ambitious policies to tackle energy poverty, committing to protect vulnerable households. In the 2019 "Clean Energy for All Europeans" package, energy poverty was set as one of the key energy policy priorities. Although each Member State is allowed to establish its own criteria for measuring and assessing energy poverty (Faiella and Lavecchia 2021), the need to use a common definition across Europe is well-established, to further facilitate the monitoring and mitigation of the situation—and so is the need to set clear objectives for energy poverty reduction in the National Energy and Climate Plans (NECPs) of each Member State (European Commission 2019). In addition, provisions for dealing with energy poverty have been introduced in a series of European directives.

Indicatively, *Directive 2019/944/EU*[1] outlines the internal electricity market measures aiming at protecting vulnerable and energy-poor consumers in the context of the internal electricity market (social or energy policy measures to help pay

[1] *Directive (EU) 2019/944/EU of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU.*

electricity bills), launching investments to improve energy efficiency and/or protect consumers (including prohibition of disconnection of energy-poor consumers in critical periods), as well as providing measures other than public interventions in setting the prices for the supply of electricity. For the internal gas market, following up on *Directive 2009/73/EE*,[2] *Directive 2019/692/EE*[3] details provisions for protecting energy-vulnerable households and prohibiting their disconnection in critical periods. Targeting energy efficiency, *Directive 2018/2002/EC*[4] outlines measures aimed at tackling energy poverty and lowering the vulnerability of consumers; while *Directive 2018/844/EU*,[5] outlining the building energy performance framework and the long-term renovation strategy of the built environment, explicitly includes actions and measures to alleviate energy poverty among European households, according to criteria established by the Member States. Finally, *Regulation 2018/1999/EU*[6] (Governance of the Energy Union and Climate Action) requires that consolidated NECPs of EU Member States include estimates of the number of energy-poor households, set a national target to mitigate energy poverty, and provide progress reports including the number of energy-poor households and the policy measures in place to address the issue.

It is, therefore, evident that energy poverty is high on the European Commission's agenda, especially amidst an energy crisis that is partly driven by Covid-19 recovery efforts as well as the skyrocketing gas and electricity prices caused by changing demand–supply dynamics and by Russia's invasion of Ukraine in 2022. The EU policy response included the REPowerEU strategy and national measures to reduce reliance on imported gas from Russia and protect vulnerable households from the rising energy prices. It also advocated for the adoption of behavioural changes that can boost energy efficiency. In particular, the proposed measures in the REPowerEU Plan include increasing the energy savings target (from 9 to 13% reduction in final energy consumption compared to the Reference 2020 Scenario), the diversification of the energy supply mix alongside the groundwork for a new "joint purchasing mechanism" for gas imports, accelerated roll-out of renewable energy to replace fossil fuels (upgrading the 2030 target from 40 to 45%), and reduction of fossil-fuel use in all sectors. To support the implementation of the REPowerEU Plan, additional

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[2] *Directive 2009/73/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC.*

[3] *Directive (EU) 2019/692 of the European Parliament and of the Council of 17 April 2019 amending Directive 2009/73/EC concerning common rules for the internal market in natural gas.*

[4] *Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency.*

[5] *Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.*

[6] *Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council.*

smart investments are deemed necessary across all sectors and levels (national, cross-border and EU). In essence, REPowerEU means that Member States strengthen any national efforts and proactive measures they had kicked off in as early as September 2021 to mitigate the impacts of the looming energy crisis (Sgaravatti et al. 2021).

2.2 National Policy Context

The Greek energy policy framework comprises laws and regulations that are largely harmonised with most of the relevant EC directives and policy measures aiming at protecting vulnerable consumers and especially low-income households. However, much like delays in harmonising national and European energy efficiency legislation in Greece (Nikas et al. 2019), important EU directives (D2019/944/EU[1], D2018/2002/EU[4]) have not yet been fully adopted in the national policy framework.

Nevertheless, significant progress has been made in defining the categories of vulnerable consumers (financially vulnerable, dependent on continuous and uninterrupted energy supply, elderly, people with health problems and residents of disadvantaged areas), whereas several policy measures have been enforced to protect vulnerable consumers, including:

- the provision of reduced invoices, or a discount on each supplier's published invoices,
- the installation of prepaid meters,
- the provision of more favourable terms for paying the electricity and gas bills,
- the adoption of alternative ways of accessing service and bill payment services,
- the subsidisation of the electricity and fuel (oil, gas, biomass) consumption, and
- the prohibition of disconnection of such consumers during critical periods.

In addition, criteria, and procedures for the inclusion of consumers in the above measures as well as obligations of energy providers/suppliers are defined. However, since an official definition for energy poverty at national level has not yet been established (Arsenopoulos et al. 2020) and, considering the lack of a common definition across the EU, identifying the energy-poor population in the country can be challenging.

In 2021, the Greek parliament approved the National Energy Poverty Alleviation Plan (NEPAP 2021), according to the NECP (2019) provision. The plan constitutes the Greek national strategy against energy poverty for 2021–2030 and aims to outline a comprehensive understanding of the situation by mapping and analysing the characteristics of the affected households, focused on those with the highest vulnerability. The NEPAP also proposes effective planning and implementation of the necessary policy measures to achieve the quantitative goals set within the framework of the Greek NECP for a reduction by at least 50% of its relevant energy poverty indicators by 2025, and by 75% by 2030, compared to 2016 (baseline year). Specifically, the Action Plan has been based on the identification of households affected by energy poverty using specific quantitative criteria; the development of a specialised process for recording, monitoring and evaluating the course of alleviating the phenomenon until 2030; the formulation of a well-defined set of policy measures to tackle energy poverty; the development of a mechanism for monitoring and evaluating the effects of each policy measure, to assess their effectiveness or need for adjustments; and the exploration of specific schemes to address energy poverty in vulnerable households either through existing policy measures or through new ones.

3 Measuring the Problem

3.1 The Diversity of Indicators to Identify and Measure Energy Poverty

There are three prevailing measurement methods to identify energy poverty, including (i) expenditure-based indicators that estimate the magnitude of energy poverty on a household by considering the household's energy costs and income and comparing them to a selected threshold; (ii) consensual-based indicators, based on which inhabitants assess their household's living conditions, regarding thermal comfort and other conditions (humidity, insulation, etc.), and their ability to afford expenditures required to secure healthy living conditions; and (iii) direct measurement, which sets a standard for an offered energy service (heating/cooling) and assesses energy poverty against this standard (Siksnelyte-Butkiene et al. 2021). However, Thomson and Snell (2016) suggest another measurement method to identify energy-poor households at local level, using welfare benefits, area-based approaches, demographic criteria or a mix thereof.

The first method used to measure energy poverty was the ten-percent rule proposed by Boardman in 1991. The ten-percent rule identifies as energy poor those households that spend on energy expenses more than 10% of their net income. The rule has been contested about its success to identify the phenomenon when other factors (e.g., energy efficiency, social factors, etc.) are considered. Other indices proposed to face the inadequacies of this rule include the Low Income-High Cost (Hills 2012) and the Minimum Income Standard indicator (Moore 2012). However, these are based on inflexible thresholds that are mostly theoretical, disregard actual energy costs and the equivalised ratio between income and energy-related expenditures or the difficulties in accounting different energy services (Tirado Herrero 2017).

Another approach on measuring energy poverty is that of Equivalisation of Modelled Energy Costs, proposed by Antepara et al. (2020) to face the problem of unreliable energy consumption data or behavioural practices due to socio-economic factors that may modify domestic energy use patterns. This methodology models energy bills on building energy conditions and consumption patterns and relates them to socio-demographic weighted (equivalised) variables.

To integrate more aspects, several multidimensional energy poverty indices have been established in the literature (e.g., Nussbaumer et al. 2012; Bersisa 2019; Ntaintasis et al. 2019; Crentsil et al. 2019). One of the first attempts to introduce composite indicators was that from Healy and Clinch (2002), who used 6 subjective indicators. Recently, Delugas and Brau (2018) identified energy poverty as a factor of wellbeing, Gouveia et al. (2019) combined energy performance with social and economic indicators, while Sokolowski et al. (2020) combined five quantitative (monetary) and qualitative (non-monetary) indicators, aiming to address limitations of previous single- or multi-dimensional indices.

