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Distributional Consequences of Climate Change Impacts on Energy Demand across Italian Households

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Abstract

The paper evaluates the distributional implications of climate-induced temperature changes on energy demand and energy poverty in Italy. We use two different simulation approaches that make it possible to analyze to what extent general equilibrium substitution and income effects moderate or amplify the first-order changes induced by climate change. Climate change impacts are regressive. While rich households reduce expenditure on heating fuels more than the poor, less affluent households increase electricity expenditure relatively more. For a given income level, whether households increase or decrease energy expenditure depends on the size of the shock, the existing climate conditions, and the energy sources used. The increase in electricity poor households highlights a new emerging risk related to those households who will be exposed to higher temperatures and will not being able to purchase the cooling services needed to protect themselves because of credit, institutional, infrastructural constraints. We shed new light on the importance of accounting for the distributional consequences of climate change impacts when designing climate policies.

JEL Codes: D1, O52, Q43, C68

Keywords: Households, Climate Change, Energy Poverty, Computable General Equilibrium model.

1 Introduction

Concerns about the inequitable consequences of climate change policies have motivated scholars and researchers to evaluate the distributional implications of carbon pricing (Baranzini *et al.* , 2017) and of mitigation policies (Fullerton, 2017). Not only an appropriate design of mitigation policy can avoid regressive impacts, but several studies highlight how the revenue from carbon pricing schemes can be used to achieve other sustainable development goals (Jacob *et al.* , 2016) and reduce poverty (Fujimori *et al.* , 2020). When considering the distributive impacts of climate policy, policy scenarios should be compared to baseline scenarios that account for the impacts of climate change and the associated adaptation efforts. The knowledge regarding the distributional implications of climate change impacts and the related adaptation responses is still very limited. There is consensus that climate change will place a heavier burden on poor households (IPCC, 2014), though outcomes depend on how damage functions vary across geography and with population characteristics (e.g. income, access to technology) (Hsiang *et al.* , 2019), and more generally with the ability to adapt.

Adjusting final energy use is an ubiquitous form of autonomous adaptation that households adopt to maintain conditions of thermal comfort at home when exposed to warmer or colder temperature levels. Along with income and prices, climate conditions are among the well-established drivers of households energy demand. While heating and cooling are the most directly affected end-use services, other usages can also change as people spend more time at home (Zivin & Neidell, 2014) and even the efficiency of other appliances, such as refrigerators (Meier, 1995), is sensitive to outdoor climate conditions. Energy demand is therefore an important example where mitigation, adaptation, and residual impacts interact and provide different signals inducing behavioural adjustments.

While the reduced frequency of cold days lowers fuel expenditures for heating, increased exposure to hot days has the opposite effect on electricity expenditures (van Ruijven *et al.* , 2019). The response of different income groups depends on their willingness and, especially, their ability to adapt. Affluent households are more likely to increase energy demand for cooling compared to the low-income people who might be credit-constrained (Burgess *et al.* , 2014). At the household level, changes in energy expenditure can induce substitution effects that modify the overall pattern and composition of households' expenditure, for example by reducing food (Bhattacharya *et al.* , 2003) or education (Maccini & Yang, 2009) expenditure, with lasting effects on households' welfare and fuel poverty (Phoumin & Kimura, 2019). At the macroeconomic level, changes in households' expenditure patterns affect the aggregate demand of energy as well as of other goods, and therefore can bring about price adjustments that influence production and consumption choices across all sectors of the economy. In Europe, fuel poverty affects 10% to 15% of the population, depending on the Member State (Europe, 2014). Earlier studies on energy poverty have been conducted in relatively cold countries, such as in the United Kingdom, focusing on heating fuel poverty. The ongoing trends of global average temperature could bring about a new type of energy poor related to those households who need to divert a share of their income to satisfy the demand for cooling away from other types of expenditures, such as food and education.

This paper analyzes the distributional implications of climate change impacts on energy demand around 2050. We compare the response of households over the full income distribution across the Italian regions characterized by different climate conditions. We also derive the implications on selected expenditure-based indicators of energy poverty. We evaluate to what extent macroeconomic adjustments mitigate the direct impacts of climate change. The analysis focuses on Italian households. Italy offers an interesting case study because it combines a highly diverse geography with heterogeneous socioeconomic conditions. We combine a macroeconomic model with a sequential, arithmetic micro-simulation approach to develop a modular set-up to analyze how climate-induced changes in energy expenditures are distributed across regions and income groups.

To our knowledge, this paper is the first assessment that evaluates the distributional implications of autonomous adaptation to climate change through the use of energy. We contribute to the literature in three ways. First, we evaluate how the impacts of climate change on the use of oil products, natural gas, and electricity varies across households belonging to different income groups and regions, and examine whether they are regressive or progressive. Second, we evaluate the implications on selected indicators of energy poverty count and intensity. Third, we investigate to what extent general equilibrium adjustments through changes in income and prices, and budget considerations mitigate the initial, direct, climate-induced shocks.

Our results show that the direct impacts of temperature shocks are a good approximation of the final, general equilibrium effects at the country level as well as across income groups. The macroeconomic adjustments vary significantly across Italian regions and fuels, and they mostly affect electricity. Changes in energy expenditures lead to a reduction in the number of energy poor and in the intensity of energy poverty, whereas electricity poor increase in hotter and more populated regions both without and with higher-order, macroeconomic adjustments. Our results suggest that mitigation policies, by limiting the future increase in global average temperature, can bring about economic benefits in terms of reduced electricity poverty. We also show that price adjustments and budget constraints limit the extent of household adaptation compared to the first-order direct climate shocks, pointing at the persistence of residual damages and at interactions with other forms of expenditure (e.g. health).

The remainder of the paper is articulated as follows. Section 2 briefly reviews the relevant literature. Section 3 describes the methods and the framework of the analysis. Section 4 presents the results. Section 5 concludes.

2 Literature review

A broad literature investigates the distributional implications and the welfare incidence of policies, such as fuel and carbon taxes, as reviewed by Fullerton & Muehlegger (2019) and Pizer & Sexton (2019). Three are the main mechanisms through which a carbon or a fuel tax affects households' welfare. First, the direct component or forward cost-shifting, representing the direct increase in energy prices faced by consumers, leading to higher expenditure. Second, the indirect component leading to changes in the production costs of all, energy and non-energy commodities. Third, the behavioral changes in consumption and production. On the consumption side, budget-constrained households adjust their consumption mix responding to changes in relative prices. On the production side, firms substitute the more expensive energy-intensive inputs with other inputs, including the imported ones, a channel leading to carbon leakage. Behavioral responses on the production side can also affect the sectoral returns to the primary factors of production labor and capital, and therefore households' income.

Indirect and behavioral responses are second-order effects that can be evaluated by general equilibrium analyses such as those based on Computable General Equilibrium (CGE) models. The indirect and economy-wide impacts of a tax on consumers across income levels (vertical equity) can differ significantly from the direct impacts,which affect only energy, whose budget share is larger among the lowest deciles of the income distribution. Indirect changes have a widespread effect on other goods/sectors, whose budget share is lower among poor people. Therefore, direct impacts are only a first approximation of the overall shock effect. Other studies based on a general equilibrium approach suggest that regressivity can also be reduced over the long-run because demand is more elastic, leading to a larger fraction of the burden falling on producer and on capital and energy resource owners (Bovenberg & Goulder (2001); Paltsev *et al.* (2007); Rausch *et al.* (2011)). Moreover, since the share of energy expenditure on overall expenditure is generally small, the direct component can be expected to be the main driver of the distributional implications.

Hassett *et al.* (2007) decompose the burden of a carbon tax on consumers for the U.S. into the direct and indirect components. They conclude that the direct component, e.g. higher energy expenditure, is the main driver of the regressivity of a carbon tax. They also show how the extent to which the burden is disproportionately larger on poorer households depends on how welfare is measured. Using lifetime consumption or current consumption actually decreases the regressivity of the tax compared to calculations based on annual income. Income is subject to shocks and annual fluctuations, and its profile exhibit life-cycle patterns. Assuming households prefer to smooth consumption over time, current or lifetime consumption correspond more closely to lifetime income (Poterba, 1989). Grainger & Kolstad (2009) come to similar conclusions. In addition, they show that the degree of regressivity depends on whether the burden is calculated at the household level or on a per-capita basis with equivalence scales. Accounting for the different household size (in the U.S. larger households are found among the wealthier families) increases the regressivity of the policy.

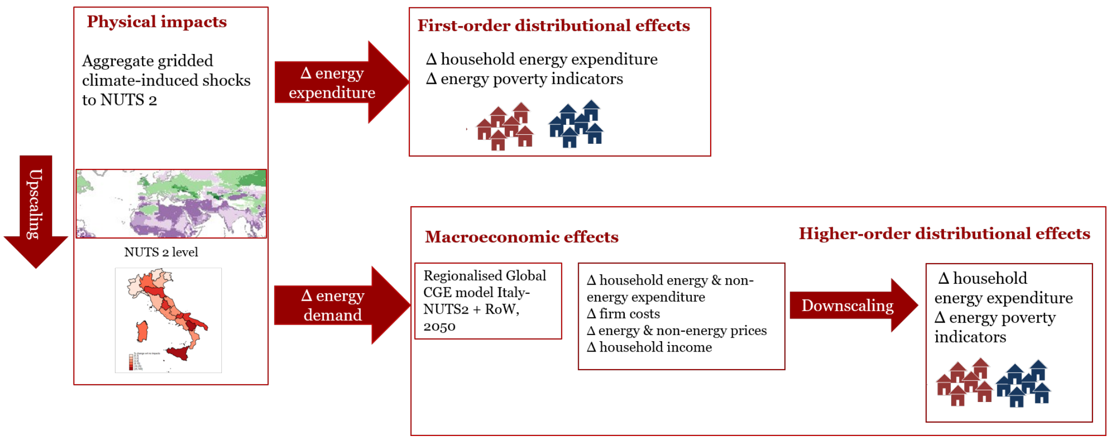
Pizer & Sexton (2019) also shows that the regressivity of energy taxes depends on the commodity that is being taxed. Electricity taxes are highly regressive compared to heating fuel taxes, whereas gasoline taxes can be neutral or even progressive, especially in less-developed countries (Flues & Thomas, 2015). While most literature has focused on vertical equity, only a few studies analyze horizontal equity impacts, that is how households with a similar income level are differently affected by an energy tax because of heterogeneity in geography (e.g. climate conditions) or housing conditions. While distributional policies can more easily be designed to address vertical equity, horizontal equity hinges upon dimensions (e.g. geography, built environment, households' characteristics) that are more difficult to be addressed by policy.

Different methods that can be used to examine the general equilibrium and indirect impacts of climate policies rely on alternative approaches to represent heterogeneity across households van Ruijven *et al.* , 2015. First, CGE models can include an explicit representation of multiple household types as opposed to only one representative household. Second, a macroeconomic model, such as a CGE, can be coupled with a micro-simulation model. Third, the income distribution based on historical data can be directly included in the models. The second approach can simulate outcomes for a large number of households consistent with aggregate changes in prices, factor remuneration, supplied and consumed quantities of energy and non-energy goods determined by the macro model, and can be characterized by different levels of detail, e.g. sequential (top-down) or iterative (top-down/bottom-up), arithmetic, non-behavioral, accounting or including behavioral changes. Each methodology has its own advantages, in terms of applications, and disadvantages, in terms of data requirement and computational time. Most long-term, global analyses have relied on the arithmetic, sequential, micro-simulation approach (van Ruijven *et al.* , 2015). This is the approach that has been used to analyze the distributional implications of long-term climate change impacts at global scale (Hertel *et al.* , 2010).

3 Data and methodology

Our methodological framework is articulated in the four steps illustrated in Figure 1. The first module calculates the physical impacts by combining empirically-based estimates of income and temperature elasticities with socio-economic and climate projections. The second module combines the physical impacts from step 1 with household consumption expenditure data to evaluate the direct, first-order distributional effects of climate change impacts. The third step sets up a multi-region CGE model to analyze the macroeconomic consequences of the climate-induced shocks in 2050. The last step is a downscaling module for analyzing distributional implications of second-order macroeconomic impacts on household income and welfare. Specifically, we use a sequential arithmetic micro-simulation approach (van Ruijven *et al.* , 2015) that can characterize the distributional consequences of climate impacts across different household types.

Figure 1: Methodological flow



3.1 Physical climate change impacts

Here we employ the ex-ante energy demand gridded shocks from De Cian & Sue Wing (2017), which uses a panel data of national energy demand, energy prices, income per capita, and weather covariates (temperature and humidity) for hundred of countries over the period 1970-2014 to derive income elasticities and temperature semi-elasticities of sectoral energy demand in tropical and temperate regions for three energy carriers (electricity, natural gas, petroleum products) in five sectors (residential, commercial, industry, agriculture, transport). In this paper we only focus on the residential sector. Gridded shocks are aggregated to the regional administrative units of the Italian household survey and of the CGE model of NUTS2 [1] by using

[1]We used the shape file for the political borders within Europe at NUTS2 to extract only the grid-cells of interest with the R package sp, https://www.rdocumentation.org/packages/sp/versions/1.3-

the mean function of the shocks across all grid-cells belonging to a specific NUTS region.

