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Assessing Macro-economic Effects of Climate Impacts on Energy Demand in EU Sub-national Regions

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Abstract

European policy makers are increasingly interested in higher spatial representations of future macro-economic consequences from climate-induced shifts in the energy demand. Indeed, EU sub-national level analyses are currently missing in the literature. In this paper, we conduct a macro-economic assessment of the climate change impacts on energy demand at the EU sub-national level by considering twelve types of energy demand impacts, which refer to three carriers (petroleum, gas, and electricity) and four sectors (agriculture, industry, services, and residential). These impacts have been estimated using climatic data at a high spatial resolution across nine Shared Socioeconomic Pathway (SSP) and Representative Concentration Pathway (RCP) combinations. The impacts feed into a Computable General Equilibrium model, whose regional coverage has been extended to the sub-national NUTS2 and NUTS1 level. Results show that negative macroeconomic effects are not negligible in regions located in Southern Europe mainly driven by increased energy demand for cooling. By 2070, we find negative effects larger than 1% of GDP, especially in SSP5-RCP8.5 and SSP3-RCP4.5 with a maximum of −7.5% in Cyprus. Regarding regional differences, we identify economic patterns of winners and losers between Northern and Southern Europe. Contrasting scenario combinations, we find that mitigation reduces adverse macro-economic effects for Europe up to a factor of ten in 2070, from 0.4% GDP loss in SSP5-RCP8.5 to 0.04% in SSP2-RCP2.6.

Keywords Macro-economic impacts of climate change · Energy demand · CGE models · Sub-national regions · Europe

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1 Introduction

Energy demand is increasing globally, leading to greenhouse gas emissions from the energy sector to increase as well (IEA 2022). In the European Union, final energy consumption rose by almost 5% between 1995 and 2019 (Eurostat 2022). At the same time, the energy sector is heavily affected by climatic stressors, with temperature being one of the major drivers of energy demand, affecting summer cooling and winter heating behaviour of households and firms. Future climatic conditions are likely to increase the demand for energy required for cooling, while demand for heating might decrease due to warmer weather and fewer low-temperature extremes. Cooling is predominantly powered by electricity (which is more expensive), while heating uses a wider mix of energy sources. This, combined with changes in economic growth and population distribution, will change the fuel mix used by the different economic sectors and households. Investigating these trends is thus particularly important for the implementation of appropriate adaptation and mitigation policies (Damm et al. 2017; Eskeland and Mideksa 2010).

The impacts of climatic stressors on energy demand have been extensively researched (van Ruijven et al. 2019; De Cian and Sue Wing 2019; De Cian et al. 2013; Howell and Rogner 2014; Schaeffer 2012; Bazilian et al. 2011; Yalew et al. 2020). Kitous and Després (2018) find that heating needs in Europe can decline by 27% by the end of the century in the residential sector, but cooling needs may increase significantly by 44%. According to EC (2018), final energy use in the EU is expected to decrease by 26% by 2050, with energy demand declining in the residential, industrial, transport, and the tertiary sectors. Pilli-Sihvola et al. (2010) find that demand for heating may decline in Central and Northern Europe due to future warming. However, due to increasing temperature, cooling demand is likely to increase in Southern Europe. Eskeland and Mideksa (2010) estimate a decrease in electricity consumption in the Northern European countries, but an increase in demand in the Southern European countries due to increased cooling needs. The current literature provides limited information on the combinations of sectors and fuels affected by climatic stressors, focusing mostly on electricity and the residential sector (Schaeffer 2012).

European policy makers are increasingly interested in higher spatial representations of future macro-economic consequences from climate-induced shifts in the energy demand. However, a sub-national macro-economic assessment is currently missing. Indeed, compared to the physical impacts of climate change on energy demand, the literature on macro-economic impacts is not as extensive and the economic effects are in general small compared to those of other climate impacts such as sea level rise, changes in crop yields, or labour productivity (Aaheim et al. 2012; Roson and Sartori 2016; Dellink et al. 2019; Dasgupta et al. 2021). This is likely due to the low geographical detail adopted in the macro-economic models which are defined at the country or aggregated EU level.

This study combines econometric estimates of energy demand elasticity to cold/hot days with high spatial resolution climate projections from four Regional Climate Models (RCMs). This enables us to project the impacts of future climate change on energy demand at the NUTS[1] (sub-national) level in the EU under various warming scenarios. Projections are computed for electricity, petroleum products, and natural gas in the agriculture,

[1] Nomenclature des Unités Territoriales Statistiques (NUTS) is a geocode standard used to classify the European regions for statistical purposes. NUTS0 corresponds to the country level. NUTS1, NUTS2, and NUTS3 are sub-national classifications with increasing levels of spatial details.

industry, residential, and commercial sectors. This generates twelve fuel/sector combinations allowing a more comprehensive final assessment.