To measure energy poverty at the European level, the EU *Energy Poverty Advisory Hub* (EPAH) has proposed several different indicators, four primary and nineteen secondary.[7] The primary indicators comprise the shares of the (sub-) population that delay paying utility bills and that cannot keep their home sufficiently warm, calculated on the basis of answers to closed-ended questions (EUSilc); as well as household income and energy expenditure (with data from Household Budget Surveys—HBS)—e.g., energy expenses being more than twice the national average household income. However, caution is advised regarding structural differences in energy expenditure among households, situations where energy is often—albeit not exclusively—included in rent, and high energy efficiency standards or considerable underconsumption of energy. The secondary indicators include average prices paid by a household per kWh from district heating or generated from specific components such as fuel oil, biomass, and coal; electricity and gas prices for different types of consumers; energy consumption expenditure on electricity, gas, and other fuels as a share of income for 5 income quintiles; accommodation-related indicators such as average number of rooms per person in owned, rented, and all dwellings; location (densely populated or intermediate residential area); dwelling condition (leakage, dampness, or rot); and people at risk of poverty or social exclusion or death in winter.

The 2030 framework of the *Covenant of Mayors* also commits to contributing to energy poverty alleviation,[8] based on six classes of indicators: climate, facilities/housing, mobility, socio-economic aspects, policy and regulatory framework and participation/awareness-raising. The climate category includes the energy consumption for space heating and cooling a building and the frequency of hot and cold waves per month each year. Facilities or housing indicators leverage various data that may be available at the municipal level—e.g., on buildings, households, etc. This data may include energy consumption such as the percentage of municipal energy consumption per capita over national energy consumption per capita, or information on the living conditions such as the percentage of population/households with leakage, dampness, or rot in their dwelling, the percentages of households/individuals experiencing discomfort in heating or cooling and those connected to the electricity or gas

[7] *Energy Poverty Advisory Hub* https://energy-poverty.ec.europa.eu/energy-poverty-observatory/indicators_en.

[8] *Covenant of Mayors for Climate & Energy EUROPE* https://www.eumayors.eu/support/energy-poverty.html.

grid. Indicators also report systems for heating and cooling, e.g., central heating, oil boilers, wood boilers, conventional gas boilers and central cooling systems. There also exist indicators relating to the energy efficiency of buildings, specifically for categories F, G, H, the percentages of buildings refurbished each year that have an Energy Performance Certificate (EPC) higher than B. In addition, there are assessments on occupants, social housing flats to total flats, and social housing energy demand of the national median demand. Finally, this category is completed by indicators relating to the share of households with absolute energy expenditure above a defined share of the national average, considering the average age of buildings by period of construction, and the ratio of households/individuals relying primarily on clean fuels and related technology. The mobility category includes indicators focusing on public transport (distance to nearest station, frequency of transit to serve the public, household access to essential services by foot, bicycle, or public transport, share of social housing households without easy access to public transport and of households receiving support to pay for public transport services). Socioeconomic indicators include unemployment, inability to keep the house sufficiently warm or cool, money spent on electricity or gas consumption, citizens' spending on energy services compared to their income and national average, arrears on utility bills, age, education level, household situation (vulnerability, poverty and at-risk-of-poverty, state aid, and GDP- or income-based indicators). Policy and regulatory indicators report on the status of energy poverty strategy, incentives for owner schemes, rent regulation and specific energy-poverty policy measures. Finally, participation/awareness-raising refers to the existence of a deterrent to rent increases due to energy retrofits, and engagement and cooperation with local actors on energy poverty.

3.2 Measuring Energy Poverty in Greece

Among the several methodological approaches for identifying energy-poor households, the Hellenic Ministry of Environment and Energy has selected the 4 EPAH indicators to make an initial assessment of the situation in the country (NEPAP 2021). The Centre of Renewable Energy Sources and Saving (CRES), in charge of the National Observatory of Energy Poverty, has proposed an additional indicator, namely the coverage of basic energy needs per household, calculated as the ratio of actual recorded energy consumption to theoretically required energy consumption for specific uses; particular attention is paid at how required household energy uses are determined.

In the context of the NEPAP (2021), it is desirable to identify energy-poor households through a combined multi-dimensional index, which considers as many factors as possible, as proposed by Directive 2019/944/EU[1] (and related to income, purchasing costs of energy products, and energy efficiency of residential buildings).

Finally, an additional indicator, $I\&II_{eq,}$ is also included to target the households that simultaneously meet both of the following requirements:

- the annual cost of the total household's energy is lower than 80% of the annual cost to cover the minimum required energy consumption (Condition I), and
- the equivalised net income of each household (based on the equivalent number of household's members according to the OECD scale) on an annual basis is lower than the 60% of the median of the corresponding income for all households according to the definition of relative poverty (Condition II_{eq}).

According to the $I\&II_{eq}$ indicator's initial calculation, the percentage of affected households in 2016 amounted to 14% of all households (approximately 573,000 households). The latest progress report,[9] issued in 2021, calculates the $I\&II_{eq}$ at about 12% (approximately 497 thousand households). Continuous evaluation of this indicator to measure energy poverty is a priority, in order to make adjustments to policy measures and regulations as needed according to new scientific evidence on the factors that impact energy poverty.

4 Energy Poverty Alleviation Measures in Greece

National efforts to deal with the situation in Greece follow the NECP (2019) and NEPAP (2021) provisions. Actions are promoted towards three axes: consumer protection (financial support to households affected by extreme conditions of energy poverty, and protection through regulatory measures), energy efficiency and RES diffusion (financing measures with long-term impact, such as improvement of deep building renovations, energy efficiency improvements and increased use of Renewable Energy Sources), and informative and training actions for affected consumers and professionals of energy saving actions. All actions that have been implemented or are currently in place today are listed in Table 1.

5 Implications of the European Green Deal on Energy Poverty and Equity

This section aims to analyse the accruing impacts if the EU implements the Fit-for-55 target of reducing its greenhouse gas (GHG) emissions by at least 55% in 2030, compared to 1990 levels, and then achieves the goal of climate neutrality by 2050. This requires the adoption of strong climate policies (e.g., high carbon pricing) to drive a complete restructuring of the EU and Greek energy system towards renewable

[9] Annual Progress Report of the National Energy Poverty Alleviation Plan, year 2021, December 2021, Version 4 (https://ypen.gov.gr/wp-content/uploads/2022/04/SDEE-Annual-report-2021-v4-14032022-clean.pdf).

Table 1 Energy poverty alleviation measures in Greece

Name	Description	Beneficiaries	Put in force	In place as of fall 2022
Social Household Tariff	Special tariff to reduce electricity prices for vulnerable households, provided by all electricity providers, since 2011. The subsidy is provided for a certain amount of energy (kWh) per month and is higher for energy-poor households	Vulnerable & energy-poor households	2011	Yes
Solidarity Services Tariff	Tariff of reduced cost, applicable to public legal entities and NGOs, who provide social care services, provided by all electricity suppliers	Legal entities and NGOs on social care sector	2013	Yes
Heating allowance	A heating allowance to households for consumption of subsidised types of heating fuels or thermal energy, due to increases in the final price of specific energy products; in 2021, biomass (firewood, pellets) was added to fossil fuels. The allowance is given according to defined criteria (income, place of residence, etc.)	Vulnerable & energy-poor households	2012	Yes
Electricity allowance—PowerPass	Subsidy of electricity bills to consumers with variable tariffs, starting in 2022 amidst the energy price spikes following gas supply cut-offs associated with (policy responses to) Russia's invasion in Ukraine. Its amount and beneficiaries are determined by the government based on social and economic criteria	All energy consumers	2022	Yes
Replacement of old, energy-consuming electrical appliances (Recycle-Replace appliance)	A 2022 subsidy for replacing old, high-consuming electrical appliances (air conditioners, refrigerators, and freezers) with new, more efficient ones. The subsidy is higher for low-income households	All households	2022	Yes

(continued)

Table 1 (continued)