3.2 First-order distributional effects

First-order distributional effects are computed by combining the spatially-resolved physical impacts on energy demand described in Section 3.1 with a survey on household expenditure for the Italian economy. The way climate shocks will affect energy expenditure across households depends on i) the total energy expenditure patterns of different income groups (e.g. share on overall expenditure or income), ii) the energy mix, as different energy sources are heterogeneously affected by climate change (electricity demand mostly increases, whereas natural gas and petroleum products decline), iii) the way these two characteristics interact with the geography of the country analyzed. By looking at how the distribution of energy expenditure for different energy commodities varies across regions and income deciles, we provide a first approximation of how different income groups across the geography of Italy will be affected by climate change impacts, highlighting the interplay among regional heterogeneity of climate impacts, energy consumption, and income structure. We use the ISTAT Household Budget Survey (HBS)[2], which describes consumption expenditure of Italian households. We focus on the 2007 wave for consistency with Section 3.3.

The critical assumptions behind the calculation of the first-order impacts are two. First, future climate shocks are imposed on the 2007 economy and energy mix, without considering variation in income and preferences. Second, there are no-

1/topics/sp. Grid cells have been aggregated using the simple mean function. Grid-level impacts have been converted to spatial points, which have then being intersected with the EU NUTS2 polygons using the point in polygon R function.

[2]The HBS is representative of Italian population with 28000 households surveyed.

behavioural adjustments, as price changes are not taken into consideration. Climate impact shocks on residential energy demand at NUTS2 level are used to scale energy expenditure of Italian households of electricity, gas and petroleum products with respect to 2007 survey levels, assuming there are no budget constraints.

We directly attributed the climate change impacts on energy demand at regional level described in Section 3.1 to Italian households depending to their location[3]. The after-shock expenditure $EXP_{h,f,r}^{\text{Climate}}$ of household h, in fuel f, region r and scenario *Climate*, i.e. RCP4.5 or RCP8.5, is obtained by perturbing the HBS household expenditure $EXP_{h,r,f}^{\text{HBS}} = P_{h,r,f}^{\text{HBS}} * Q_{h,r,f}^{\text{HBS}}$ with the percentage change in regional residential energy demand [4] due to climate change $\phi_{r,f}^{\text{Climate}}$ (Equation 1):

$$EXP_{h,f,r}^{\text{Climate}} = EXP_{h,r,f}^{\text{HBS}} \times (1 + \phi_{r,f}^{\text{Climate}}/100) \tag{1}$$

The household expenditure in electricity, gas and petroleum products under climate change, $EXP_{h,f,r}^{\text{Climate}}$, is compared to the HBS levels and used to compute after-shock total household expenditure and new expenditure shares.

3.3 Higher-order macroeconomic and distributional effects

In a general equilibrium context, direct changes in energy use due to climate change will also affect fuel prices and the demand of other services and goods. Consumers will adjust their consumption mix and producers will respond with changes in the supply, in the use of intermediates and primary factors of production, leading to changes in

[3]For privacy reasons, in the survey the highest level of detail about household location is represented by the 20 NUTS2 Italian regions.

[4]All commodity prices remain unaltered and the expenditure change is the result of a consumption quantity change. All households falling within the same NUTS2 are imposed the same shock. Results differ across households because of the different baseline starting expenditure.

prices and income that will further feedback on consumers' choices and welfare. Moreover, the structure of the economy that in 2050 will be affected by the climate shocks will be different from that of the base year (2007), as population, income, technological progress, and prices will change over time, modifying consumption choices of households (baseline scenario).

CGE models can track the indirect, higher-order implications of a shock. The systemic, General Equilibrium features of the model connect the fuel demand shift to energy price changes that influence cost functions of all products and therefore their price and supplied quantity. This lead to further adjustments in the household and government consumption bundle. Income generation is also affected by the climate shocks because variations in firm costs and production choices determines shifts in the primary factor (labour, capital and natural resources) remuneration owned by households, and therefore in their budget constraint. Finally, climate shocks can also modify the competitive advantages or disadvantages for different regions across sectors, with implications for international trade flows.

We use a multi-sector and multi-country recursive-dynamic CGE model, ICES (Eboli *et al.* , 2010), enriched with a more detailed regional representation for the Italian economy at NUTS-2 region-level, as illustrated in (Carrera *et al.* , 2015). The description of the model and of the database can be found in Annex 1.

In terms of model structure and equations, the regionalized model maintains the same structure as ICES. Household preferences are represented with a Constant Differences of Elasticities implicitly additive expenditure function (CDE) by Hanoch (1975) that is a flexible and well-behaved function assuming non-constant marginal budget shares. The linearized consumption demand has the following formulation:

$$qp_{i,r} - pop_r = \sum_k \epsilon^P_{i,k,r} * pp_{k,r} + \epsilon^Y_{i,r}(y_r - pop_r) \tag{2}$$

where the percentage change of per capita demand for good i in region r ($qp_{i,r} - pop_r$) depends on percentage change in consumer prices ($pp_{k,r}$) and the cross-price elasticity ($\epsilon^P_{i,k,r}$), where k are the good and services different from i, plus the percentage change in per capita income ($y_r - pop_r$) multiplied by income elasticity ($\epsilon^Y_{i,r}$). The percentage change of demand for a certain good is a mix of domestically produced and imported good, where the proportion of this two sources is regulated by Armington elasticities (Corong *et al.* , 2017). In the regionalized version of the model, we have country/macro-region-specific demand functions, with the exception of Italy where the private demand is specified at NUTS2 level (Annex 1).

The baseline scenario updates the socioeconomic picture of the base year (2007) in each region and country according to the characteristics of a possible future scenario. For the period 2007-2016 we rely on historical data. After 2016, the historical trends are extended up to 2050 as in the Middle of the Road Shared Socioeconomic Pathway 2 (SSP2).

Climate impacts are applied to the baseline scenario. Climate impacts on residential energy demand at NUTS2 level computed as in Section 3.1 are imposed as an exogenous percentage change of regional private consumption of electricity, gas and petroleum products (equation 3)[5]. In the model, we impose an exogenous shift ($\gamma_{f,r,s}$ in equation 4) on the endogenous change of private consumption of fuels ($qp_{f,r,s}$), whereas equation 5 describes the adjustment of consumption bundle regarding the

[5]Fuels are represented by the set f that is a subset of commodities i. The complementary set is called o.

other goods:

$$\gamma_{f,r,s} = \phi^{\text{Climate}}_{f,r,res} \tag{3}$$

$$qp_{f,r,s} - pop_r = \gamma_{f,r,s} + \sum_k \epsilon^P_{f,k,r} * pp_{k,r} + \epsilon^Y_{f,r}(y_r - pop) \tag{4}$$

$$qp_{o,r,s} - pop_r = \gamma_{o,r,s} + \sum_k \epsilon^P_{o,k,r} * pp_{k,r} + \epsilon^Y_{o,r}(y_r - pop) \tag{5}$$

The CGE analysis tracks how climate-induced energy demand shocks spread into the economy through the induced changes in prices of energy goods, production costs in non-energy sectors, income, and consumption in different regions.

A micro-simulation module is sequentially used to arithmetically downscale the aggregate changes in prices and quantities across household expenditure deciles and guarantee the consistency with the macro results. Applying the macroeconomic changes generated by the ICES model to the expenditure of all households in the survey HBS determines a discrepancy between the aggregate changes in household expenditure and the percentage variation observed in the ICES model. The inconsistency emerges also at the regional level. The downscaling module minimizes this discrepancy transforming the 2050 expenditure at household level into an adjusted one by using the cross entropy maximization method (McDougall, 1999; Golan & Judge, 1996), see the Appendix for more details.

The downscaling module returns a household-specific picture of consumption choices in 2050 under baseline and impact scenarios. The higher-order distributional implications of climate change impacts on energy demand are derived by comparing how energy expenditure shares change in a mild and severe global warming scenario with respect to the baseline one.

It is worth noticing that the proposed methodology makes it possible to account for the behavioural response of household demand to price changes, but the optimization process takes place at regional level. This means that all households belonging to a specific NUTS2 region will be subject to the same commodity price and quantity percentage change. Bearing these limitations in mind, this methodology makes it possible to compare the burden of direct and indirect climate change impacts on the energy used by Italian households, as well as its overall distributional implications. By looking at the distribution of this burden, we will highlight the either regressive, progressive, or neutral implications of energy use for adaptation, highlighting the role of adjustment mechanisms induced by price changes and income effects.

3.4 Energy poverty indicators

We study the climate-related distributional implications on households by comparing energy expenditure shares before and after climate shocks across regions and expenditure deciles, and by considering two fuel poverty indicators from the literature on fuel poverty (Romero *et al.* 2018; Rademaekers *et al.* 2016; Miniaci *et al.* 2008).

The first indicator compares households' actual fuel expenditure shares with the minimum affordable basket required in order not to be socially excluded, as defined in Miniaci *et al.* (2008).[6] This index combines the concepts of absolute poverty with that of fuel poverty, and the resulting Fuel Poverty Prevalence index shares some features with the Low income/high cost (LIHC) indicator, currently in use in the UK and other countries (Rademaekers *et al.* , 2016).[7] Following Miniaci *et al.* (2008), we define the reference, minimum affordable budget share of fuels f in

[6]All variable considered, i.e household total and fuel-specific expenditures, are per adult equivalent.

[7]LIHC considers energy poor those households whose income share spent on energy is above national median, and income net of energy costs is below the national poverty line.

region r, $r^{rbs} = \frac{\overline{P}_{f,r} * \overline{Q}_{f,r}}{\overline{EXP}_r} * 100$, as the median energy budget share of households below absolute poverty line in 2007 (2050 for future projections) in that region.[8] We define as energy poors with respect to a specific fuel those households whose actual expenditure share $\frac{P_{f,r} * Q_{h,f,r}}{EXP_{h,r}}$ is higher than $r^{rbs}_{f,r}$. The actual Fuel Poverty Prevalence index based on the minimum affordable basket reads as follows:

$$FPP^{abs}_{f,r} = \frac{1}{n}\sum_{h=1}^{n} 1\left(\frac{P_{f,r} \times Q_{h,f,r}}{EXP_{h,r}} \times 100 > \frac{\overline{P}_{f,r} \times \overline{Q}_{f,r}}{\overline{EXP}_r} \times 100\right) \tag{6}$$

This first indicator uses households' actual energy expenditure shares, which on average are higher among poor households, and represent an upper bound of energy poverty. As discussed in Miniaci *et al.* (2008b), there are many other reasons resulting in high energy budget shares, including preferences (e.g. a higher number of appliances) and technological constraints (e.g. poor housing conditions, inefficient heating and cooling systems, leading to over-consumption).

A second indicator that provides a more restrictive measure of fuel poverty, yielding a lower bound estimate, compares the potential budget devoted to buy the minimum necessary energy services, defined as the median regional expenditure of poor households below the absolute poverty line, $\overline{P}_{f,r} * \overline{Q}_{f,r}$, over the actual household expenditure with the reference minimum affordable budget share r^{rbs}. The potential Fuel Poverty Prevalence index, FPP^{pbs} is computed as follows:

$$FPP^{pbs}_{f,r} = \frac{1}{n}\sum_{h=1}^{n} 1\left(\frac{\overline{P}_{f,r} * \overline{Q}_{f,r}}{EXP_{h,r}} \times 100 > \frac{\overline{P}_{f,r} \times \overline{Q}_{f,r}}{\overline{EXP}_r} \times 100\right) \tag{7}$$

Note that the difference between $FPP^{abs}_{f,r}$ and $FPP^{pbs}_{f,r}$ is the numerator on the

[8] The use of a region-specific thresholds acknowledges that independently from the income availability, different Italian regions are characterized by heterogeneous climatic characteristic and, therefore, energy needs.

left hand side. The first index uses actual expenditure and actual expenditure share, whereas the second one uses the potential expenditure associated with minimum energy bundle divided by the actual total expenditure, leading to the potential expenditure share.[9]

The literature on fuel poverty offers a wide set of indicators (Faiella & Lavecchia, 2019). Some of them are close to the actual budget share index considered in Equation 6, both in formulation and results, but use a different reference point, such as twice the the median energy budget share or a 10% threshold. Two additional measures proposed in Miniaci *et al.* (2008b) are based on the residual income approach and define fuel poor those households that cannot afford the necessary amount of energy services after purchasing the minimum quantity of other goods or/and that cannot afford to buy the necessary amount of other goods after purchasing energy commodities[10]. A first index (i) includes all households with affordability problems in any commodity above and below absolute poverty line, considering also households with an overconsumption in one commodity that in turn determines under consumption in the others. This index is rooted on a wider definition of fuel poverty and offers outcomes similar to the actual budget share index defined in Equation 6 accounting for those households who are not poor, but underconsume energy, e.g. due to more efficient appliances, or overconsume energy, e.g. due to higher demand of energy services. A second index (ii) combines the concept of affordability to that

[9]When computing the index with climate change impacts and in future periods, the potential expenditure on the left hand side are updated considering the median expenditure of households in poverty after imposing baseline changes and climate shocks. The threshold on the right is constant in the first-order impact assessment and is updated when considering higher-order impacts acknowledging economic growth and a change of energy expenditure.