These physical impacts on energy demand are then used as inputs to the multi-country, multi-sector recursive-dynamic Computable General Equilibrium (CGE) model ICES (Inter-temporal Computable Equilibrium System) (Parrado and De Cian 2014). Impacts are implemented as sector-specific energy-efficiency changes in the macro-economic model. The underlying assumption is that firms in a given sector are able to satisfy a certain level of energy requirements using less/more energy inputs if the energy demand decreases/increases in the sector because of temperature changes. For example, we implement a lower efficiency in the electricity use because climate change substantially increases the demand for this energy input.

In the present study, a relevant innovation with respect to the standard practice is the increased regional granularity of the CGE model which has been extended to 138 NUTS regions (García-León et al. 2021). Another novel feature of the current assessment is that renewable energy sources are disentangled from the electricity bundle and are represented at the sub-national level.

Finally, to control for the uncertainty coming from both socio-economic developments and emission trends, nine reference scenarios based on different combinations of Shared Socioeconomic Pathways (SSPs) (Riahi et al. 2017) and Representative Concentration Pathways (RCPs) (Van Vuuren et al. 2011) are considered.

The paper is structured as follows. Section 2 briefly presents the data along with the regional and sectoral aggregations used for the macro-economic analysis. Section 3 explains the main elements of the theoretical structure of the CGE model relevant in our exercise. Section 4 describes the reference scenarios, Sect. 5 the inputs for the CGE assessment stemming from the econometric analysis and their implementation in the model. Section 6 provides the results from the CGE model, while Sect. 7 discusses the main outcomes of the study and the limitations of our approach.

2 Data

We start with the Global Trade Analysis Project (GTAP) database (Narayanan et al. 2012) version 8.1 consisting of a collection of Social Accounting Matrices (SAMs) for 57 sectors and 134 countries (or groups) in the world for the reference year 2007. To extend the EU geographical resolution to the sub-national detail, we use information from Eurostat (Economic Accounts for Agriculture, 2018; Structural Business Statistics, 2018; Gross value added at basic prices by NUTS3 regions, 2018). For the fishery sector we also use information from the Regional Dependency on Fisheries report (EU 2007) and for the forestry sector we rely on information from the Global Forest model (Di Fulvio et al. 2016).

Our sectoral aggregation is reported in Table 1. To calibrate the Transmission and Distribution sector we first regionalise the electricity sector at the sub-national level using Eurostat data. Then, we use the World Electric Power Plants Database (WEPP) (PLATTS 2014) to further split the electricity sector into different technologies. Unfortunately, the WEPP database does not provide information on Transmission and Distribution at the sub-national level. Therefore, we assume that the share of Transmission and Distribution over the total valued added of the electricity sector in the sub-national region is the same as the respective country. Table 6 in the Appendix shows these shares for the EU countries coming from the GTAP-power database for the year 2007 (Peters 2016). The regional aggregation for the EU is shown

Table 1 Final sectoral aggregation

1	Vegetables and fruits	13	Wind power generation
2	Other crops	14	Hydropower
3	Livestock	15	Solar power generation
4	Timber	16	Other renewables
5	Fishery	17	Heavy industry
6	Coal	18	Construction
7	Oil	19	Light industry
8	Gas	20	Transport road
9	Petroleum products	21	Transport water
10	Transmission and distribution	22	Transport air
11	Nuclear	23	Services
12	Fossil power generation	24	Public services

Country	Number of Regions	NUTS level
Austria	3	NUTS1
Belgium	3	NUTS1
Bulgaria	1	NUTS0
Cyprus	1	NUTS0
Czech Republic	8	NUTS2
Germany	16	NUTS1
Denmark	1	NUTS0
Estonia	1	NUTS0
Spain	17	NUTS2
Finland	1	NUTS0
France	22	NUTS2
Greece	4	NUTS1
Hungary	1	NUTS0
Croatia	1	NUTS0
Ireland	1	NUTS0
Italy	20	NUTS2
Lithuania	1	NUTS0
Luxembourg	1	NUTS0
Latvia	1	NUTS0
Malta	1	NUTS0
Netherlands	4	NUTS1
Poland	6	NUTS1
Portugal	5	NUTS2
Romania	1	NUTS0
Sweden	3	NUTS1
Slovenia	1	NUTS0
Slovakia	1	NUTS0
United Kingdom	12	NUTS1
Total	**138**	

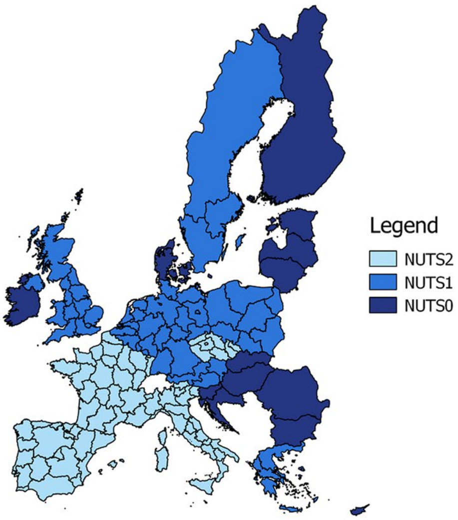

Fig. 1 NUTS regions in the ICES model

in Fig. 1. We report the mapping between EU regions of the ICES model and NUTS 2013 EU code in Table 5 of the Appendix along with the description of the methodology used to regionalise the GTAP database and balance the regional SAMs (section A1).