Name	Description	Beneficiaries	Put in force	In place as of fall 2022
Horizontal electricity subsidy	A subsidy provided by the "Energy Transition Fund" to support electricity end-users. It is applied to all consumers without exception, regardless of income or other property criteria (households, businesses, etc.). The amount of the subsidy per MWh varies by type of consumer's tariff and consumption and is increased for energy-poor households	All energy consumers	2022	Yes
Horizontal gas subsidy	A subsidy provided to all gas consumers (households and businesses) to support them against the increased gas prices. The subsidy is applied to all consumers without exception, regardless of income or other property criteria, and it is foreseen to cover 50% of the last year increases. The subsidy size per MWh varies according to the consumer's tariff	All gas consumers	2022	Yes
Biomass grant	A grant dedicated to the supply of firewood to citizens residing in mountainous areas, supporting them to cover part of their winter needs for biomass. The implementation of the action is promoted collectively or individually and is supervised by the relevant forestry authority per geographical area	Citizens of mountainous municipalities	2022	Yes

(continued)

Table 1 (continued)

Name	Description	Beneficiaries	Put in force	In place as of fall 2022
Fast-track reconnections	One-off special aid (only for 2021) to support low-income consumers, who have been disconnected from the electricity supply network due to arrears. The purpose of the allowance is to enable them to submit a reconnection request and grant them a fast-track reconnection even if the arrears remain	Extreme energy-poor households	2021	No
Regulatory package	Measures for the protection of vulnerable electricity/gas consumers that bind all energy providers through the Supply Code Amendment. The measures include an extension of the deadline (to at least forty days) for paying the bill and flexible facilitation in the payment methods, suspension of supply cuts due to arrears during the winter and summer periods, strict conditions for contract termination, etc	Vulnerable & energy-poor households	2016	Yes
Households Energy retrofits subsidies	Increased funding from financing tools for retrofitting interventions aimed at houses of low energy efficiency, belonging to low-income citizens that are unable to afford all residence upgrade expenses. The interventions concern deep renovations of the buildings, installation of efficient, low-carbon heating and cooling systems (e.g., heat pumps), and installation of RES technologies with storage	All households	2011	Yes
Tax deduction for renovation costs	Taxpayers implementing building renovations that include energy efficiency interventions can use this incentive to reduce their final tax. 40% of the cost of the works is deducted from the annual taxable income (spread to a period of 4 years)	Citizens	2021	Yes

(continued)

Table 1 (continued)

Name	Description	Beneficiaries	Put in force	In place as of fall 2022
"Save-Renovate for Young People"	A subsidy to homeowners (aged 18 to 39) of up to 90% for energy efficiency interventions and 30% for renovation works to their residence	All citizens aged 18 to 39	2022	No
Support of Just Transition Plan to Coal regions	Interventions foreseen for 10,000 vulnerable households, especially in the areas covered by the Just Transition Plan. Financial support is provided for the radical renovation of homes, with a subsidy of up to 90%, in combination with the installation of RES systems. The establishment of energy communities to address energy poverty is also foreseen	All households within the Coal Regions	2021	Yes
Energy communities	Actions to support vulnerable consumers and address citizens' energy poverty through the scheme of energy communities (Energy Communities 2018). Indicative measures include renewable energy supply or use of virtual net metering, communication activities, home energy retrofits, or other relevant actions that reduce energy consumption for vulnerable homes	All households and energy consumers	2018	Yes
Implementation of technical and/or behavioural measures (Energy efficiency obligation schemes)	Energy businesses (fuel and energy service providers, electricity suppliers etc.) are obliged to contribute to national energy saving and efficiency targets by using their own capital to promote technical and/or behavioural support to (vulnerable) households Measures taken to support energy-poor households provide them with a premium coefficient on calculating achieved energy savings Modifications are expected to cover large-scale interventions	All households	2017	Yes

(continued)

Table 1 (continued)

Name	Description	Beneficiaries	Put in force	In place as of fall 2022
Net-metering subsidy	A subsidy provided to at least 250,000 roofs PV units for net-metering expansion. Beneficiaries include households and small businesses in urban and rural areas, covering (part of) their electricity needs through solar energy. The subsidy is intended to cover 40–60% of the investment	Households and small businesses in rural and urban areas	Expected in 2022	No
Energy poverty alleviation subsidy for municipal actions through energy communities	Subsidies to municipal and regional authorities to establish energy communities and install RES units to support vulnerable consumers and mitigate energy poverty in their citizens. The subsidy is intended to cover up to 100% of the costs of setting up the Energy Communities and implementing the relevant investments	Vulnerable and energy-poor households	Expected in 2022	No
Communication and education	Provision of targeted communication and training actions for affected households, and of professionals involved in supporting these households (facilitation practices for covering energy costs, awareness on existing protection measures, availability of financing to improve energy efficiency, etc.)	Energy poor and vulnerable households, Professionals	Expected in 2022	No
Price Comparison Tool of energy products	A platform for comparing prices and terms of tariffs offered by electricity and natural gas providers. Complaints and requests to network operators and electricity/gas service providers can be accepted, with monitoring of the progress of said request	All energy consumers	2020	Yes

Source Authors’

energy technologies, clean fuels and energy efficiency improvements. However, high carbon pricing would entail large-scale economic restructuring directly impacting the production, demand and competitiveness of different sectors. The decarbonisation of the energy system is not expected to impact uniformly all sectors of the economy, with large reductions expected in carbon-intensive activities, such as mining/extraction, refineries and fossil-based power generation. These changes in the structure of energy-economic systems will be accompanied by changes in fuel and electricity prices as well as changes in financing requirements: the purchase and operation of energy and electrical equipment/appliances will change with increasing capital expenditures (CAPEX) and lower operating and fuel purchase expenditures (OPEX).

The implications of decarbonisation on economic systems are manifested via large changes in capital and labour markets, which in turn impact the activities of all economic agents. Strong carbon pricing may also cause regressive distributional impacts, disproportionately affecting disadvantaged population groups that face high energy expenditures as a share of their income combined with difficulties in accessing low-cost funding. The imposition of additional taxes on energy products would increase the risk of energy poverty along with other challenges that low-income households in Greece and the EU face.

The analysis in this section is based on the state-of-the-art GEM-E3-FIT model, a computable general equilibrium (CGE) model for assessing the implications of energy and climate policies. Typically, general equilibrium models feature a single representative household in each national economy that averages incomes and consumption patterns. However useful when large-scale modelling is required, this aggregation may mask critical insights regarding social and distributional implications of climate policies among diverse households; distributional impacts refer to how costs and benefits of a policy or sets of policies are distributed among different regions, sectors, and households. Ignoring such distributional effects in climate policymaking may result in regressive distributional impacts and increased societal inequalities due to the lack of measures to mitigate negative impacts on vulnerable population groups. For this reason, GEM-E3-FIT is further expanded to represent ten household income classes in EU Member States, to consistently capture the potential distributional impacts of ambitious energy and climate policies for Greece until 2050 (a detailed description of the model expansion can be found in Fragkos et al. 2021).

5.1 Inequality and Energy Poverty Indicators

Rising income inequality is a global concern, implying that economic growth is not inclusive and its benefits are not equally distributed to all households (EC 2017). Income inequality can reduce economic growth, while raising concerns about sustainable growth, as the gap between rich and poor widens (EC 2018b). Income inequality is defined as inequality in earnings received from employment, private income from investments and property, transfers between households, state benefits, pensions and rent (UN 2015).

There has been considerable debate on the drivers of income inequality (IMF 2015), which typically include:

- changes in labour market, which directly impact unemployment and the distribution of wages—e.g., part-time and temporary employment, gender gap, workers with low labour skills who are commonly the first to be substituted (OECD 2011)
- labour institutions, which may lead to reduced wage dispersion (IMF 2015)
- technological change, which increases productivity and well-being but requires higher skilled labour contributing to increased inequality—e.g., digitisation and automation changing occupational structures with replacement of routine-based jobs (OECD 2011)
- trade globalisation, which tends to widen the income gap, negatively influencing the wages of unskilled labour despite trade increasing competitiveness and efficiency, thereby boosting economic growth (IMF 2015)
- financial globalisation, which facilitates efficient international allocation of capital but can also aggravate income inequality, since foreign direct investments are mostly directed to technology development, increasing demand for high-skilled workers (Furceri and Loungani 2013)
- education, which determines occupational choice, access to jobs, and the level of wages (Stiglitz and Greenwald 2014);
- redistributive policies, with tax and transfer systems playing a major role in income equality, with types of taxes and socially security contribution having different impacts on inequality (OECD 2012)
- household composition and ageing population (Bubbico and Freytag 2018),
- distribution of wealth, as return on capital is a large source of households' income (Piketty 2014; Cagetti and De Nardi 2008).