[10]The necessary amount of goods is defined as the affordable expenditure for households below poverty line.

of absolute poverty, excluding therefore households above poverty line that underconsume energy or overconsume other goods. This index is conceptually comparable to the potential budget share index defined in Equation 7 whether only affordability problem in purchasing energy is accounted for.

The two indices considered here, based on the actual and potential budget share, provide a lower and upper bound estimate of fuel poverty, but they do not inform about the severity of fuel poverty. We therefore consider a Fuel Poverty Gap index, $FPG_{f,r}^{pbs}$ (Foster *et al.* , 2010) which, starting from the index $FPP_{f,r}^{pbs}$ described in Equation 7, $FPG_{f,r}^{pbs}$ considers an additional term accounting for the depth of poverty measured as distance from the minimum affordable budget share (r^{rbs}):

$$FPG_{f,r}^{pbs} = \frac{1}{n}\sum_{h=1}^{n} 1\left(\frac{\overline{P}_{f,r} \times \overline{Q}_{f,r}}{EXP_{h,r}} \times 100 > r^{rbs}\right) \times \left(\frac{\overline{P}_{f,r} \times \overline{Q}_{f,r}}{EXP_{h,r}} \times 100 - r^{rbs}\right)^{\alpha} \quad (8)$$

where $r^{rbs} = \frac{\overline{P}_{f,r} * \overline{Q}_{f,r}}{\overline{EXP}_{r}} * 100$ and α describes the depth of concern for the affordability issue. When $\alpha = 1$ (poverty gap index), the indicator sums up the gaps of households' energy budget shares from minimum affordable budget share, r^{rbs}, and therefore it may highlight a wider gap even if the number of households with affordability problems reduces. When $\alpha = 2$, we have a Squared Fuel Poverty Gap, also called poverty severity index, that attributes higher weights to wider poverty gaps.

4 Results

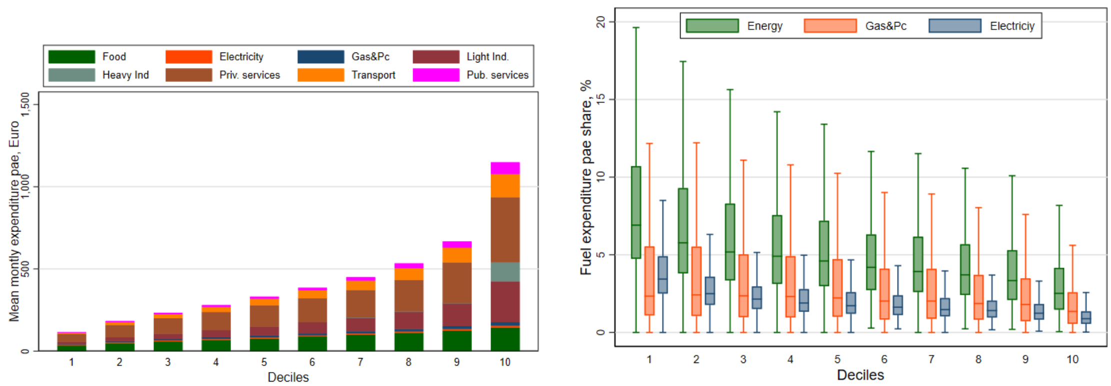
4.1 Energy expenditure and poverty in the base year

Energy expenditure represents a small share of the overall household budget also for the average Italian family, about 5% of the overall consumption expenditure, whereas most of the budget goes to private services, followed by food and light industry. Italian regions show some heterogeneity in terms of energy expenditure mix reflecting whether the prevailing end-use is heating or cooling. The share of electricity varies between 1.8% in Piedmont/Aosta Valley and 3.5% in Sicily, whereas that of other fuels (oil, gas, petroleum products) is between 1.6% in Sicily and 4.8% in Piedmont/Aosta Valley.

Looking at the expenditure mix across different deciles, Figure 2 (left) shows the non-linear increase in total expenditure per adult equivalent (pae) as we move from the bottom to the top deciles. Total monthly expenditure per adult equivalent is about 115 euros in the first decile and about 1150 euros in the top decile, 10 times higher. The expenditure pattern across the first nine deciles increases more gradually, from 115 to about 669 euros. Compared to total expenditure, energy expenditure increases in a more gentle way across deciles, with the top decile spending about 3.5 times the amount of the first decile. While energy expenditure increases from about 10 to 34 euros per adult equivalent (electricity expenditure per adult equivalent goes from 5 to 11 euros) across deciles, the share of energy expenditure (Figure 2- right) falls from about 9% to 3% (4% to 1% for electricity). The decline of heating fuel expenditure share across deciles is slower.

In Italy a high portion of energy is used for heating (61%). The remaining energy expenditure is in electricity providing a wide array of service, including Air Conditioning (AC), which in Italy is still of limited diffusion (with the exception of some regions, such as Sicily where indeed the share of electricity expenditure is higher). Average AC ownership rate per household is relatively low, about 28%. Sicily and Sardinia have the largest share of electricity expenditure per adult equivalent (3.5 and 3.4%, respectively) and they are among the regions with the highest AC ownership rate (42 and 43%, respectively). AC ownership rates are also high in

Figure 2: Mean monthly expenditure per adult equivalent (pae) across deciles (left) and energy expenditure per adult equivalent shares (right). Istat HBS 2007.

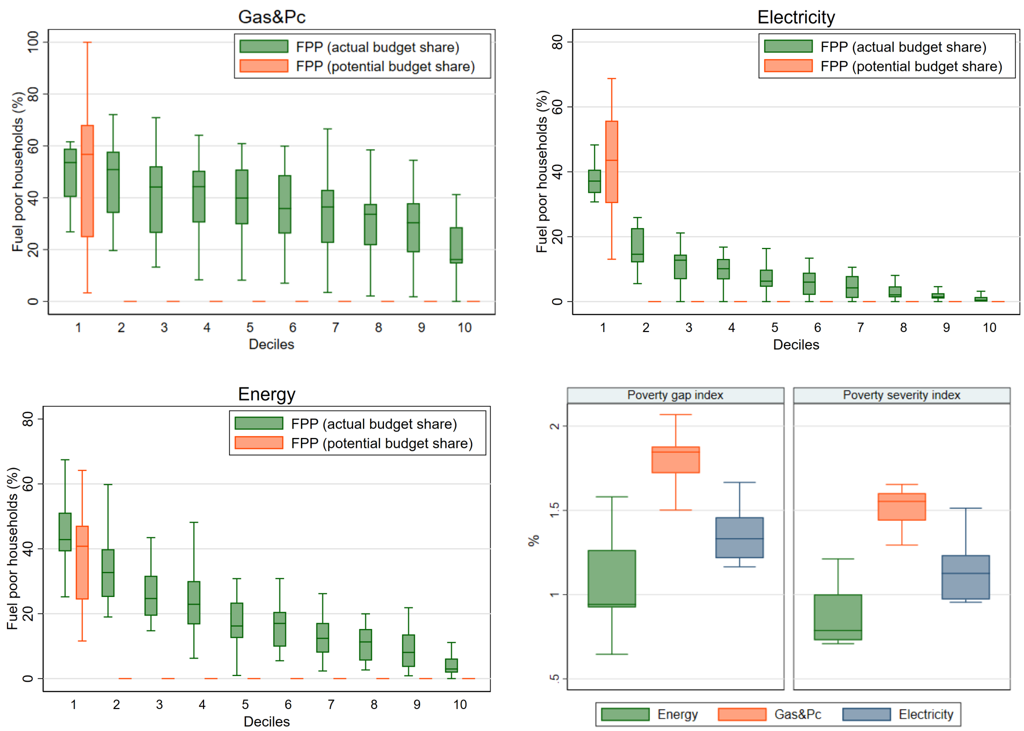


highly-urbanized regions, Veneto and Emilia-Romagna (53 and 41 %).

In Italy, the average percentage of energy poor households is 23% (FPP actual budget share) and 4% (FPP potential budget share)[11]. Poverty prevalence due to heating fuels ranges between 41 and 5% and that related to electricity use between 11 and 5%. The wide gap between the two fuel prevalence measures depends on the persistence of fuel poor households across deciles in the case of the indicator based on actual budget shares, $FPP^{abs}_{f,r}$, which cannot distinguish whether energy expenditure share above the threshold is for purchasing necessary goods or other non-necessary energy services. When this factor is accounted for ($FPP^{pbs}_{f,r}$), fuel poverty prevalence at country level is lower and it gathers only in the first decile (Figure 3). In the poorest decile, the $FPP^{pbs}_{f,r}$ is 45% for all energy, 52% for heating and 47% for electricity.

[11]The two poverty prevalence indicators are described in Section 3.2

Figure 3: Fuel poverty prevalence and severity across deciles and fuels. Boxplots show heterogeneity across regions.



4.2 First-order distributional impacts of climate-induced energy shocks

The direction and the magnitude of the impacts of climate change on energy demand depend on geographic location.[12] Climate change reduces the frequency of cold days, and therefore the needs for heating especially at at higher latitudes, whereas hot days occur more often, making cooling services needed more. Climate-induced shocks unequivocally reduce the use of heating fuels such as natural gas (from -11% to -45%)

[12] All households within the same region receive the same shock, in percentage changes, which modifies the 2007 consumption of electricity, gas and petroleum products.

and petroleum products (from -10% to -41%) under moderate warming. Reductions are more pronounced under vigorous warming (gas, -26% and -69%, petroleum products, -23% and -66%). Impacts on electricity go in the opposite direction, and range between 0% and +16% (0% and +28%) under moderate (vigorous) warming. Basilicata, Sicily, Umbria, Apulia, and Emilia-Romagna face the largest percentage increase in electricity demand.

Figure 4 shows the first-order effect of global warming on energy expenditure, with details on the main fuels used for heating and cooling across households and RCPs. Energy expenditure per adult equivalent unequivocally declines on average by 9.7% in RCP4.5 and 14.7% in RCP8.5, respectively between -3 and -4 euros per month. Looking at regional level, under moderate (intense) global warming, Piedmont is gaining the most, as energy expenditure falls by 25.3% (30.3%) compared to Sicily where expenditure drop by 2.0% (2.2%). Natural gas is the most relevant fuel used in 80.5% of heating systems and its variations drive the overall reduction in energy consumption. On average monthly expenditure per adult equivalent drops by 23.6% (36.7%) in the moderate (extreme) scenario. Gas consumption for heating shrinks between 43.6% (68.8%) in Calabria and 11.3% in Abruzzo (25.2% in Umbria). Electricity expenditure per adult equivalent rises on average by 5% (8.2%) with moderate (intense) climate change, around 0.42 (0.7) euros per month. The largest increase is observed in Sicily and Basilicata, respectively of 16.3% (27.6%) and 12.8% (25.9%) under moderate (intense) global warming, because of the net increase in electricity demand and the relatively large share of electricity in these regions. Milder regions, such as Emilia-Romagna and Lombardy, also show significant increases in electricity demand due to the relatively large share of AC, especially in large urban centers. Figure 4 also highlights the much larger heterogeneity characterizing impacts on natural gas as opposed to electricity, which with the exception of southern regions, showing a much smaller variation.