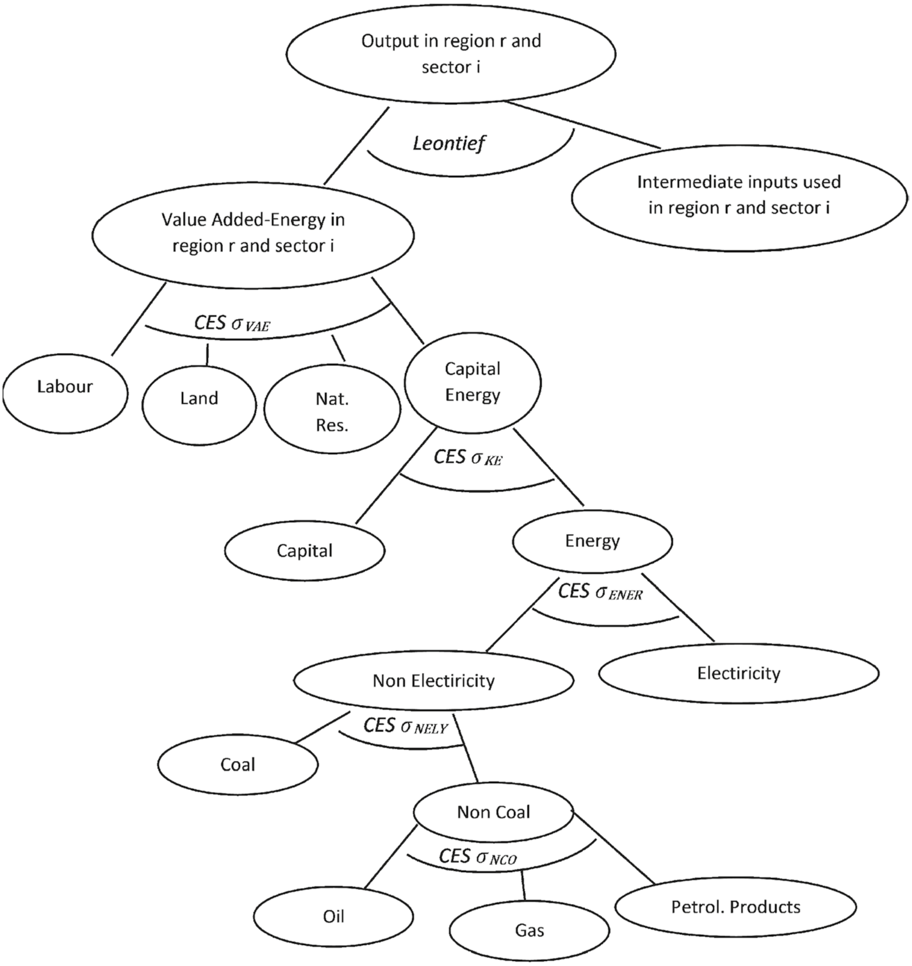

Fig. 2 GTAP-E supply structure

3 Model

The theoretical structure of the model shares its main features with the GTAP-E model (Burniaux and Truong 2002), but we also introduce renewable energy sources at the EU sub-national level. In the following sections, we examine the main structural elements of the model which are important in our analysis.

3.1 Production Side and Technology Nests in ICES

The ICES supply side builds upon the GTAP-E model which, in turn, extends the GTAP supply structure (Hertel 1997) to consider CO_2 emissions and examine the implementation of mitigation policies. The GTAP-E supply structure is summarised in Fig. 2. The emission