Most of these drivers are featured in GEM-E3-FIT modelling framework, including:

- a detailed representation of the labour market with endogenous involuntary unemployment for five different occupation and skill types
- endogenous technological change through learning by doing and learning by R&D, particularly for low-carbon technologies
- a detailed representation of ten income classes through multiple households
- endogenous bilateral trade of goods and services
- an endogenous representation of human capital development and the decision of households for education enabling an upgrade of skills
- a detailed representation of direct and indirect taxes, subsidies and other benefits

Table 2 includes the most common indicators to measure income inequality. The Gini coefficient is the most established and popular indicator, while the decile dispersion ratio presents the ratio of the average income of two deciles. However, this indicator does not use information about the distribution of income within deciles and does not provide information about incomes in the middle of the distribution. Other indicators

Table 2 Indicators to measure income inequality

Indicator	Description/relevance for inequality
Mean and median income by household	The mean income is the amount obtained by dividing the total aggregate income of a group by the number of units. The median is the income level that divides the population into two groups of equal size. The use of the median corrects potential distortion that may be caused by the existence of extreme values
Decile dispersion ratio	This measure presents the ratio of the average income of e.g., the richest 10% of the population divided by the average income of the poorest 10% (Haughton and Khandker 2009). The indicator is vulnerable to extreme values and outliers
S80/S20 income quintile share ratio or 20:20 ratio	Comparing the income received by the top 20% of the population with the bottom 20% of the population
Gini coefficient	The Gini coefficient is based on the Lorenz curve, a cumulative frequency curve that compares the distribution of income with the uniform distribution that represents equality. It represents the extent to which the distribution of income differs between an equal distribution (Gini coefficient of 0) and perfect inequality (Gini coefficient of 1)
Atkinson index	This index is based on the Gini index and includes a sensitivity parameter, which can range from 0 (meaning indifference about the nature of the income distribution), to infinity (where the focus is on the lowest income group) (De Maio 2007)
At-risk poverty rate	The share of people with an equivalised disposable income below the at-risk-of-poverty threshold, which is set at 60% of the national median equivalised disposable income (Eurostat 2019)
Severely and materially deprived	It reflects the inability of a household to afford some goods and services considered to be necessary for an adequate life (Eurostat 2019). The indicator measures the share of population that cannot afford three (material deprivation) or four (severe material deprivation) of the nine items listed in a reference year

Source Authors'

have been developed to improve understanding about income distribution, e.g., the Generalised Entropy family (e.g., the Theil index) and the Atkinson index.

The analysis of distributional impacts focuses on the income changes between deciles. The indicators of income inequality can be estimated using a combination of modelling results, and additional income data. This chapter focuses on the Gini coefficient and the Decile Dispersion ratio (S80/S20), as these indicators complement each other.[10]

Extreme poverty and income inequality have decreased globally after 2000, largely owing to the decrease in inequality between countries (Revenga and Dooley

[10] For example, the Gini coefficient is particularly sensitive to income differences around the centre of the distribution and thus it should be used in combination with the S80/S20 ratio that gives information about the distribution between lower and upper deciles. It should be noted that changes in within-group inequality are not measured in GEM-E3-FIT, thus losing information on inter-group income disparities.

2019). In 2020, the Gini coefficient for the EU was 30.0, compared to 30.2 in 2010, showcasing stability in income inequality. Bulgaria has the highest Gini coefficient, while the lowest inequality in the EU is observed in Belgium, Finland, Czech Republic, Slovenia and Slovakia (Eurostat 2019). Greece registers a value close to the European average, with signs of inequality reduction in the last decade (the Gini coefficient declined from 32.9 in 2010 to 31.4 in 2020). In 2020, the EU-28 S80/S20 ratio was 4.9, implying that the richest 20% of the population receives about five times higher income relative to the poorest 20%. This share has been stable in the 2010s. Greece ranks slightly higher than the EU average, but with clear signs of reducing inequalities, with the S80/S20 indicator declining from 5.61 in 2010 to 5.23 in 2020.

A combination of energy-inefficient housing and appliances, high energy prices and low-income levels typically determine if a household is at risk of energy poverty (Pye et al. 2015; Gouveia et al. 2019). Our study focuses on expenditure-based indicators to assess energy poverty dynamics that can be quantified using GEM-E3-FIT model outcomes on energy expenditure and income per decile, in particular the share of energy expenditure in income (2 M). This indicator measures the share of households, whose share of energy expenditure relative to their disposable income is more than twice the national median share. The highest income group has a very low share of households in energy poverty (Bouzarovski et al. 2020, as the richer a household is, the lower the share of income is dedicated to energy expenditure. The proportion of households whose share of energy expenditure in income is more than twice the national median share is estimated at 16.2% in 2015 in the EU, with Greece being very close to the EU average (Fig. 1). However, this hides remarkable differences across income deciles in Greece, with more than half of those in the first decile facing substantial energy poverty risks.[11]

5.2 *Modelling Income Inequality and Energy Poverty with GEM-E3-FIT*

Macroeconomic models enhanced with a representation of different socio-economic groups (e.g., income classes) can be used to evaluate the distributional implications of climate policies. Despite the challenges in terms of data integration and computational modelling issues, the introduction of multiple households enhances the capability of conventional macroeconomic models to assess income distribution effects (Zhang 2019). The representation of multiple households in CGE modelling has been long established (Cockburn 2001; Rutherford et al. 2005; Balasko and Tourinho 2014) but is usually constrained by limited data availability. There are ways to differentiate households, but income class is the most relevant for distributional analysis. The main caveat of this approach is that it does not capture inequality

[11] https://energy-poverty.ec.europa.eu/energy-poverty-observatory/indicators_en.

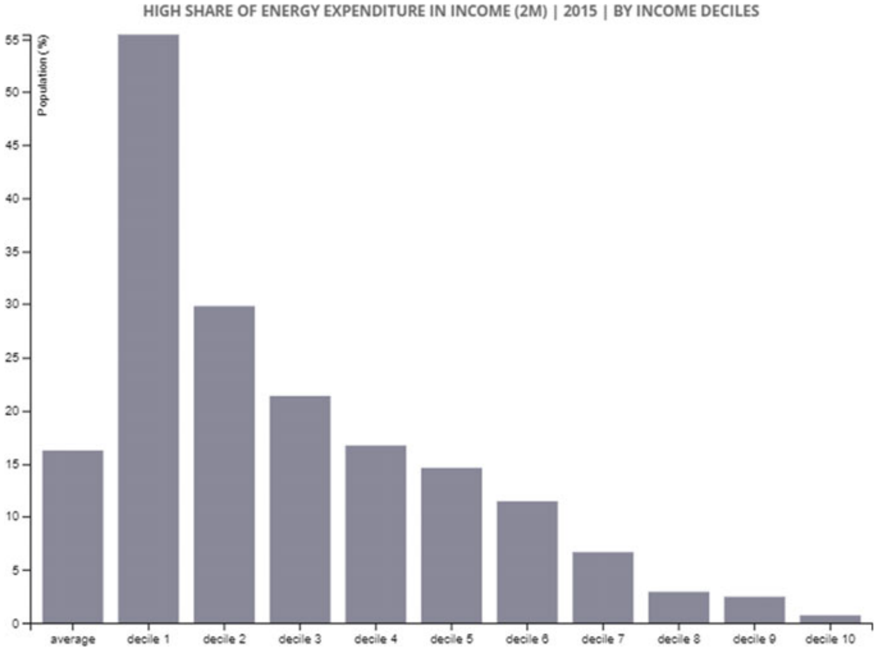

Fig. 1 Share of energy expenditure in income by income decile in Greece *Source* Authors'

within the income deciles and the fact that households can switch deciles and change compositions (CPB 2011).

GEM-E3-FIT is multiregional, multi-sectoral, recursive-dynamic, providing details on the macroeconomy and its complex interactions with the environment and the energy system. The model has been recently enhanced with a representation of ten income classes aiming to assess the distributional implications of climate policies. It simultaneously represents 46 regions (including the EU countries individually) and 53 activities linked through bilateral trade flows and runs until 2050 (E3Modelling 2017). It covers the interlinkages between productive sectors, consumption, labour and capital, bilateral trade, investment dynamics and price formation of commodities. GEM-E3-FIT formulates the supply and demand behaviour of economic agents that are assumed to exhibit optimising behaviour while market-derived prices are adjusted to clear markets. It allows for a consistent comparative analysis of policy scenarios as it ensures that the economic system remains in general equilibrium.