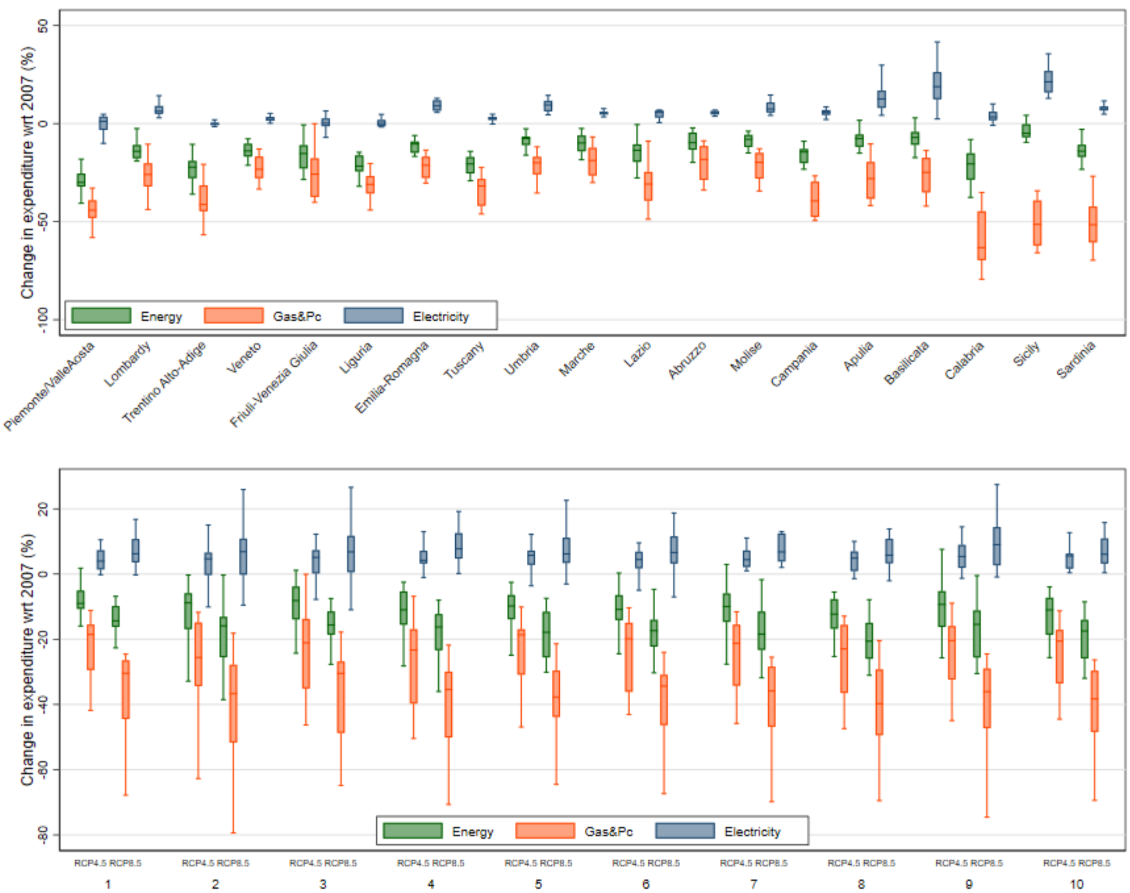
Looking at the distribution of climate change impacts by decile, the bottom panel in Figure 4 shows variation across households and Italian regions. Benefits - measured in terms of reduced energy expenditure - are larger among the richest layers of the population, ranging between a reduction of 13.5% (20.3%) in energy expenditure under moderate (intense) global warming compared to 6.9% (10.7%) among the poorest 1^{st} decile. These changes imply a discount in the energy bill of 4.5(6.8) euros per month and per adult equivalent in 10^{th} decile and of 0.7 (1.1) euros in the 1^{st} decile. This result mainly depends on the interaction of different impacts on heating and for cooling across deciles. Gas bills drop by 25.2% (38.5%) in the richest decile and by 25% (40.5%) in the poorest one, therefore slightly favouring the poorest layers of population. Smaller, but regressive is instead the influence on electricity expenditure that increases by 6.5% (11.3%) in the 1^{st} decile and by 3.9% (6.3%) in the 10^{th} decile.

The first-order implications of climate change impacts on fuel poverty are synthesized in Table 1 showing the number of fuel poor households in each region in the base year (computed according to Equation 7) and how the figures changes under climate change.

Overall, climate change impacts reduce the number of energy poor households across Italian regions and across global warming scenarios (-104 thousands under RCP4.5 and -189 thousands under RCP8.5). This result can be decomposed into a strong reduction of heating fuel poverty (-794 thousands under RCP4.5 and around -1 million under RCP8.5) and a rise in cooling fuel poor households (+249 thousands under RCP4.5 and +446 thousands under RCP8.5[13]. At regional level, Piedmont and

[13]The number of energy poor households are not the sum of fuel-specific figures because the poverty thresholds are specified independently for heating, electricity and overall energy.

Figure 4: First-order effects of climate change on energy expenditure per adult equivalent (pae) by region. Boxplots show the variation across deciles and RCPs by region (top) and by decile (bottom).

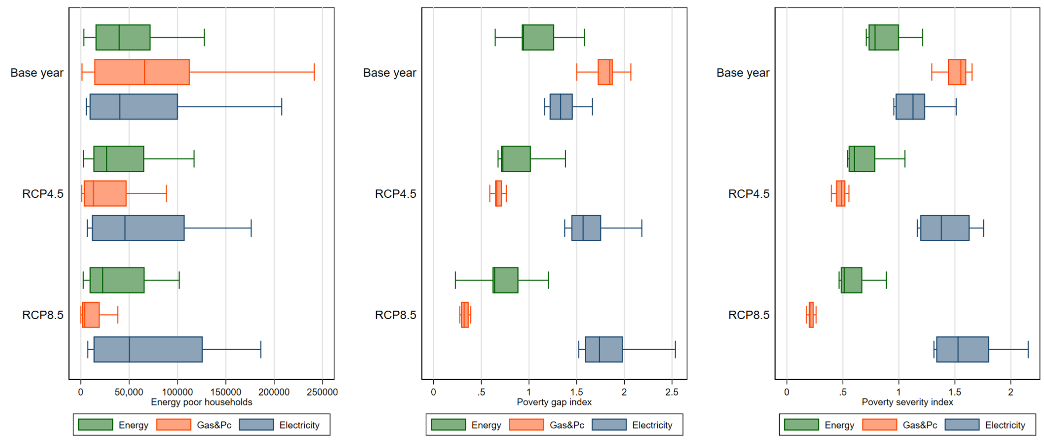


Tuscany (Apulia) are the regions benefiting the most from the moderate (intense) climate shocks with a reduction of 17 thousands (26 thousands) energy poor households due to a contraction of gas expenditure in this area. In Sicily (Emilia-Romagna) energy poverty slightly increases: +18 thousands (+8 thousands) fuel poor household under moderate (intense) climate change. This aggregate result combines a reduction in gas-poor households of -210 (-82) thousands and a rise in electricity-poor households of +103 (+46) thousands. Figure 5(left) synthesises regional energy poverty count across scenarios and fuels. Figure 5(center) highlights a decreasing pattern in the poverty gap index due to climate change. The strongest reduction is observable under RCP4.5 and is led by the drop of number of heating-fuel-poor and their larger distance from the poverty threshold. The effect is mitigated by the further increase in mean temperature that characterizes the RCP8.5. As similar pattern is observable for the poverty severity index (Figure 5 - right).

Table 1: Number of energy poor households in the base year a and first-order effect of climate change on these figures, by region and scenario. Unit: thousands.

	Energy			**Gas&Pc**			**Electricity**		
	2007	**RCP4.5**	**RCP8.5**	**2007**	**RCP4.5**	**RCP8.5**	**2007**	**RCP4.5**	**RCP8.5**
	# poor	**Δ wrt 2007**	**Δ wrt 2007**	**# poor**	**Δ wrt 2007**	**Δ wrt 2007**	**# poor**	**Δ wrt 2007**	**Δ wrt 2007**
Piedmont/AostaValley	41	-17	-16	102	-73	-86	100	7	13
Lombardy	105	-12	-12	113	-60	-84	113	22	35
Trentino Alto-Adige	9	-1	-2	17	-13	-16	9	0.8	2
Veneto	40	-5	-12	117	-47	-82	40	13	20
Friuli-Venezia Giulia	35	-8	-22	66	-25	-53	40	0.9	3
Liguria	39	-9	-17	42	-30	-35	39	3	3
Emilia-Romagna	58	0	8	120	-54	-82	80	22	46
Tuscany	41	-17	-20	69	-50	-60	13	4	6
Umbria	7	-1	-3	14	-7	-10	6	1	2
Marche	4	0	0	1	0	0	7	0	0
Lazio	72	-7	-9	106	-58	-86	106	9	21
Abruzzo	16	-2	-7	5	-0.9	-3	9	2	4
Molise	3	-0.4	-0.5	8	-5	-6	8	0.7	2
Campania	125	-13	-24	66	-53	-63	160	16	26
Apulia	128	-11	-26	154	-66	-117	73	20	40
Basilicata	15	-2	-0.9	4	-2	-4	17	8	14
Calabria	29	-4	-6	16	-15	-16	40	5	10
Sicily	260	18	-4	241	-210	-241	208	103	187
Sardinia	44	-13	-14	30	-27	-30	49	11	13
ITALY	***1073***	***-104***	***-189***	***1292***	***-794***	***-1074***	***1116***	***249***	***446***

Figure 5: Energy poor households (count), energy poverty gap and severity indices in the base year and climate change scenarios: First-order effects. Boxplots show variation across regions.



4.3 Second-order macroeconomic and distributional impacts

The Italian economy that in 2050 will be affected by the climate shocks will have a different structure compared to the base year 2007. We project a future baseline (BAU) in 2050 without climate policies and climate impacts as a continuation of historical trends of Gross Domestic Product (GDP) and population growth rates as described in the socioeconomic scenario Shared Socioeconomic Pathway SSP2 (O′Neill *et al.* , 2017).[14] In 2050, on average, the aggregate demand of all goods across Italian regions increase by 51% and aggregate prices decrease by 33%. We use the downscaling module described in Section 3.3 to evaluate how the aggregate changes in prices and quantities affect individual households' expenditure patterns, taking into account variations across regions and assuming all other characteristics of households remain constant. Expenditure deciles in 2050 are then redefined on

[14]The calibration process is described in the Appendix 4

the basis of the updated expenditure distribution and consumption patterns are compared to those of the base year 2007. Baseline energy expenditure goes up in most regions, driven by an increase in electricity expenditure across all regions (Figure A5). Sicily and Sardinia experience the highest reduction in energy expenditure driven by the prevailing contraction in heating fuel demand. In the bottom decile, baseline energy expenditure increases on average by 5.3% and by 27% in the top decile (Figure A6). Disbursements for electricity follow a similar trend but stronger in magnitude, +31.3% in the 1st decile and +74.3% in 10th decile. The expenditure on heating fuels drops the most in the poorest decile (-24%) and slightly increases at the 10th decile (2.1%).[15]

Figure 6 (top panel) describes how energy expenditure changes in each region and across impact scenarios with respect to the baseline in 2050. In 2050 most regions increase the expenditure on electricity and reduce that in natural gas and petroleum products. There is diversity across regions, with Basilicata increasing electricity expenditure the most (+13%) and Trentino Alto-Adige reducing it (-6.9%). Climate change has a dampening effect on future energy expenditure expenditure because of a generalised contraction in heating fuel demand, as observed in the FO effect assessment (Section 4.2). Climate change impacts have a regressive effect (Figure 6-bottom panel) and they reduce energy consumption more among the top deciles than among the bottom ones (-5.6% in the 1st decile and -10.5% in the 10th decile). The net effect is driven by the regressive effects on electricity expenditure, while climate change impacts on heating fuel expenditure are progressive.

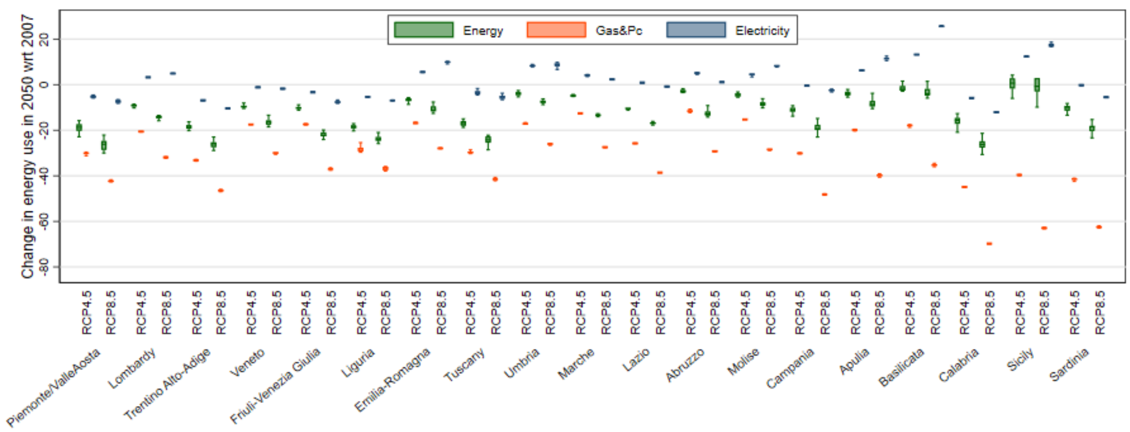
[15] In the baseline scenario, there are no specific assumptions about the evolution of expenditure distribution, therefore fuel poverty prevalence does not change up to 2050 at aggregate level and variations in the range -1.4% and 1.5% percentage points with respect to 2007 are observed at regional level. The number of poor instead rises due to population growth.

Under moderate (intense) climate change the number of poor households will be lower by 283 (410) thousands with respect to 2050 BAU (Figure 7-left and Table 2). Climate change impacts reduce the number of heating fuel poor households while increase that of electricity poor households, but the former effect prevails because the share of heating fuels on final energy is larger. Poverty gap and severity indices show similar patterns, and their values reduce under climate change for energy and heating fuels but increase for electricity (Figure 7 - center and left).

Table 2: Additional number of energy poor households in the baseline and first-order effect of climate change on these figures, by region and scenario. Unit: thousands.