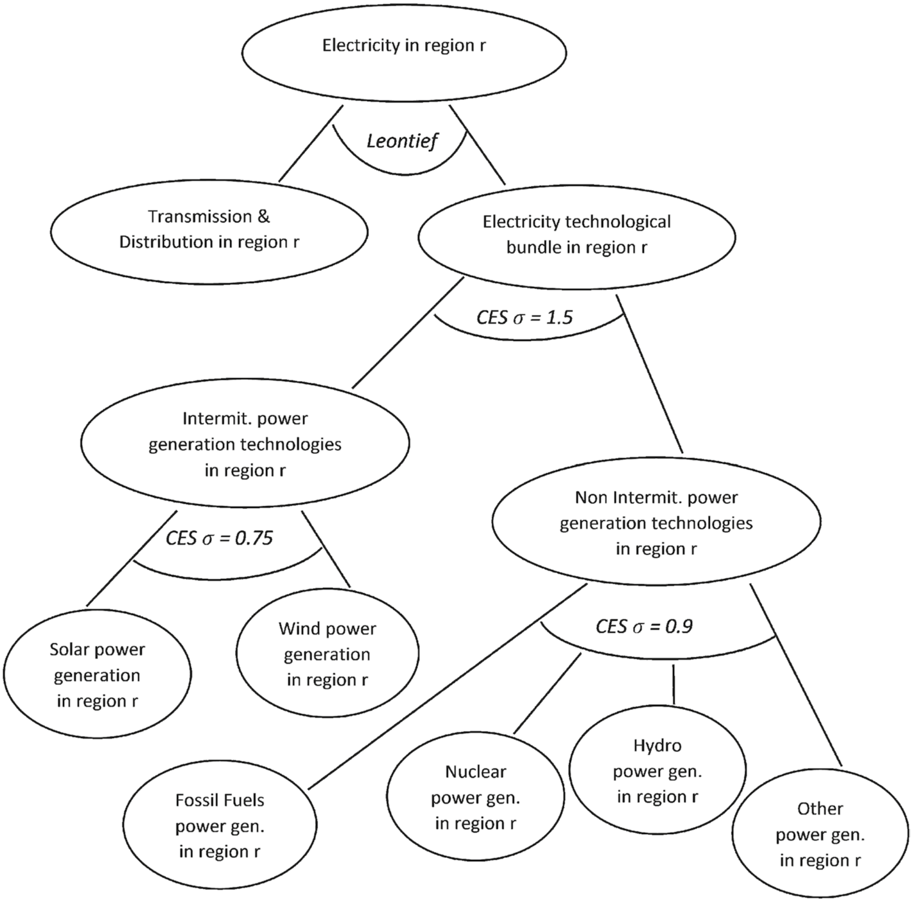

Fig. 3 ICES supply structure for the electricity sector

reduction process taking place after the introduction of a climate policy is driven by the elasticity of substitution between energy and capital, electricity and non-electricity energy sources and between different fossil fuels. The parametrization of these substitution elasticities is derived from Beckman et al. (2011). We adjust some of the elasticities according to the specific scenario analysed as detailed in Sect. 4.

While the main structure of Fig. 2 remains unchanged in ICES, we add further detail to the electricity carrier, thus creating additional opportunities for substitution between clean and polluting technologies within the electricity sector. The electricity generation tree is summarised in Fig. 3. The elasticities are calibrated based on McFarland et al. (2004), Paltsev et al. (2005), and Bosetti et al. (2009).

3.2 International and Intranational Trade Structure in ICES

A standard feature in the CGE framework to model the trade relationships among countries is the imperfect substitutability between domestic and imported goods, the so-called Armington assumption (Armington 1969). The GTAP model (Hertel 1997) also introduces

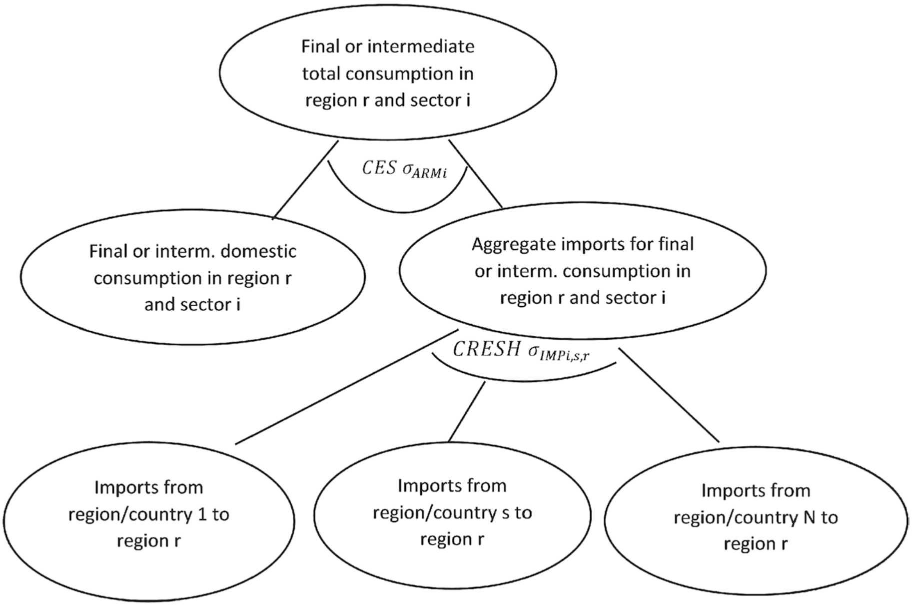

Fig. 4 Trade structure in the ICES model

this assumption through a double Constant Elasticity of Substitution (CES) nest which first links domestic goods and aggregate imports and then breaks the aggregate imports according to the different country-source of the product. Though we follow this double nest approach, in the lower nest we employ a Constant Ratios of Elasticities of Substitution Homothetic (CRESH) function (Hanoch 1971; Pant 2007) which allows for more flexibility in the choice of the bi-lateral elasticity of substitution for each couple of spatial units. Figure 4 represents our model trade structure.