Industries operate within a perfect competition market regime and maximise profits, considering the possibilities of input substitutions between capital, labour, energy and materials. Household demand, savings and labour supply are derived from utility maximisation using a linear expenditure system (LES) formulation. Households receive income from labour supply and from holding shares in companies. Investment by sector is dynamic, depending on adaptive anticipation of capital return and activity growth by sector. A distinctive feature of GEM-E3-FIT (Fig. 2) is

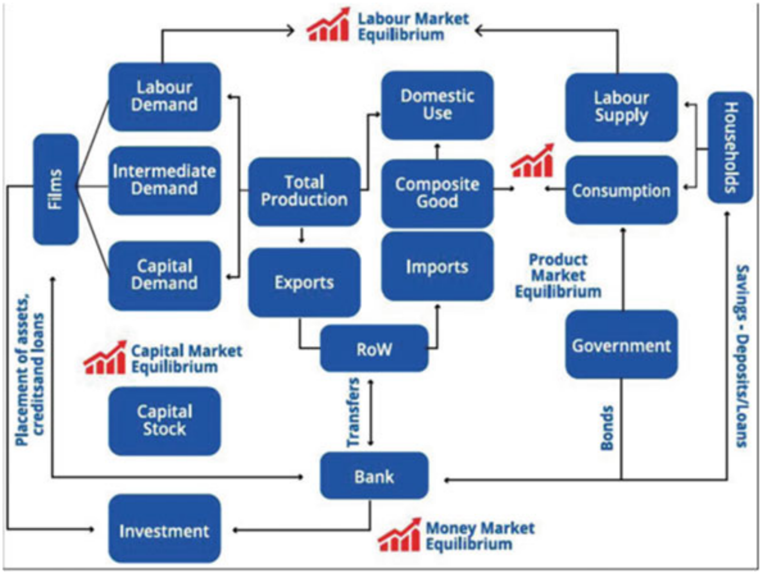

Fig. 2 GEM-E3-FIT model structure

the representation of imperfect labour markets through involuntary unemployment, simulated by an empirical labour supply equation that links wages and unemployment levels for five labour skills.

Various policy instruments can be represented in GEM-E3-FIT, including energy and climate measures, and their interactions with policies related to labour market, economy, trade and innovation. Policies are evaluated based on their impact on sectoral growth, income distribution, employment, economic competitiveness and GDP. GEM-E3-FIT can assess the impacts of market-oriented policy instruments, such as carbon taxes and pollution permits, and investigate market-driven structural changes. It can analyse policy impacts in the allocation of capital, income, trade and labour, and provide insights on compensating measures aiming at alleviating adverse distributional effects among and within countries.

The representation of multiple households in CGE models is a challenging task both from a computational and data point of view (Zhang 2019). In the current study, this is implemented with a linkage of the CGE GEM-E3-FIT model with a satellite module with multiple households, through a sequential exchange of prices, incomes and demands until an equilibrium point is established (Rutherford and Tarr 2004; Rausch et al. 2011). This approach is easier to implement in large-scale CGE models with manageable computational complexity (compared to the hard-link approach) and it is thus adopted in GEM-E3-FIT. This was driven by the empirical findings of Rutherford and Tarr (2004), who showed very limited benefits from using the hard-link representation compared to the sequential approach. Considering the large geographic and sectoral granularity of the model and the need for short running time, we adopted the soft-link approach in the current study. The methodology is described in detail by Fragkos et al. (2021).

The equivalised disposable income by decile is used to calculate inequality indicators, but GEM-E3-FIT produces total disposable income by decile. The estimation of equivalised disposable income can be implemented by assuming that the equivalised household size by decile remains constant over 2015–2050 combined with a simplified assumption about the number of households by decile. GEM-E3-FIT results on income by decile can be used to quantify the Gini coefficient, by estimating 10 points of the Lorenz curve, each one representing an income decile group. The area under the Lorenz curve can be calculated by summing the areas of the 10 trapeziums, allowing to estimate the Gini coefficient as equal to the area below the line of perfect equality minus the area calculated below the Lorenz curve divided by the area below the line of perfect equality (0.5). The decile dispersion indicators (S80/S20 ratio) can be directly estimated via the income by decile quantified by GEM-E3-FIT. The disposable income of the last two and first two decile groups is utilised to calculate the S80/S20 indicator using GEM-E3-FIT results.

The "share of energy expenditure in income" indicator is used to identify energy poverty and can be estimated using the decile's total energy expenditure and total disposable income. However, this indicator requires information on the distribution of absolute energy expenditures and incomes on household level to derive changing median values. GEM-E3-FIT cannot provide the median of these indicators; thus, we estimate only an adjusted 2 M indicator using the model output (i.e., the average share of energy expenditure in income by decile). While this approach does not reflect the unequal distributions within a decile, it provides insights regarding the economic burden of energy-related expenses on household budgets. In the analysis below, two indicators are used to measure the impacts of decarbonisation by decile group, namely "the share of energy expenditure for fuels and electricity in household income" (Indicator 1) and "the share of energy expenditure for fuels/electricity and energy equipment in household income (Indicator 2)".

The integration of multiple households in GEM-E3-FIT requires data for disaggregating household expenditure by product category and income class, household earnings by branch and income class and data for calculating energy poverty indicators. Two key data sources are used: the EU Survey on Income and Living Conditions (SILC) and the Household Budget Survey (HBS).[12] We use SILC data for disaggregating income sources and HBS data for detailing household consumption and calculating expenditure-based energy poverty indicators. Income and expenditure disaggregation are based on the micro data on an average per-household level and per-income decile. Data for each country and for each income decile is extracted

[12] Both datasets provide relevant information to characterise the different households but have methodological differences; EU-SILC largely focuses of income data at EU level, while the HBS comprises data on household consumption expenditures. HBS and SILC data are based on different samples and cannot easily be matched, as income data vary considerably. SILC data is harmonised across EU countries by Eurostat, while the HBS data are gathered by national statistical offices in a partially harmonised manner (harmonised multi-regional HBS data are published for selected years), not ensuring comparability between countries.

from the SILC and HBS microdata for the latest available year, including data for the structure of population (e.g., number and size of households, occupation), income (income sources per occupation, benefits, transfers, allowances, dividends and property income and saving rates), expenditures (taxes, transfers and consumption per purpose) and indicators on energy poverty and income inequality. It should be noted that the model-based development and data analysis is conducted at muti-regional pan-European level (with a focus on Greece) as other European countries influence the national Greek economy through various modelling channels, including international trade, technology innovation capital and labour transfers.

Income deciles are constructed using national household sample weights included in the HBS dataset and each household in the dataset is assigned to a decile. Subsequently, average expenditures of households within each decile by Classification of Individual Consumption by Purpose (COICOP) category are calculated, using sample weights to obtain the actual distribution in the population. For energy expenditure and net income, standard deviations and skewness by income decile are calculated in the same way. To calculate the average share of energy expenditure in household income by decile, household energy expenditures are divided by incomes. Then, weighted averages, standard deviations and skewness by country and income decile were calculated, using household sample weights. Data for other variables are extracted from the SILC database: total gross and disposable incomes, decile-specific top cut-off points, standard deviations, skewness, income per occupation (ISCO-88), tax payments, income from other sources: various household and personal-level benefits and transfers, interests, properties and pensions.

Two key data-related challenges have emerged: the first relates to data structure that represents how individuals are nested in households, and the second to GEM-E3-FIT representing only household income. As household-level information is key to macroeconomic modelling, we assigned household-level income deciles to individuals for calculating resulting per-capita averages and per-decile totals. For most variables, macro-level data published by Eurostat cannot be replicated and thus Eurostat data is used for calculating the respective shares.