	Energy				**Gas&Pc**				**Electricity**			
	2007	**2050**	**RCP4.5**	**RCP8.5**	**2007**	**2050**	**RCP4.5**	**RCP8.5**	**2007**	**2050**	**RCP4.5**	**RCP8.5**
	# poor		**Δ wrt BAU**		**# poor**		**Δ wrt BAU**		**# poor**		**Δ wrt BAU**	
Piedmont/AostaValley	41	83	-28	-34	102	143	-94	-111	100	137	-32	-37
Lombardy	105	181	-27	-28	113	163	-88	-122	113	163	18	21
Trentino Alto-Adige	9	19	-7	-10	18	27	-20	-24	9	13	-3	-4
Veneto	40	51	-14	-21	117	171	-68	-120	40	60	-2	-2
Friuli-Venezia Giulia	35	53	-20	-36	66	88	-33	-70	40	56	-8	-13
Liguria	39	47	-18	-23	42	55	-43	-47	39	50	-7	-7
Emilia-Romagna	58	90	-13	-13	120	180	-90	-129	80	115	27	45
Tuscany	41	66	-38	-51	69	104	-75	-91	13	21	-6	-6
Umbria	7	8	-3	-4	14	19	-9	-13	6	8	1	1
Marche	4	10	0	-2	1	2	0	0	7	10	0	0
Lazio	72	156	-26	-53	106	162	-99	-132	106	162	0	-7
Abruzzo	16	24	-1	-11	5	8	-1	-5	9	13	3	0
Molise	3	5	2	1	8	10	-6	-8	8	11	0	1
Campania	125	209	-21	-47	66	91	-73	-87	160	224	2	-9
Apulia	128	162	-20	-31	154	210	-89	-162	73	100	25	42
Basilicata	15	20	5	12	4	6	-2	-5	17	24	11	18
Calabria	29	32	-7	-12	16	19	-19	-19	40	51	-18	-23
Sicily	261	335	-40	-32	241	310	-271	-309	208	263	102	149
Sardinia	44	46	-6	-16	30	41	-37	-41	49	75	0	-12
ITALY	***1073***	***1595***	***-283***	***-410***	***1292***	***1809***	***-1119***	***-1498***	***1116***	***1555***	***114***	***156***

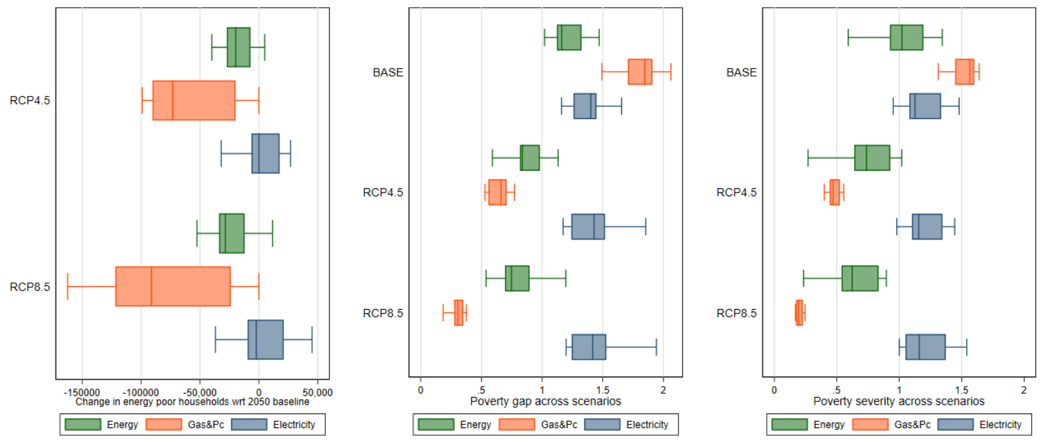
Figure 6: Climate-induced changes in household energy expenditure across regions (top) and expenditure deciles (bottom) relative to 2050 baseline.



4.4 Assessment of the higher-order, macroeconomic adjustments

The higher-order (HO) effects induced by price-driven general equilibrium adjustments slightly mitigate the overall direct reduction in energy expenditure observed as first-order (FO) effects, from the range -12% to -18% to the range -10% to -16%.

Figure 7: Climate-induced changes in energy poor households (count), poverty gap and severity by scenario compared to the 2050 BAU across regions.

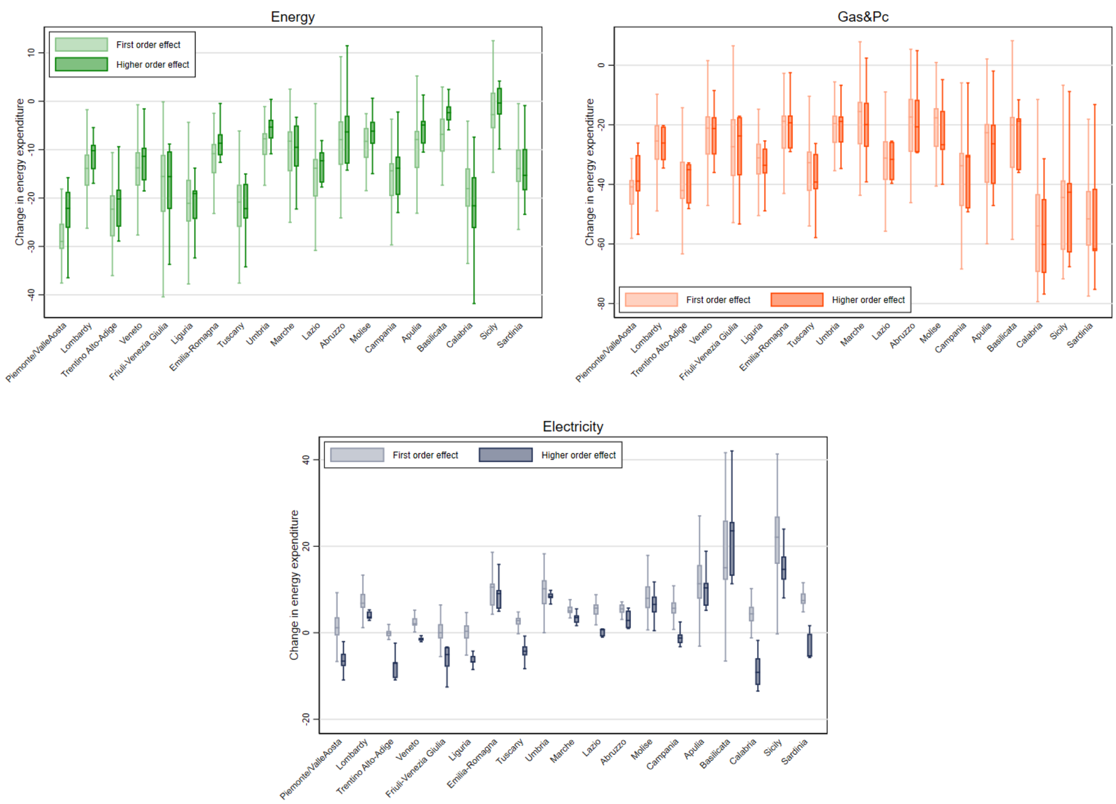


Higher-order adjustments mostly affect electricity expenditure, which is significantly reduced from 5-8% to 1.3% in both climate change scenarios. Moving to the scenarios with a higher degree of global warming amplifies these results for most of regions.

While FO effects only account for quantity changes, HO effects take into account the further adjustments induced by price changes - induced by the climate shocks - and the budget constraints faced by households; the total (fuel and other goods) expenditure is not unconstrained as in the FO impact case but need to be consistent with model results. For this reason, we observe that in some region the energy expenditure is lower under HO impact case that required to adapt to climate change (FO impact case).

Differences between FO and HO impacts at decile level in Figure 9 are negligible. Even though HO adjustments slightly reduce the extent of the regressivity, climate change impacts remain regressive and the overall reduction in energy expenditure remains slightly larger in the highest deciles. The result is amplified under

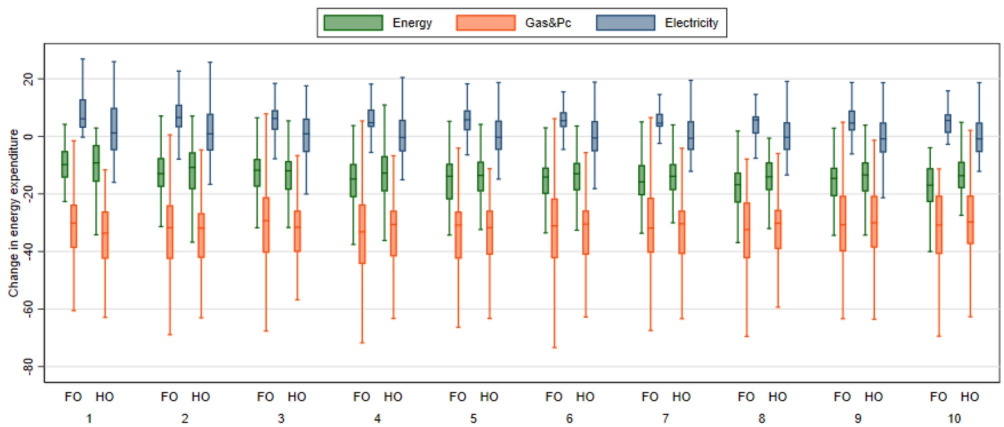
Figure 8: First and higher-order effects of climate change on households' energy expenditure per adult equivalent (pae) by region. Boxplots show variation across deciles and RCPs within the same region.



RCP8.5. Climate-induced variation in heating fuel expenditure becomes more progressive when HO effects are taken into account, especially with a more intense global warming. The change in electricity expenditure, which is regressive considering both first and higher-order effects, is less regressive in the second case.

When the higher-order effects are accounted for, the average number of energy poor households due to climate change is lower compared to first-order estimates by 179 (221) thousands under moderate (vigorous) climate change. With respect to

Figure 9: First- and Higher-order effects of climate change impacts on household energy expenditure per adult equivalent in 2050, by decile. Boxplots show variation across regions and RCPs within the same decile. Percentage changes show variation compared to 2007 (FO) and to the 2050 baseline (HO).



first-order impacts, heating fuel poor households fall by 325 (424) thousands while electricity poor change between -135 and -290 thousands.

This small change in the number of energy poor households at country level hides wider variations at regional level. Figure 10 maps the change in fuel poor households at regional level in 2050 (RCP4.5) using first- and higher-order estimates (see Figure A8 for RCP8.5 results). Under the higher-order effect case, Basilicata experiences a rise in energy poor households (+5 thousands) as well as Molise (+2 thousand), i.e. the macroeconomic adjustments worsen the impact of climate changes increasing the share of energy expenditure for several households. We see an opposite pattern in Sicily, a reduction of energy poor population (-40 thousand poor) when higher-order effects are taken into account with respect to first-order effect case (+18.4 thousand poor). This result must be cautiously judged: in our framework energy poverty prevalence is strictly related to the expenditure share used to purchased necessary fuel quantity. In Sicily, these share shrinks because the increase of energy prices determines a more than proportional reduction of fuel consumption, i.e households can not afford anymore to buy the energy necessary to adapt to climate change and they reduce it. In Sicily, we observe lower energy poverty prevalence in the higher-order effect case, because households are force to adapt partially not fully to climate change. The partial adaptation will imply the persistence of residual economic and health costs for households.

The maps of electricity show that several regions experience a drop in poverty when higher-order effects are accounted for: Piedmont/Aosta Valley, Veneto, Liguria, Tuscany, Lazio, Campania, Basilicata, Apulia and Sardinia. Moreover, in Liguria and Aosta Valley, we observe only partial adaptation under higher-order effect case due to the high rise of electricity prices. The highest increase in electricity poor households is observed in Sicily, Emilia-Romagna, Apulia and Lombardy (respectively 102, 27, 25 and 18 thousand poor). These results are coherent with the heterogeneous impacts of climate change on electricity expenditure shown in Figure 6 and depend on the magnitude of impact on energy consumed and the consequent region-specific adjustments of equilibrium prices. Macroeconomic adjustments tend to increase the number of energy poor in the regions where climate-induced electricity goes up the most and where the share of electricity increases relatively more in the future energy mix. Consider for example Sicily and Basilicata. These two regions face similar climate shocks and have similar first-order effects on electricity expenditure with different impacts one energy poor population which rises more in Sicily than in Basilicata). Yet, the higher-order adjustments are quite different, Basilicata increases electricity expenditure with respect to the first-order effect case, Sicily reduces it (Figure 6 - bottom). This is the result of slightly increasing electricity prices in Basilicata and decreasing ones in Sicily under taking place in the CGE model. The outcome in terms of energy poverty is again heterogeneous: a stable situation for Sicily with respect to the first-order effect case and the increase of poverty prevalence in Basilica (Figure 10).

Figure 11 shows how accounting for macroeconomic adjustments increases the dispersion of the climate impacts on energy poor households, mostly due to the increase in the dispersion of electricity poor.