In practice, we keep the original values of the Armington elasticities from GTAP. However, when trade relations refer to two sub-national units belonging to the same country, we increase these elasticities by 50%. This modelling choice aims to capture the greater fluidity of intra-country trade and is consistent with results of the trade literature about the border effect (Anderson and Wincoop 2003; McCallum 1995).

4 Reference Scenarios

To examine a wide spectrum of socio-economic and temperature trends, the macro-economic assessment has been performed on nine reference scenarios based on combinations of SSPs and RCPs (Table 2).[2] All the reference scenarios cover the period 2007–2070 while the impact assessment is conducted for the 2015–2070 period.

The SSPs define different demographic and economic development trajectories in explicit quantitative terms. The SSP narratives also enable a qualitative interpretation

[2] The likelihood of RCP8.5 is now considered low (IPCC 2021). However, to have a complete view and to cover the extreme cases, we also include the SSP5-RCP8.5 combination.

Table 2 Main modelled features of the reference scenarios (SSPs-RCPs combinations)

	Trade openness (Armington elasticities)	Substitutability between capital and energy	Substitutability between electricity and fossil fuels	Efficiency in clean energy sources (% annual growth in the period 2010–2070)*	Climate policy (global carbon tax)
SSP1-RCP2.6	Default values	1.5	2.5	~3.24	Yes
SSP1-RCP4.5	Default values	0.75	2.5	~2.12	No
SSP2-RCP2.6	Default values	1.2	2.5	~2.90	Yes
SSP2-RCP4.5	Default values	1	2	~2.35	No
SSP2-RCP6.0	Default values	0.75	2	~1.06	No
SSP3-RCP2.6	Default values reduced by 25%	1	2	~2.75	Yes
SSP3-RCP4.5	Default values reduced by 25%	1	1.8	~0.56	No
SSP5-RCP4.5	Default values	1	1.5	~0.98	Yes
SSP5-RCP8.5	Default values	0.75	1.5	~0.26	No

*The efficiency measure reported in the column is the mean between efficiency improvement in the intermediate use of the renewable sources from all other sectors and efficiency improvement of primary inputs (e.g. labour and capital) used in the value added function of the renewable itself of features such as the macro-sectoral composition of the economic systems, their trade openness, technology, and energy prices. For instance, SSP1 can be considered an environmentally friendly scenario where sustainability issues are particularly important; SSP5 describes a fossil-fuel-based development coupled with strong economic growth. SSP2 is an intermediate or "middle of the road" scenario and SSP3 is characterised by regional rivalry with potential negative ripple effects on the economic growth and disruption of trade.[3]The purpose of having different SSPs in the assessment is to disentangle the role of socio-economic development in influencing the final impacts of climate change on energy demand.

These socio-economic characteristics, in turn, interact with different emission profiles which are given by the RCPs. Replicating specific social and economic storylines (i.e. the SSPs) in combination with chosen emission patterns is challenging, especially in a model specified at the sub-national scale. To do so, first we replicate the GDP and population targets available from the SSP database (Riahi et al. 2017). We assume that sub-national regions follow the country projections. Then, we calibrate the global CO_2 emissions according to the respective RCP trends (Van Vuuren et al. 2011). This is not trivial because GDP targets from the SSP database are not matched with the emission profiles implied by the RCPs. For this reason, to characterise a specific SSP-RCP combination and be consistent with the SSP narrative, we use a mix of instruments, summarised in Table 2.

Among these instruments, trade openness has been modelled varying the value of the Armington elasticities which make the trade more or less fluid. Different degrees of development in the green sectors have been implemented with higher or lower values of the elasticity of substitution parameters (e.g. those between capital and energy, between electricity and fossil fuels) and efficiency of clean energy sources.

The highest increase in the efficiency of clean energy sources among the SSP-RCP combinations is under SSP1-RCP2.6 while the lowest increase is under SSP5-RCP8.5 (Table 2). This allows the model to endogenously move the economy away from fossil fuels and progressively increase renewable-power generation given the cost-minimising behaviour of the firms. We also assume that the substitutability between electricity and fossil fuels is the highest under SSP1-RCP2.6, making it easier for the regions to shift from fossil fuels to renewables and increase electrification. The carbon tax is also an important variable to control the global emissions in scenarios combining with the "low-warming" RCP2.6 but also in the SSP5-RCP4.5, where emissions are driven high by the very strong economic growth in SSP5.