5.3 Scenario Design

The Reference (REF) scenario is a projection of the future evolution of the global economic and energy system based on existing trends, exogenous assumptions and scientific expertise on specific fields. Socio-economic developments replicate IEA assumptions (IEA 2019) and are consistent with the SSP2 scenario widely used by the IPCC. For the EU, socio-economic assumptions are based on the Ageing Report of the European Commission (EC 2018a, 2018b). The scenario assumes that already adopted climate policies and pledges, including the Nationally Determined Contributions (NDCs), are implemented by 2030. After 2030, no additional emission reduction effort is assumed, implying that the carbon prices resulting from NDCs in 2030 are kept constant until 2050. The costs of power generation and other energy

Table 3 Scenario description

	Scenario Description	EU Climate target	Non-EU climate targets
REF	Reference scenario	Meets the EU NDC in 2030, no additional efforts after 2030	Meet their NDCs in 2030, policy ambition does not increase beyond 2030
DECARB	EU meets EGD Targets by 2030 & 2050, Global decarbonisation to 2 °C	EU achieves 55/97% emissions reduction in 2030/2050 relative to 1990	Countries adopt ambitious universal carbon pricing to meet the 2 °C target

technologies are calibrated to IRENA (2020), while technology progress is included for low-carbon technologies. ETS carbon revenues are recycled through the public budget.

We also develop a scenario consistent with the Paris Agreement goal to limit global temperature increase to well below 2 °C, which is proxied with the imposition of a global cumulative CO_2 budget of 1000 $GtCO_2$ over 2010 in line with the IPCC 6th Assessment Report (IPCC 2022). A universal carbon price is implemented from 2020 onwards to reach the global cumulative CO_2 budget. As the stringency of the mitigation effort increases over time, the global carbon tax grows from 80\$/$tnCO_2$ in 2030 (in line with IEA 2019) to about 350\$/$tnCO_2$ in 2050. In addition, the EU implements the Green Deal targets of GHG emission reduction of 55% in 2030 and net-zero transition by mid-century. The policy mix adopted to drive the EU energy system decarbonisation includes various instruments—e.g., strengthened EU ETS, subsidies insulation in buildings, accelerated expansion of renewable energy, ambitious technology standards, increased electrification of energy services and uptake of innovative mitigation options (e.g., carbon capture storage, hydrogen, etc.) (Table 3).

5.4 *Results on Socio-Economic Variables and Distributional Effects*

In the REF scenario, economic activity and emissions are found to gradually decouple by 2050 with emissions intensity of GDP declining in all countries, by about 2% annually over 2020–2050. This is a result of the accelerated uptake of renewable energy and low-carbon technologies, the more efficient use of energy resources, fuel switching and stricter environmental regulations. As we aim to analyse the distributional impacts of climate policies, the disaggregated household-related projections by income decile should be constructed to ensure consistency with the national-level GEM-E3-FIT outputs—here, for Greece. The projections for income deciles are based on the income level and source, occupation, consumption patterns and savings, through empirically estimated relations to disaggregate household energy demand by income decile.

In Greece, the recent evolution of income distribution among deciles shows limited changes in the last decade with small variations in the income shares of the bottom and top income quintiles. As there are large differences in earnings of different occupation types, the income distribution in the study is modelled via wage evolution of different occupation types and their respective distribution across deciles depending on sectoral evolution and labour intensity of the economy. According to OECD (2006), savings are highly concentrated at the top of the income distribution and saving rates increase with income. Over time, saving rates by decile as a percentage of disposable income do not vary largely (Eurostat 2019) and can be assumed as constant in the REF scenario by 2050. The disaggregation of GEM-E3-FIT output into income deciles requires additional assumptions:

- Within decile, the income distribution is assumed constant over time
- The equivalised household size is assumed constant
- Consumption patterns and tax rates by decile are assumed constant over time
- Distribution of personal and household benefits and allowances from government by deciles is assumed constant over time

Technical progress, ageing population, changes in consumer behaviour, consumption patterns, industrial competitiveness and policies shape the structure of socio-economic developments in Greece. Changes in income distribution in the country are largely driven by GDP growth, labour supply and demand, technical progress, sectoral growth, wage differentials across skills, the distribution of skills, capital earnings and transfers across deciles. The composition of value added differs significantly across sectors indicating that policies can have different distributional effects across countries. Income inequality is mostly influenced by inequality in labour skills and wages (Keeley 2015; Harrison et al. 2011). In the model, each household receives a share of the total wage income, based on the distribution of income by decile for each skill. The wage income from low-skilled occupations and service workers is more equally spread across different deciles, while income from high-skilled occupations (e.g., managers, technicians) and dividends is mostly directed to higher income deciles in Greece. In contrast, low-income households receive most of social benefits and other allowances. Economic development in the REF scenario involves a gradual transition towards a more service-oriented, technology-rich economy, resulting in a slight redirection of labour demand towards higher skills. Over 2020–2050 there is a slight decline in the value-added share generated by low-skilled occupations (e.g., agricultural jobs) and an increase in the share of higher skilled jobs (e.g., managers). The change in occupations and labour skills has direct impacts on the distribution of income (Fig. 3). As demand for high skills grows, a higher share of total wages would be directed towards higher deciles. Low-income groups receive income mainly from low-skill occupations, and thus their income is negatively affected. However, low-income deciles are dependent on government benefits and allowances, while higher deciles receive income mostly from labour and capital endowments.

The transition towards a high-skilled and capital-intensive Greek economy results in increasing income inequality in the REF scenario as indicated by the Gini coefficient and the S80/S20 index. The inequality indicators strongly depend on the assumption of constant distribution of occupations across deciles, which faces limitations as it does not consider the impacts of potential labour supply adjustments

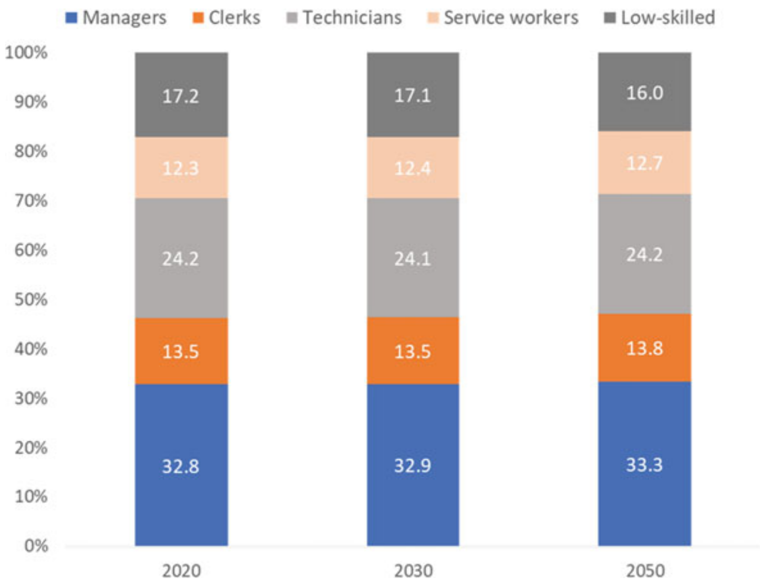

Fig. 3 Composition of Greek labour value added by skill in the REF scenario *Source* Authors'

induced by the transition to high skills, which may change skill distributions across the deciles.

The REF scenario dynamics result in limited increase in the Gini coefficient in Greece from 2020 levels (30.5%) by 0.7 percentage points (pp) in 2030 (31.2%); however, in the longer term, increased automation, digitisation and higher requirements for labour skills drive a larger increase in income inequality, with the Gini coefficient increasing to 33.8 in 2050 (Fig. 4). Greece is expected to remain close to the EU average in terms of the Gini coefficient until 2050 (the EU Gini coefficient is projected to slightly increase from 30% in 2020 to 32.8% in 2050). The S80/S20 indicator is projected to increase over time in the REF scenario, from 5.2 in 2020 to 5.45 in 2030, and further to 6.1 in 2050.