Figure 10: Climate-driven change in energy poor households. First and higher-order effects, RCP4.5

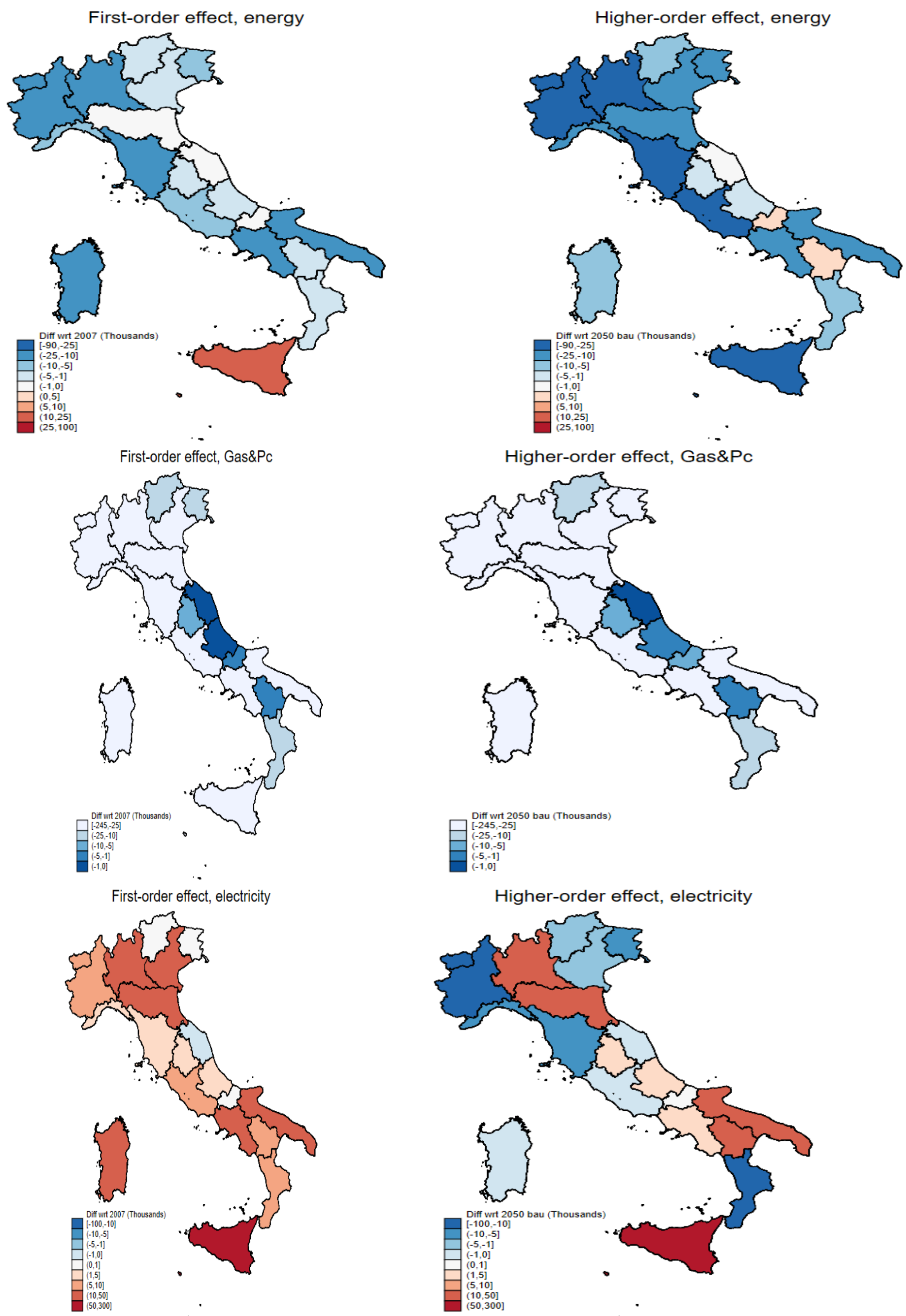
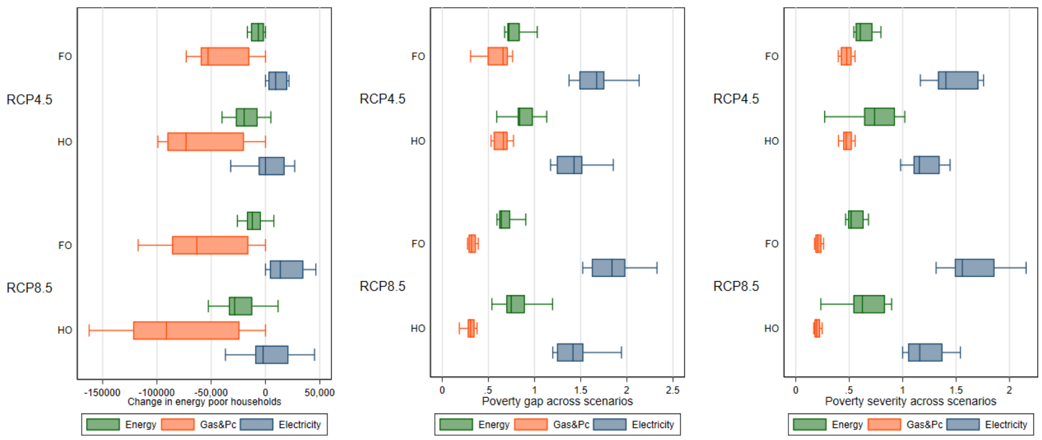


Figure 11: First-order (FO) and higher-order (HO) changes in climate-induced poor households, poverty gap and severity indices, by scenario.



5 Conclusions

We analyze the distributional implications of climate-induced changes in temperature around 2050 on household energy expenditure. We compare the response of different Italian regions, characterized by various climate conditions, and of different income groups. We also derive the implications on selected expenditure-based indicators of energy poverty. We evaluate to what extent macroeconomic adjustments in prices mitigate the direct impacts of climate change.

The first-order impacts of climate change are slightly regressive and this results from the combination of rich households reducing expenditure on heating fuels more than the poor, less affluent households increasing electricity expenditure relatively more. Even within income deciles results are highly heterogeneous, and whether a household increases or decreases her total energy expenditure depends on the size of the shock, on the climate conditions, as well as on the energy mix. On average, households living in southern regions, such as Sicily, increase electricity and cut on heating fuels the most.

Price changes and households' budget constraints, which characterise the higher-order effect case, tend to mitigate the direct impact of climate-induced shocks on expenditure, and lead to more moderate increase and reductions in electricity and heating fuel expenditure, respectively. These higher-order adjustments do not fully offset the regressivity of climate change impacts, which persists. Energy expenditure is a small fraction of the overall households' budget, and therefore the general equilibrium effects are moderate.

Despite the net reduction in the number of energy poor observed in the higher-order effect case, there are important distributional implications even within Italy. Hot regions, such as Molise or Basilicata, for the characteristic of their economy are more likely to experience an increase in the number of energy poors. In Sicily, higher-order effects reduce the number of energy poors, but mask a lower level of adaptation and residual damages due to the stringency of budget constraints.

Overall results on aggregate indicators, such as nation-wide energy poverty, mask the fact that household energy poverty can be heterogeneous across fuels, deciles and regions. Climate change and the related increase in electricity poor households highlights a new emerging risk for those households who will be exposed to more heat and will have to devote a higher share of their income to electricity expenditure (becoming poor) or will not being able to purchase the cooling services needed to fully protect themselves. Results on electricity poverty are unequivocal and tend to persist in most regions even when considering the higher-order adjustments brought about by price changes. In addition, in few region, we also observe insufficient adaption actions despite the decrease of fuel poverty prevalence.

Whereas the distributional implications of a carbon tax can be addressed by designing appropriate revenue recycling schemes, climate-driven energy shocks do not generate revenue and hinge upon characteristics such as geography and housing conditions that are more difficult to address. It is therefore important to accounting for the distributional consequences of climate change impacts when designing socially-acceptable climate policies. For example, the comparison of the two warming scenarios analyzed in this study indicates that, even moderate climate change mitigation policy reduces the risk of electricity-related energy poverty by 42-197 thousands in 2050.

It is also important to clarify that this paper looks at how households with different income levels and located across different regions respond to temperature shock by changing their energy expenditure. Therefore, it looks at the distributional implications of adaptation, without discussing the potential uneven distribution of the residual damages on health. We have highlighted the difference between first-order changes, which represent the full potential adaptation needs without constraints and price feedback, and higher-order changes, which instead represent adaptation constrained by budget considerations and price changes. Under higher-order effects, the extent of adaptation is smaller, pointing at the existence of residual impacts and therefore other types of costs (e.g. health costs) that we are not able to account for in the present framework.

The major caveat of this paper is the use of an arithmetic sequential micro-simulation approach that simply downscales the aggregate second-order changes in prices induced by behavioural adjustments of the representative consumer and producer. In this framework, different income groups do not respond to the climate shocks in a heterogeneous way. To what extent including heterogeneous behavioural adjustments across household groups widens the difference between first- and second-order climate change impacts is a topic to be explored in future research.

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Annex

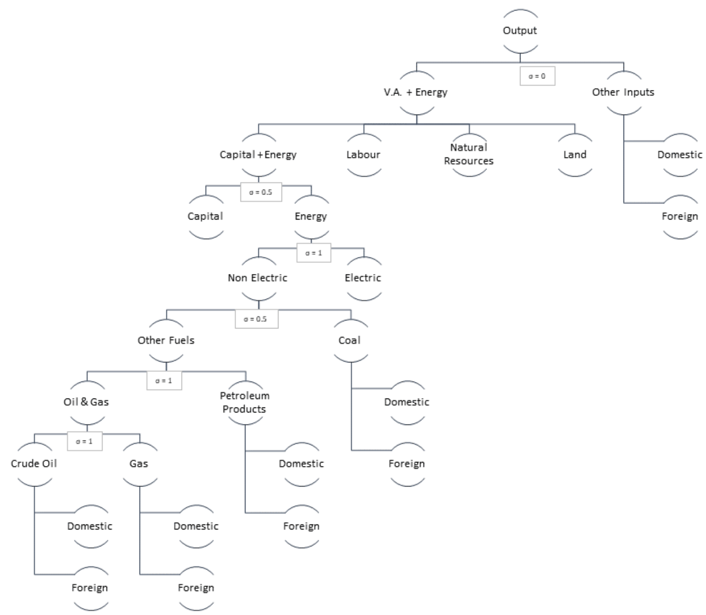
1 ICES model description

ICES is a recursive-dynamic multiregional Computable General Equilibrium (CGE) model developed to assess the impacts of climate change on the economic system and to study mitigation and adaptation policies (Eboli *et al.* , 2010). The core structure of ICES derives from the GTAP-E model (Burniaux & Truong, 2002), which in turn is an extension of the standard GTAP model (Corong *et al.* , 2017). The General Equilibrium framework makes it possible to characterise economic interactions of agents and markets within each country (production and consumption) and across countries (international trade). Within each country the economy is characterised by a number of industries n, a representative household and the government. Industries are modelled as representative cost-minimizing firms, taking input prices as given. In turn, output prices are given by average production costs. The production functions (Figure A1) are specified via a series of nested Constant Elasticity of Substitution (CES) functions. In the first nest, a Value-Added-Energy nest ($QVAEN$) (primary factors, i.e. natural resources, land and labour, and a Capital+Energy composite), is combined with intermediates (QF), in order to generate the output. Perfect complementarity is assumed between value added and intermediates. This implies the adoption of a Leontief production function. For sector i in region r final supply (output) results from the following constrained production cost minimization problem for the producer:

$$\begin{aligned} min \quad & PVAEN_{i,r} * QVAEN_{i,r} + PF_{i,r} * QF_{i,r} \\ & s.t. \quad Y_{i,r} = min(QVAEN_{i,r}, QF_{i,r}) \end{aligned}$$

where $PVAEN$ and PF are prices of the related production factors.

Figure A1: ICES production tree



The second nested-level in FigureA1 represents, on the left hand side, the value added plus energy composite ($QVAEN$). This composite stems from a CES function that combines four primary factors: land ($LAND$), natural resources (NR), labour (L) and the capital-energy bundle (KE) using σ_{VAE} as elasticity of substitution. Primary factor demand on its turn derives from the first order conditions of the following constrained cost minimization problem for the representative firm:

$$min \quad P_{i,r}^{Land} * LAND_{1,r} + P_{i,r}^{NR} * NR_{i,r} + P_{i,r}^{L} * L_{i,r} + P_{i,r}^{KE} * KE_{i,r}$$

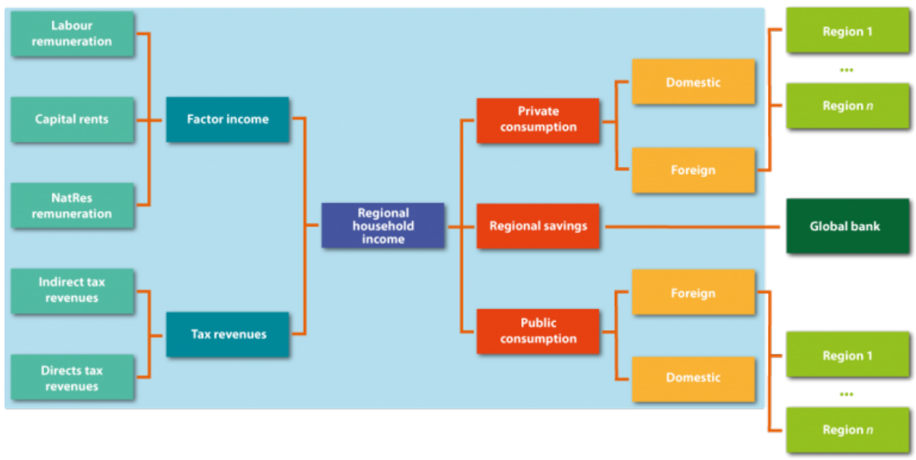
$$s.t. \quad QVAEN_{i,r} = (LAND_{i,r}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}} + NR_{i,r}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}} + L_{i,r}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}} + KE_{i,r}^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}})^{\frac{\sigma_{VAE}-1}{\sigma_{VAE}}}$$

On its turn, the KE bundle combines capital with a set of different energy inputs. This is peculiar to GTAP-E and ICES. In fact, energy inputs are not part of the intermediates, but are associated to capital in a specific composite. The energy bundle is modelled as an aggregate of electric and non-electric energy carriers. In this version of the model, Electricity is a heterogeneus sector including electricity produced with fossil and clean energy sources. The Non-Electric bundle is a composite of sub-nests Coal, Natural Gas, Crude Oil and Petroleum Products. All elasticities regarding the inter-fuel substitution bundles are those from GTAP-E (Burniaux & Truong, 2002).