5 Impact Modelling

Climate change impacts on energy demand are the basis of the input shocks to the CGE model. These impacts have been computed using the econometric estimates of energy demand elasticity to hot/cold days from De Cian and Sue Wing (2019). The authors estimate the elasticity of demand for electricity, petroleum products, and natural gas in the agriculture, industry, services, and residential sectors. Future regional trends in climate-induced energy demand are obtained combining these elasticities with high spatial resolution ensemble-mean temperature projections from four Regional Climate Models (RCMs): KNMI RACMO22E, IPSL-CM5A-MR, MPI-ESM-LR, and CNRM-CM5 (Jacob et al. 2014). In the CGE model, this means that twelve different impacts (i.e. the number of

[3] For a detailed description of the SSP storylines reader can refer to O'Neill et al. (2015).

Table 3 Elasticity of energy demand to hot/cold days, changes in temperature, and % changes of energy demand over the period 2015–2070

	Eu28	South Europe	North Europe
Delta Temp. (°C) Rcp 2.6	1.42	1.64	1.28
Delta Temp. (°C) Rcp 8.5	2.23	2.61	1.98
Elast. Ely Agriculture (hot days)	0.008	0.008	0.008
% ch Ely Agriculture demand RCP2.6	0.20	0.48	0.01
% ch Ely Agriculture demand RCP8.5	0.87	2.07	0.03
Elast. Ely Industry (hot days)	0.009	0.009	0.009
% ch Ely Industry demand RCP2.6	0.20	0.46	0.01
% ch Ely Industry demand RCP8.5	0.91	2.15	0.03
Elast. Ely Services (hot days)	0.047	0.047	0.047
% ch Ely Services demand RCP2.6	8.66	7.07	10.89
% ch Ely Services demand RCP8.5	25.88	39.89	15.94
Elast. Ely Residential (hot days)	0.015	0.015	0.015
% ch Ely Residential demand RCP2.6	0.34	0.79	0.01
% ch Ely Residential demand RCP 8.5	1.59	3.76	0.05
Elast. Gas Agriculture	NS	NS	NS
% ch Gas Agriculture demand RCP2.6	0.00	0.00	0.00
% ch Gas Agriculture demand RCP8.5	0.00	0.00	0.00
Elast. Gas Industry (hot days)	0.033	0.033	0.033
% ch Gas Industry demand RCP2.6	0.54	1.24	0.03
% ch Gas Industry demand RCP8.5	4.52	10.73	0.11
Elast. Gas Services	NS	NS	NS
% ch Gas Services demand RCP2.6	0.00	0.00	0.00
% ch Gas Services demand RCP8.5	0.00	0.00	0.00
Elast. Gas Residential (cold days)	0.023	0.023	0.023
% ch Gas Residential demand RCP2.6	−22.05	−22.76	−21.55
% ch Gas Residential demand RCP8.5	−43.36	−45.48	−41.86
Elast. Petrol. Agriculture	NS	NS	NS
% ch Petrol. Agriculture demand RCP2.6	0.00	0.00	0.00
% ch Petrol. Agriculture demand RCP8.5	0.00	0.00	0.00
Elast. Petrol. Industry	NS	NS	NS
% ch Petrol. Industry demand RCP2.6	0.00	0.00	0.00
% ch Petrol. Industry demand RCP8.5	0.00	0.00	0.00
Elast. Petrol. Services RCP8.5 (cold days)	0.012	0.012	0.012
% ch Petrol. Services demand RCP2.6	−12.37	−12.65	−12.17
% ch Petrol. Services demand RCP8.5	−25.47	−26.98	−24.40
Elast. Petrol. Residential (cold days)	0.021	0.021	0.021
% ch Petrol. Residential demand RCP2.6	−20.57	−21.21	−20.12
% ch Petrol. Residential demand RCP8.5	−40.06	−42.10	−38.61

North Europe includes Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, Germany, Hungary, Ireland, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Slovakia, Sweden, and UK. South Europe includes Bulgaria, Croatia, Cyprus, France, Greece, Italy, Malta, Portugal, Romania, Slovenia, and Spain. Response to cold days implies $T < 12.5$ °C. Response to hot days implies $T > 27.5$ °C. NS means not statistically significant energy carriers times the number of economic activities) are implemented for four warming scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5).