The implementation of ambitious climate policies towards the long-term climate neutrality target (DECARB scenario) would have large-scale impacts triggered by the accelerated uptake of renewable energy and energy efficiency, the massive electrification of end-uses and the deployment of CCS and green hydrogen. The imposition of high carbon pricing drives energy system transformation towards a more capital-intensive structure, with increased investment to renewable energy, electric vehicles and energy efficiency projects, leading to increases in CAPEX and a drop in OPEX and energy purchasing costs. As GEM-E3-FIT assumes optimal use of available capital resources in the REF scenario, reallocation of investments towards low-carbon, energy-efficient technologies in the DECARB scenario leads to the so-called "crowding-out effect", as firms and households finance their clean energy investment by spending less on other commodities and investment purposes. High carbon prices

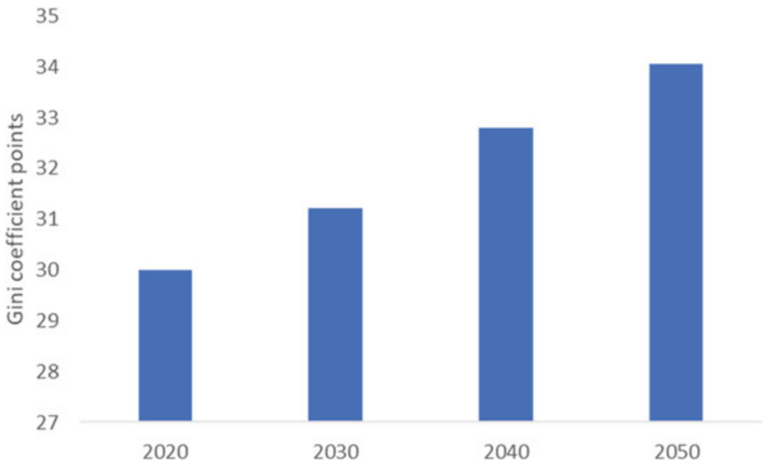

Fig. 4 Evolution of the Gini coefficient in Greece in the REF scenario *Source* Authors'

increase the cost of energy services for firms and households and, hence, production costs throughout the economy, with a depressing effect on consumption and GDP; this is partly alleviated by increased investment in low-carbon technologies. Overall, the net-zero transition is projected to lead to a slowdown of EU economic growth by 0.3% in 2030 and 1.1% in 2050 compared to the REF levels with differential impacts across countries, depending on their economic structure, their relative position in international trade (especially for fossil fuels and low-carbon technologies) and the mitigation effort. The DECARB scenario impacts differently specific sectors in Greece, with sectors directly related to fossil fuels (e.g., mining, refineries, and fossil-based power plants) facing pronounced negative effects due to the shift towards low-carbon energy sources. In contrast, increased electrification of energy services drives increased activity in the electricity sector, required for electric vehicles and heat pumps, and the emergence of green hydrogen after 2035. The output of energy-intensive industrial sectors declines by about 2% with regard to the REF scenario, due to their carbon-intensive structure, as energy costs represent a high share of production costs. Energy efficiency improvements imply increased requirements for construction directed to building retrofits and thermal insulation.

The employment impacts of DECARB are relatively limited and are driven by declining GDP counterbalanced by the uptake of more labour-intensive technologies—e.g., renewable energy and energy efficiency (Fragkos and Paroussos 2018). This aggregate effect masks large differences across productive activities, with some sectors facing extensive job losses (e.g., lignite mining, refineries) due to reduced output, while others are influenced positively by the transition (e.g., electricity, construction). These employment shifts across sectors require extensive re-allocation of workforce and the development of labour skills related to decarbonisation. The labour markets will be influenced by the transition, not only in activities directly linked to the transition, but also for workers at various levels of the supply chain or in sectors that observe a knock-on impact through multiplier effects (construction, agriculture).

The DECARB scenario would have a depressing effect in the Greek economy with GDP projected to decline by about 1% in 2050 compared to REF levels. Private consumption and employment are also negatively impacted. Higher unemployment levels would negatively influence average wage rates, with total income reducing by 0.4% in 2030 and 1.5% in 2050. The largest impacts are felt in low-income deciles, with the income of the lowest decile dropping by 2% from REF levels in 2050, while impacts are limited (less than 1%) in high-income groups; overall, we project a slightly increasing income inequality in Greece. This implies a slight increase in Gini coefficient from 33.8 in REF to 34.2 in DECARB in 2050.

The net-zero transition would also impact the composition of the Greek value added with increased share of high-skilled occupations to the detriment of low-skilled ones, due to higher demand for high-skilled labour required for the transition and the wage differential across different occupations and skills (as increased demand for managers results in a relatively higher increase in their respective share in income). The skills transition entails replacement of labour-intensive and low-skill occupations (Fig. 5), such as lignite mining, by skill-intensive occupations for the design, manufacturing, development and installation of clean technologies and innovative low-carbon products—these include manufacturing and software engineers, project designers, land development advisors and other high-skilled professional or managerial positions (Fragkos et al. 2021).

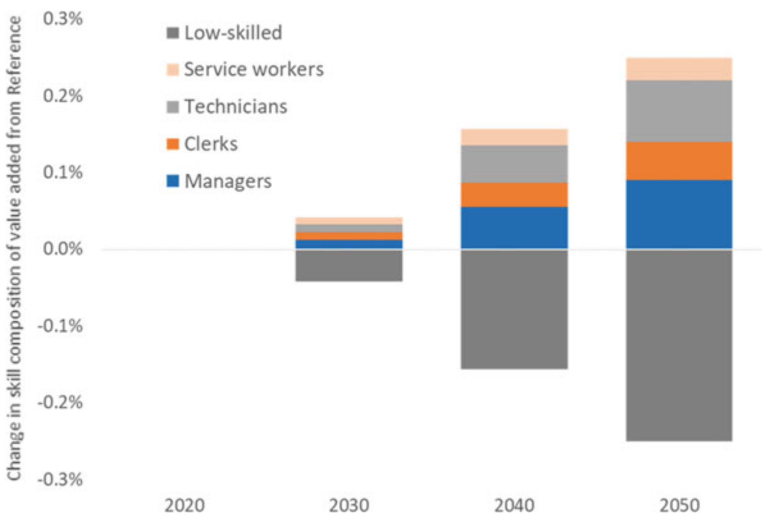

Fig. 5 Changes in the composition of value added by skill in Greece in DECARB compared to REF *Source* Authors'

5.5 *Results on Energy Poverty*

The deep energy system transformation towards net-zero requires large-scale investment by households targeted to the renovation of buildings and the purchase of energy-efficient equipment and low-carbon technologies, which are capital-intensive and increase CAPEX, thereby posing challenges for low-income classes. The latter cannot afford energy-efficient appliances, houses and cars, which fuels the threat of energy poverty. Energy affordability is affected by how income inequality changes due to decarbonisation, as the amount of disposable income available for energy-related expenditure is impacted. The energy expenditure indicators (introduced in the previous section) are quantified using GEM-E3-FIT results combined with data on expenditure for fuels, electricity and energy equipment from PRIMES-Buimo (Fotiou et al. 2022).

The share of energy expenditure in income differs across income deciles, indicating the different levels of vulnerability to changes in energy prices, with lower income deciles having the highest vulnerability. The share of energy expenditure to income (Indicator 1) is estimated at 19% in 2020 for the lowest decile in Greece but is only 3% for the high-income deciles (Fig. 6). When also considering the expenditure for energy equipment (including appliances, heating devices, cars, transport equipment), the share of energy expenditure (Indicator 2) increases by an average of 5.5 pp, ranging from 8 to 22% across income deciles. The increases are relatively higher in high-income deciles that commonly purchase more expensive equipment, highly efficient appliances and more luxurious cars relative to low-income groups.

In the REF scenario, the share of energy expenditure to income declines somewhat in the longer term across income deciles, as household incomes increase faster than energy consumption and energy prices. The same trend is also evident when expenditure for energy and transport equipment is considered as well (Indicator 2), with this indicator dropping by about 1–2% across income groups.