The demand of production factors (as well as that of consumption goods), can be met by either domestic or foreign commodities which are however not perfectly substitute according to the "Armington" assumption. In general, inputs grouped together are more easily substitutable among themselves than with other elements outside the nest. For example, the substitutability across imported goods is higher than that between imported and domestic goods. Analogously, composite energy inputs are more substitutable with capital than with other factors. In ICES, two industries are treated in a special way and are not related to any country, viz. international transport and international investment production. International transport is a world industry, which produces the transportation services associated with the movement of goods between origin and destination regions. Transport services are produced by means of factors submitted by all countries, in variable proportions. In a similar way, a hypothetical world bank collects savings from all regions and allocates investments in order to achieve equality in the absolute change of current rates of return.

Figure A2 describes the main sources and uses of regional income. In each region, a representative regional household receives income, originated by the service value of national primary factors[16] (natural resources, land, labour, and capital), and by direct and indirect taxation. The regional income is the constraint in the regional household utility maximization (Cobb-Douglas) from consumption, government spending and savings.

Figure A2: Sources and uses of regional household income



Public consumption is split into a series of alternative consumption commodities according to a Cobb-Douglas specification. However, almost all public expenditure is concentrated in the specific sector of Non-market Services, including education, defence and health. Private consumption is analogously addressed towards alternative goods and services including energy commodities, that can be produced domestically or imported. The functional specification used at this level is the Constant Difference in Elasticities (CDE) form: a non-homothetic function, which is used to account for possible differences in income elasticities for the various consumption goods.[17]

[16]Capital and labour are perfectly mobile domestically but immobile internationally (investment is instead internationally mobile). Land and natural resources, on the other hand, are industry-specific.

[17]Hanoch′s constant difference elasticity (CDE) demand system (Hanoch, 1975) has the follow-

The recursive-dynamic feature is described in Figure A3. Starting from the picture of the world economy in the benchmark year, by following socioeconomic (e.g. population, primary factors stocks and productivity) as well as policy-driven changes occurring in the economic system, agents adjust their decisions in terms of input mix (firms), consumption basket (households) and savings. The model finds a new general (worldwide and economy-wide) equilibrium in each period, while all periods are interconnected by the accumulation process of physical capital stock, net of its depreciation. Capital growth is standard along exogenous growth theory models and follows:

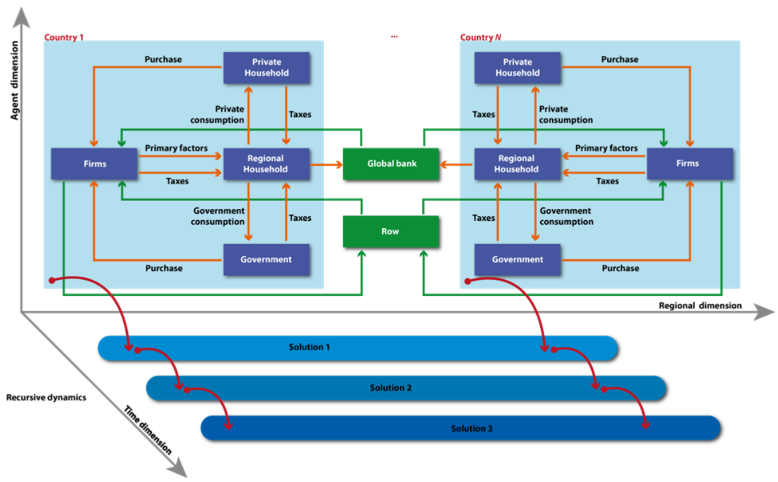
$$Ke_r = I_r + (1-\delta)Kb_r$$

where Ke_r is the end of period capital stock, Kb_r is the beginning of period capital stock, δ is capital depreciation and I_r is endogenous investment. Once the model is solved at a given step t, the value of Ke_r is stored in an external file and used as the beginning of period capital stock of the subsequent step t+1. The matching between savings and investments only holds at the world level; a fictitious world bank collects savings from all regions and allocates investments following the rule of highest capital returns.

As with capital, at each simulation step the government net deficit at the end of the period is stored in an external file and adds up to next year debt.

ing formulation: $1 = \sum B_i U^{Y_i R_i} (\frac{P_i}{X})^{Y_i}$ where U denotes utility, P_i the price of commodity i, X the expenditure, B_i are distributional parameters, Y_i substitution parameters, and R_i expansion parameters. The CDE in principle does not allow to define explicitly direct utility, expenditure or indirect utility functions. Accordingly, also explicit demand equations could not be defined. Fortunately, in a linearized equation system such as that used in GTAP, it is possible to obtain a demand function with price and expenditure elasticities.

Figure A3: Recursive-dynamic feature of ICES model



1.1 Database

ICES is a Computable model: all the model behavioural equations are connected to the GTAP 8.1 database (Narayanan & McDougall, 2012), which collects national social accounting matrices from all over the world and provides a snapshot of all economic flows in the benchmark year (57 economic sectors and 134 countries). We aggregate countries into 19 regions and macro-regions, singling out only key EU countries (Table A1). Regarding Italy, we used the economic database at NUTS-2 level (20 regions) developed in Standardi *et al.* (2017) and Carrera *et al.* (2015). Energy volumes and CO_2 emission for Italy are allocated to the different regions using economic value flows, and therefore assuming no price differentiation across Italian regions. The regional detail characterizing the final database is displayed in Table A1.

Table A1: Regional aggregation

N	Country/Region	N	Country/Region	N	Country/Region	N	Country/Region
1	Asia	11	ITA - ValAosta	21	ITA - Lazio	31	Spain
2	LACA	12	ITA - Lombardia	22	ITA - Abruzzo	32	Sweden
3	OECD	13	ITA - TrentAdige	23	ITA - Molise	33	UK
4	Benelux	14	ITA - Veneto	24	ITA - Campania	34	RoEU
5	Czech_Rep	15	ITA -FriuliGiulia	25	ITA -Puglia	35	RoEurope
6	Finland	16	ITA- Liguria	26	ITA -Basilicata	36	MENA
7	France	17	ITA- EmiRom	27	ITA -Calabria	37	Africa
8	Germany	18	ITA- Toscana	28	ITA -Sicilia	38	RoW
9	Greece	19	ITA- Umbria	29	ITA -Sardegna		
10	ITA- Piemonte	20	ITA -Marche	30	Poland		

2 Physical climate change impacts

Physical climate change impacts represent ex-ante impacts prior any direct of indirect adaptation measure or behavioural change, such as price-induced substitution and adjustments (Sue Wing, Fisher-Vanden 2013). They can be estimated using either bottom-up engineering models that are generally applied to specific sectors or regions or top-down empirical approaches, which combine historically-based elasticities with future, long-term scenarios.

Here we employ the ex-ante energy demand shocks from De Cian & Sue Wing (2017), which uses a panel data of national energy demand, energy prices, income per capita, and weather covariates (temperature and humidity) for hundred of countries over the period 1970-2014 to derive income elasticities and temperature semi-elasticities of sectoral energy demand in tropical and temperate regions for three energy carriers (electricity, natural gas, petroleum products) in five sectors (residential, commercial, industry, agriculture, transport). Semi-elasticities to hot days

(days with average mean temperature above 27.5°C) and cold days (days with average mean temperature below 12.5°C) are combined with projected changes in meteorology simulated by runs of the CMCC-CM Earth System Model (Scoccimarro *et al.* , 2011) as follows:

$$\phi^{\text{Climate}}_{c,f,s} = \exp\left\{ \sum_{j=1}^{J} \widehat{\gamma}^{T}_{j,f,s} \left(\widetilde{\varepsilon}^{T}_{j,c,\text{Future}} - \widetilde{\varepsilon}^{T}_{j,c,\text{Current}} \right) \right\} \tag{9}$$

where $\widehat{\gamma}^{T}_{j,f,s}$ are the estimated semi-elasticities of energy demand to different temperature intervals j, $\widetilde{\varepsilon}^{T}_{j,c,\text{Current}}$ and $\widetilde{\varepsilon}^{T}_{j,c,\text{Future}}$ is population-weighted temperature exposure over the current (2006-2015) and future (2046-2055) period for grid cell c, fuel f, and sector s. They describe the percentage change in sectoral demand for electricity, natural gas, heating oil due to changes in the frequency of hot and cold days. Here we only focus on the residential sector.

Gridded shocks have been aggregated to the regional administrative units of the Italian household survey and of the CGE model (see Section 2.3) of NUTS2 [18]. NUTS2-level climate shocks are the mean of the shocks across all grid-cells belonging to that specific NUTS region, $\phi^{\text{Climate}}_{r,f,s}$, where r is the NUTS2 region:

$$\phi^{\text{Climate}}_{r,f,res} = \frac{\sum_{c \in r} \phi^{\text{Climate}}_{c,f,res}}{N_{c \in r}} \tag{10}$$

where N_c is the number of grid cells in NUTS2 region r, and Climate is the climate scenario, Climate $\in \{RCP4.5, RCP8.5\}$, see Figure A4.

[18] We used the shape file for the political borders within Europe at NUTS2 to extract only the grid-cells of interest with the R package sp, `https://www.rdocumentation.org/packages/sp/versions/1.3-1/topics/sp`. Grid cells have been aggregated using the simple mean function. Grid-level impacts have been converted to spatial points, which have then being intersected with the EU NUTS2 polygons using the point in polygon R function.

3 Downscaling module

Applying the macroeconomic changes generated by the ICES model (we use an over-bar to distinguish variables output of ICES model from the others, and small letters to denote percentage changes) to the expenditure of all households in HBS, $EXP^{\text{HBS}}_{h,i,r}$

$$EXP^{\text{2050, scen}}_{h,i,r} = EXP^{\text{HBS}}_{h,i,r} \times (1 + \overline{qp}^{\text{scen}}_{i,r}/100) * (1 + \overline{pp}^{\text{scen}}_{i,r}/100)$$

would determine a discrepancy between the aggregate changes in household expenditure ($exp^{\text{2050, scen}}$) and the percentage variations observed in the ICES model ($\overline{exp}^{\text{2050, scen}}$):

$$exp^{\text{2050, scen}} \neq \overline{exp}^{\text{2050, scen}}$$

as well as a discrepancy in 2050 levels

$$EXP^{\text{2050, scen}} \neq \overline{EXP}^{\text{2050, scen}} \text{where } EXP^{\text{2050, scen}} = \sum_r \sum_h \sum_i EXP^{\text{2050, scen}}_{h,i,r}$$

The inconsistency when computing aggregate values emerges also at the regional level. The downscaling module minimizes this discrepancy transforming the 2050 expenditure at household level ($EXP^{\text{2050, scen}}_{h,i,r}$) into an adjusted one ($\widetilde{EXP}^{\text{2050, scen}}_{h,i,r}$) which satisfies the following constraint:

$$\sum_r \sum_h \sum_i \widetilde{EXP}^{\text{2050, scen}}_{h,i,r} = \overline{EXP}^{\text{2050, scen}}$$

The expenditure reconciliation is realized using the cross entropy maximization method (McDougall, 1999; Golan & Judge, 1996). We start by defining the normalised expenditure matrix $\alpha^{\text{scen}}_{h,i,r}$:

$$\alpha_{h,i,r} = \frac{EXP^{2050,\text{ scen}}_{h,i,r}}{\sum_h \sum_i EXP^{2050,\text{ scen}}_{h,i,r}} \tag{11}$$

The cross entropy method consists in minimizing the distance between a new matrix $\widetilde{\alpha}_{h,i,r}$ and the original one $\alpha_{h,i,r}$ (equation 12), respecting consistency constraints on column (equation 14) and row total (equation 13) in the adjusted expenditure matrix (Kullback & Leibler, 1951). Equation 13 guarantees the identity between the adjusted total expenditure of each household ($\sum_i \widetilde{\alpha}_{h,i,r} * EXP^{2050,\text{ scen}}_{h,i,r} = \widetilde{EXP}^{2050,\text{ scen}}_{h,i,r}$) and the reference household expenditure consistent with total regional expenditure from the ICES model ($\sum_i \overline{EXP}^{2050,\text{ scen}}_{i,r}$) and expenditure distribution across households in that region according to HBS ($\delta_h = \sum_i EXP^{\text{HBS}}_{h,i,r} / \sum_{h,i} EXP^{\text{HBS}}_{h,i,r}$). The equation 14 secures the identity between the regional and scenario-specific aggregates new expenditure in a certain good i and the expenditure from ICES model.