To better clarify how we obtain the final energy demand impacts, in Table 3 we report the elasticities in each of the twelve fuel/sector combinations, the changes in temperature in the extreme RCPs (2.6 and 8.5), and the resulting energy demand variations in three macro-regional aggregates: Europe, North Europe, and South Europe. From De Cian and Sue Wing (2019), we obtain two types of elasticities, which represent the energy demand response to cold days or hot days. Using the temperature projections from the RCMs we compute variations of cold and hot days in the different RCPs. Combining the number of hot and cold days with the elasticities in De Cian and Sue Wing (2019), we obtain the final energy demand impact. The elasticity in a given fuel/sector combination is used for all NUTS regions while temperature changes differ by RCP and region. According to climate projections, temperature increase is expected to be higher in Southern than in Northern Europe. Electricity demand increases in all sectors especially in services and Southern Europe. Gas demand is also expected to increase in the industrial sector, again more in the South. Petroleum demand declines in services and residential because of the lower number of cold days. In Table 3, it emerges that elasticities to hot days imply a more uneven pattern between Northern and Southern Europe, while elasticities to cold days are in general associated to a more uniform geographical pattern between North and South.

As the study examines four RCPs, 138 EU regions, and 12 combinations of energy carrier/sector we focus on the most significant combinations of carrier/sector (gas/industry, electricity/services, and petroleum/services), which are representative of more general economic and climatic mechanisms (Fig. 5).

From Fig. 5, we observe that energy demand for the gas/industry combination increases especially under RCP8.5 and in some regions of Southern Europe (Greece, Malta, Cyprus, Spain, Portugal, and Italy). The highest increases occur in the electricity demand from services, under RCP8.5 and in the Southern European regions. As already noted, the petroleum demand from services is expected to decrease in Europe with the highest reductions occurring under RCP8.5. The climate signal is not very different between the two intermediate RCPs and, given the spatial detail of the model, in some regions we notice stronger effects in RCP4.5 than RCP6.0 even if the two RCPs in general remain between the extreme RCP2.6 and RCP8.5.

These different trends show a general dynamic where cooling energy needs are projected to increase substantially, determining a clear efficiency loss in the energy system of the macro-economic model. We implicitly assume that the energy demand increase of the electricity/services combination may represent an increase in the cooling needs but we should also note that we are not able to disentangle air condition use form the other uses in the electricity/services combination in the current framework. On the other hand, the heating needs decrease due to warming, resulting in an efficiency gain in the energy system. However, heating uses a wide mix of energy sources, and they are not immediately detectable in the CGE. The trend of the petroleum/services combination could represent an example of this efficiency gain, but the amount of petroleum products consumed by the services sector is small in comparison with electricity and the variations are also lower in absolute value.

For sake of completeness the distribution of all energy inputs are compacted in the box-plots of Figs. 10, 11, 12 and 13 in the Appendix. The figures show an increasing spatial variability over time in the RCP8.5 while the spatial variability over time is stable in RCP2.6. We note that many energy demand impacts are concentrated around zero in most of the combinations except electricity/services, petroleum/services, petroleum/residential, and gas/residential where the distribution is not zero-centred and the regional variability is higher in general.