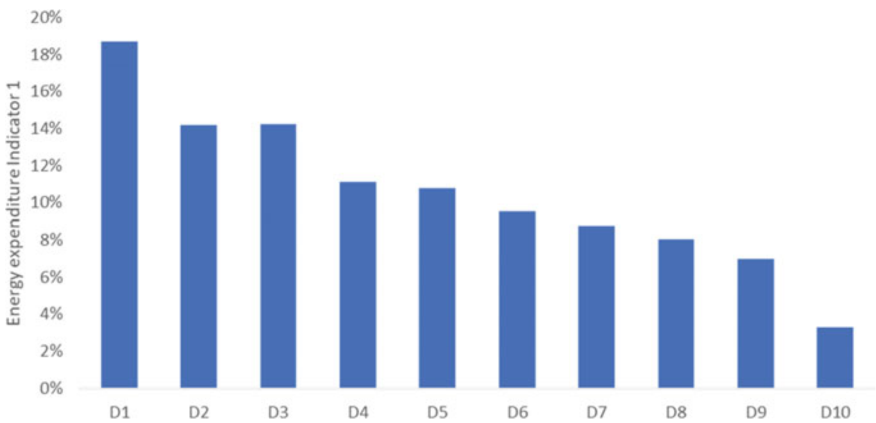

Fig. 6 Energy expenditure Indicator 1 by income decile in Greece in 2020 *Source* Authors'

Decarbonisation entails substantial changes in household energy-related expenditure, along with the subsequent income distributional changes described above. Strong carbon pricing, increased prices for energy products and the need to purchase more expensive low-carbon and efficient equipment result in increased energy expenditure across income deciles. The Energy Expenditure Indicator 1 increases by about 0.2–0.8 pp from REF in 2050, driven by increased energy-related expenditure and slight reduction in household income. The highest increases are found in low-income classes, indicating additional challenges to purchase energy and mobility services leading to higher threats for energy poverty increase. Higher increases are calculated based on the Energy Expenditure Indicator 2 that include the increased costs to purchase advanced energy-efficient equipment and low-emission cars. The highest increase is projected for low-income deciles (Fig. 7).

The reduced income and increased energy expenditure would have larger impacts on low-income groups, increasing their vulnerability to energy poverty. Several measures are discussed to alleviate such risks and pave the way for a just transition, most of them based on different ways to use carbon revenues (Budolfson et al. 2021). Here, we quantitatively assess the distributional impacts of directing the carbon revenues via lump-sum to households and via reduced social security contributions (DECARB_EQ), instead of recycling them through the public budget. The distribution of lump-sum transfers to different income groups follows the distribution of social benefits and allowances. The additional carbon revenues amount to about 1–1.5% of GDP and thus the redirection of carbon revenues has an important effect on income inequality. The available income of Greek households increases by more than 1% from REF levels, but this is moderated by the macroeconomic

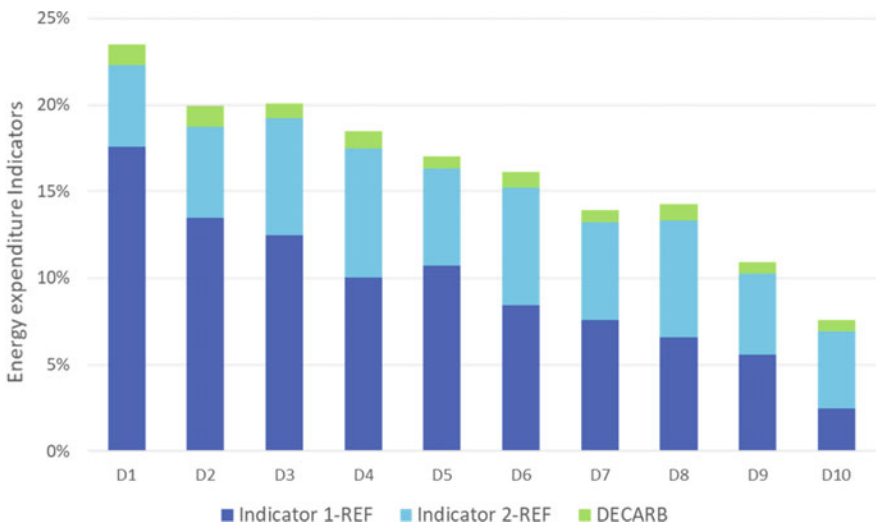

Fig. 7 Energy expenditure Indicators in Greece for each income decile in 2050 in DECARB scenario *Source* Authors'

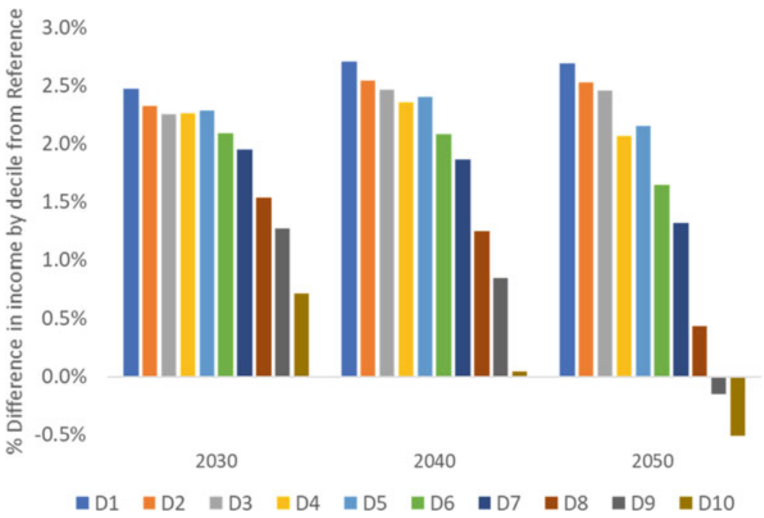

Fig. 8 Change in total income per decile group in DECARB_EQ scenario relative to REF over 2030–2050 *Source* Authors'

impacts of the transition in the longer run. Increased government benefits have large positive impacts for lower income deciles that largely depend on these benefits and allowances (their incomes increase by close to 2.5% from Reference), while the impacts are lower for high-income households and even turn negative in 2050, due to the reduced economic activity with GDP declining relative to the REF scenario. This leads to reduced income inequalities, as reflected in a reduction of the Gini coefficient, induced using carbon revenues as lump-sum transfers that mostly benefit lower income households. This measure counterbalances the regressive impacts of the skills transition and reduces income inequality with the Gini coefficient in Greece declining by 0.8 pp and 1.4 pp in 2030 and 2050, respectively, relative to REF, with similar trends observed also in the S80/S20 index (Fig. 8).

6 Conclusions

Decarbonisation efforts can result in large-scale economic restructuring with potential regressive distributional impacts, disproportionately affecting disadvantaged population groups. The imposition of additional carbon taxes on energy products and the need to purchase energy efficient albeit more expensive equipment may negatively affect low-income households that face funding scarcity while increasing the threat of energy poverty. Environmental policies are commonly associated, in literature, with regressive distributional impacts that negatively affect low-income households. Ignoring such distributional effects can result in less effective policies and increased social inequalities. Well-designed strategies and policies are required to achieve progressive outcomes by considering appropriate compensation schemes, either by increasing household income through lump-sum payments, reducing other taxes or through the social security system.

After studying the EU and national policy context, the challenges to quantifying energy poverty, and the relevant policies in place in Greece, the GEM-E3-FIT model—expanded to represent ten income deciles by differentiating their income sources, savings and consumption patterns—is used to quantify the socio-economic and distributional impacts of the transition to net zero by 2050. Decarbonisation affects employment and labour income, leading to a reduction in low-skilled labour demand combined with an increase in high-skilled jobs required for the transition. This causes negative distributional impacts through the labour market leading to higher social inequality levels. The net-zero transition can also increase the energy-related expenditure in households, especially in low-income groups, raising the issues of energy poverty and energy affordability, since these income classes already spend a large share of their income to purchase energy services and equipment.

Overall, the model-based analysis shows that decarbonisation increases modestly existing inequality across income classes, with low-income households facing more negative effects than higher income ones. However, using carbon revenues as lump-sum transfers to households and requiring reduced social security contributions has clear benefits. These include increasing total employment while significantly reducing the inequality across income classes. Since we assume that the distribution of lump-sum transfers follows the distribution of social benefits and allowances to income groups, the redistribution of carbon revenues will significantly reduce income inequality bringing high benefits for low-income households.

We find that, if Greece—alongside other EU countries—adopts the necessary carbon tax and then returns revenues to citizens on an equal per capita basis, it will be possible to meet the net-zero target in 2050 while also reducing inequality. These results indicate that it is possible for a society to implement strong climate action without hampering goals for equity and development.

An important caveat of the analysis, to be addressed in planned future research, is the assumption that income distribution remains constant over time within deciles, which is rather simplistic. If additional data is provided and model running time is improved, the GEM-E3-FIT modelling framework can be further enhanced to represent income percentiles, thus improving its simulation properties, especially when it comes to assessing policy impacts for the most vulnerable income groups. In addition, the model-based analysis can be expanded to cover the recent increases in energy prices and the RePowerEU strategies that will highly impact the economic and distributional impacts of the transition to net zero in Greece and in the rest of the EU countries.

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