The new matrix $\widetilde{\alpha}_{h,i,r}$ solves the following problem:

$$Max - \sum_h \sum_i \widetilde{\alpha}_{h,i,r} ln(\frac{\widetilde{\alpha}_{h,i,r}}{\alpha_{h,i,r}}) \tag{12}$$

$$\text{s.t.} \sum_i \widetilde{\alpha}_{h,i,r} \times EXP^{2050,\text{ scen}}_{h,i,r} = \sum_i \delta_h \times \overline{EXP}^{2050,\text{ scen}}_{i,r} \tag{13}$$

$$\sum_h \widetilde{\alpha}_{h,i,r} = 1 \tag{14}$$

The maximization is run independently and iteratively for each one of the 20 Italian regions and for each scenario (baseline, RCP4.5 and RCP8.5) and therefore lead to adjusted expenditure matrices for each region and scenario.

This simple downscaling method returns a household-specific picture of consumption choices in 2050 under baseline and impact scenarios. Comparing how energy expenditure shares change in a mild and severe global warming scenario with respect to the baseline one sheds light on the distributional implications of climate change impacts on energy demand, accounting for price-induced adaptation, as well as on the possible consequences in terms of energy poverty. In order to assess the downscaled second-order effects, we will apply the same metrics used for the first-order effect analysis, namely the change in household energy expenditure share, their distribution, and the fuel poverty prevalence measure described in Equation 7 .

It is worth noticing that the proposed methodology makes it possible to account for the behavioural response of household demand to price changes, but the optimization process takes place at regional level. This means that all households belonging to a specific NUTS2 region will be subject to the same commodity price and quantity percentage change. The downscaling module will apply the macroeconomic, regional variation in prices and quantities to different, household-specific, initial expenditure levels that will be adjusted at household level in order to solve the constrained optimization problem.

Bearing these limitations in mind, this methodology makes it possible to compare the burden of direct and indirect climate change impacts on the energy used by Italian households, as well as its overall distributional implications. By looking at the distribution of this burden, we will highlight the either regressive, progressive, or neutral implications of energy use for adaptation, highlighting the role of adjustment mechanisms induced by price changes and income effects.

4 Baseline scenario: calibration

The baseline scenario relies on historical data up to 2016 (WDI data integrated by Eurostat data at NUTS2 level for Italian regions) that are extended up to 2050 using a 'middle of the road' scenario (SSP2). SSP2 is among the five shared socioeconomic pathways (SSPs) (O′Neill *et al.* (2017)) envisioning future pathways of socioeconomic development, is defined as the 'Middle of the road' scenario being characterised by future trend observed in the past decades, medium population and GDP growth, constant reduction of energy intensity and of dependence from fossil fuels and a slow convergence towards achieving SDGs that will not be met by 2030. Historical population, working age population, labour force and employment growths are considered up to 2016 (WDI and Eurostat), afterwards the growth of overall population and working age population (age 15-64 years) follows the projections from SSP2. Furthermore, we computed the employment growth up to 2050, assuming the convergence of labour force participation rate to 70% in 2100 and that of unemployment rate to 2% (both assumptions are part of SSP2 storyline). For Italian regions, we applied the same rate of growth of population and employment of Italy.

The procedure for computing target GDP growth in the baseline was similar, we combined WDI and Eurostat data up to 2016 and afterwards we considered that GDP growth from SSP database. Italian GDP growth was applied uniformly to all regions after 2016. In Italy, per capita GDP, in purchase power parity, increases over time, with an evident North-South gap. Growth is characterized by a progressive reduction of the value added in agriculture and services and by an expansion in the industrial sector.

Energy consumption increases on average due to a contraction of gas price and a small rise of electricity price (Figure A5). Figure A6 shows how energy expenditure change varies across deciles in the baseline scenario.

Poverty prevalence in 2050 baseline is computed updating the minimum affordable budget share of fuels (right-hand term in equation 7) with downscaled results of ICES model for 2050. The poverty prevalence in 2050 does not change at country level, there are some variations at regional level that remain in the range of -1.4% and 1.5%. The population growth considered in the baseline scenario determines instead an increase of energy poor households in 2050 with respect to 2007 figures.

5 Impact scenarios

Figure A8 gives a snapshot of regional poverty change in the severe climate change scenario (RCP8.5). Results for the moderate climate change scenario are in Figure 10.

Figure A4: Climate change impacts on residential energy demand. Percentage changes in 2046-2055 compared to present climate (2006-2015). Source: Own calculations based on De Cian and Sue Wing (2017).

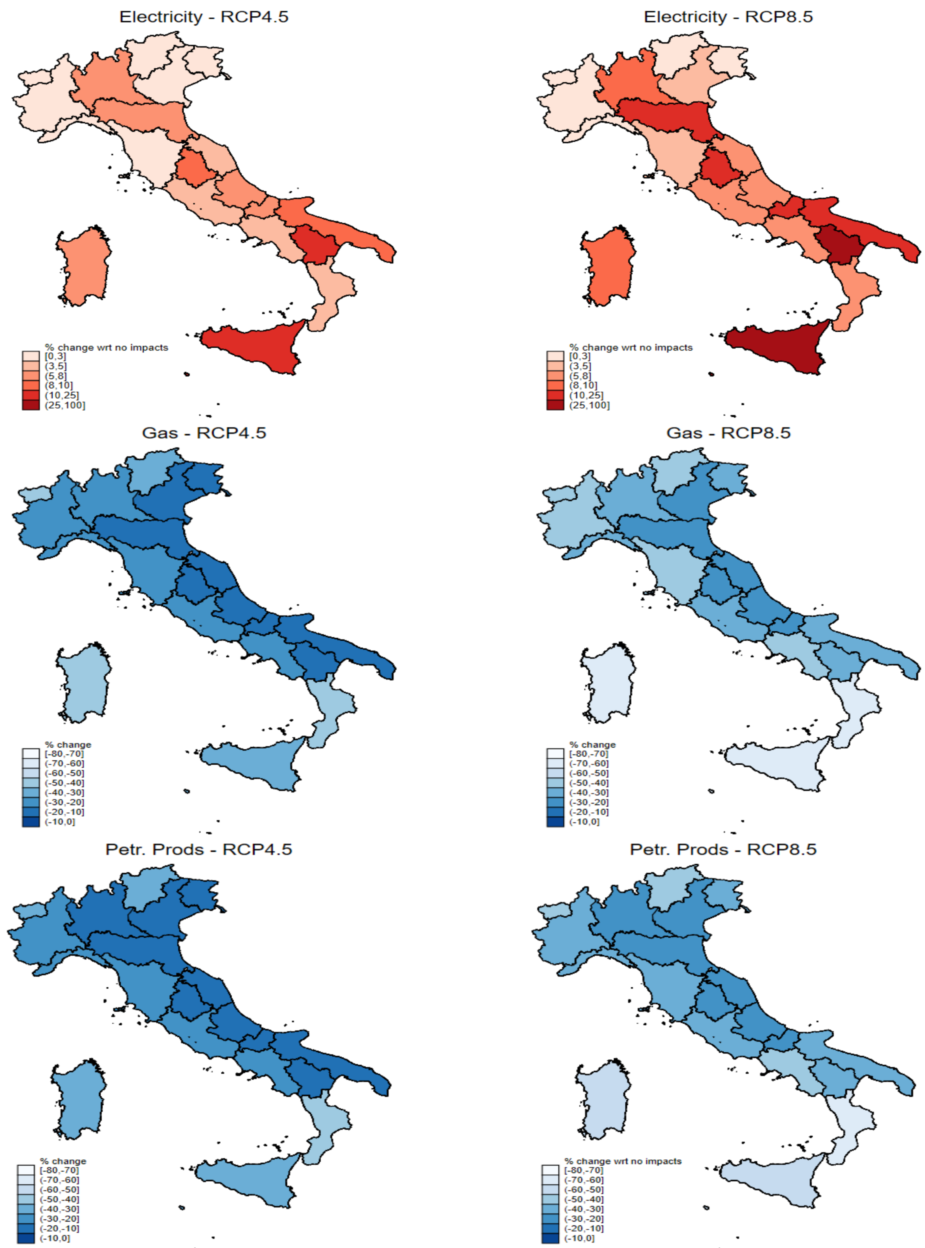


Figure A5: Change household expenditure across Italian regions in 2050 wrt 2007, baseline scenario.

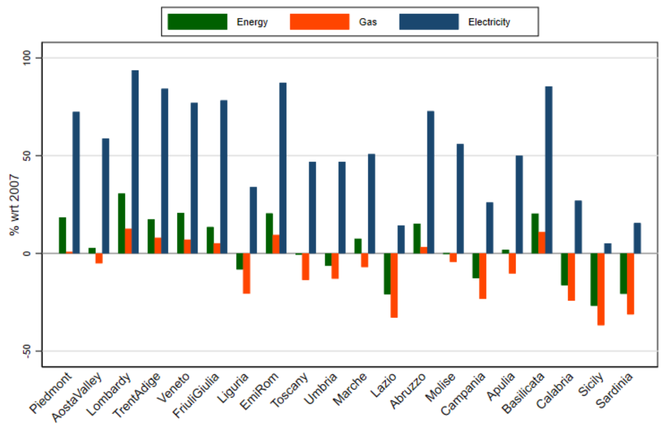


Figure A6: Change in household energy expenditure per adult equivalent in 2050 wrt 2007 by decile.

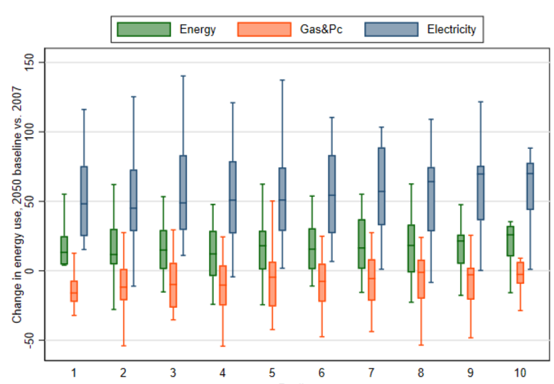


Figure A7: Change household expenditure wrt baseline scenario in 2050, across impact scenarios.

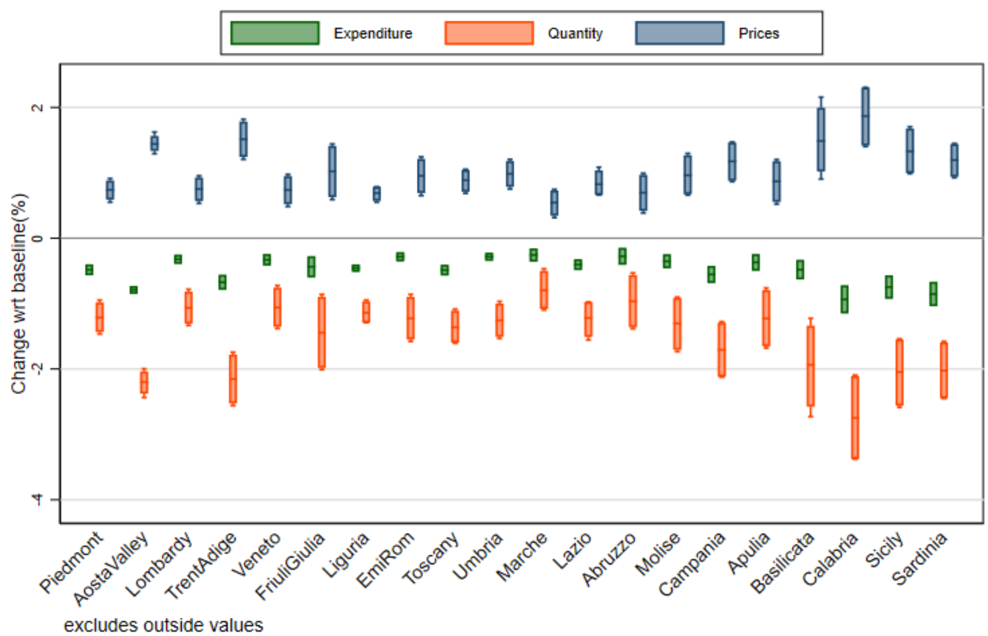


Figure A8: Climate-driven change in energy poor households. First and higher-order effects, RCP8.5