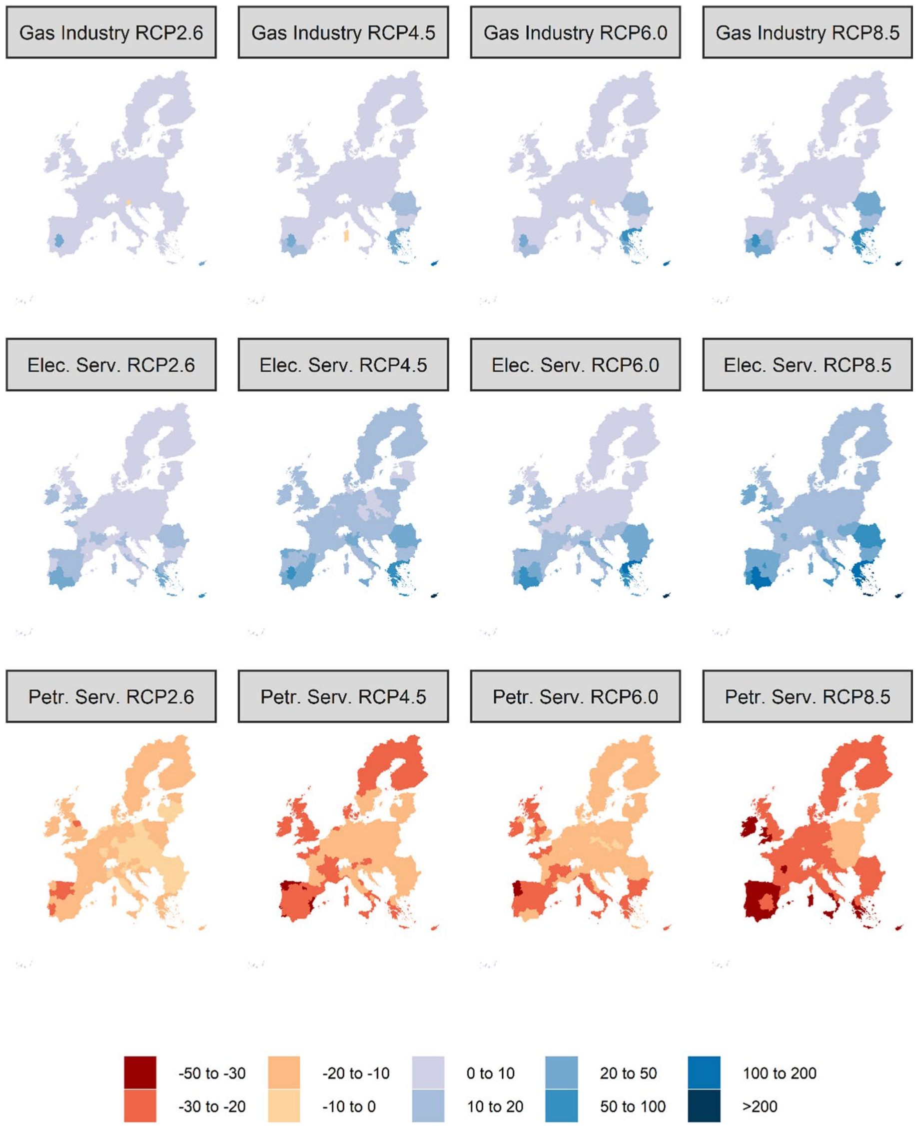

Fig. 5 Climate-induced energy demand trends in EU regions (% Ch. over the period 2015–2070)

Climate-induced changes in energy demand are modelled as sector-specific changes of the energy efficiency parameter in the agriculture, industry, and services of the macro-economic model. The underlying assumption is that the representative firm in the agriculture, industry, and services is in a better (worse) economic position if climate change decreases (increases) the energy demand for a given energy input and may satisfy a certain level of energy requirement using less (more) energy input. To reflect this condition with the CGE, we impose a higher (lower) efficiency in the use of a given energy input in a specific sector if the energy demand is projected to decrease (increase) because of climate change.

Table 4 GDP % changes compared to the reference scenarios

EU28	2030	2050	2070
SSP1-RCP2.6	−0.12	−0.26	−0.15
SSP1-RCP4.5	−0.16	−0.30	−0.21
SSP2-RCP2.6	−0.11	−0.22	−0.04
SSP2-RCP4.5	−0.14	−0.27	−0.13
SSP2-RCP6.0	−0.10	−0.20	−0.24
SSP3-RCP2.6	−0.10	−0.22	−0.11
SSP3-RCP4.5	−0.14	−0.35	−0.45
SSP5-RCP4.5	−0.14	−0.29	−0.21
SSP5-RCP8.5	−0.15	−0.33	−0.41

We adopt a different procedure in the case of the residential sector. In fact, this sector is not explicitly modelled in the CGE model. However, a large part of this energy use is included in the energy demand of the representative regional household. Therefore, energy demand shifts in the residential sector are obtained by imposing exogenous shocks to the household energy expenditure while keeping fixed the household budget constraint. This implies a re-adjustment of household consumption across all consumption items.

The first type of shock has a direct impact on production and GDP because it directly affects the productive capacity of an economic activity while the second type of shocks is more re-distributional because the overall spending capacity of the household does not change. If we examine the spatial distribution of the energy demand impacts in Fig. 5, we observe that regions located in Southern Europe are the most negatively affected in terms of efficiency loss, especially under RCP8.5.

It is also important to stress that all these energy demand shifts depend only on the energy demand elasticity and temperature projections in each RCP, and they "add" to the energy demand shifts which take place endogenously in the reference scenarios as a result of the demographic and GDP trends, and of the socio-economic and technological assumptions summarised in Table 2.

6 CGE Simulation Results

GDP impacts of climate-induced shifts on energy demand in Europe tend to be small, but vary significantly across regions. In 2030, GDP losses in the EU28 are moderate and rather uniform across scenarios (Table 4). Over time, we observe a gradual differentiation of these results across scenarios. For example, in 2070 under SSP3-RCP4.5 and SSP5-RCP8.5, the GDP losses are larger than 0.4% compared to the reference scenario while under SSP2-RCP2.6 the macro-economic loss is almost zero. At the same time, the role of the socio-economic dimension can be identified. For instance, the worst economic performance at the European aggregate level is in SSP3-RCP4.5 combination even though the climate signal is not the strongest. The explanation is the limited flexibility of SSP3 which is characterised by a lower degree of trade openness. This induces a reduced market adaptation capacity compared to the other SSPs where energy inputs can be more easily substituted in the international and intranational markets through exports and imports.

It is also interesting to note that in the most emitting scenarios (RCP6.0 and RCP8.5) and under SSP3-RCP4.5 the macro-economic impacts are increasingly negative after 2050 while in the other greener and less emitting combinations, the opposite occurs. There are

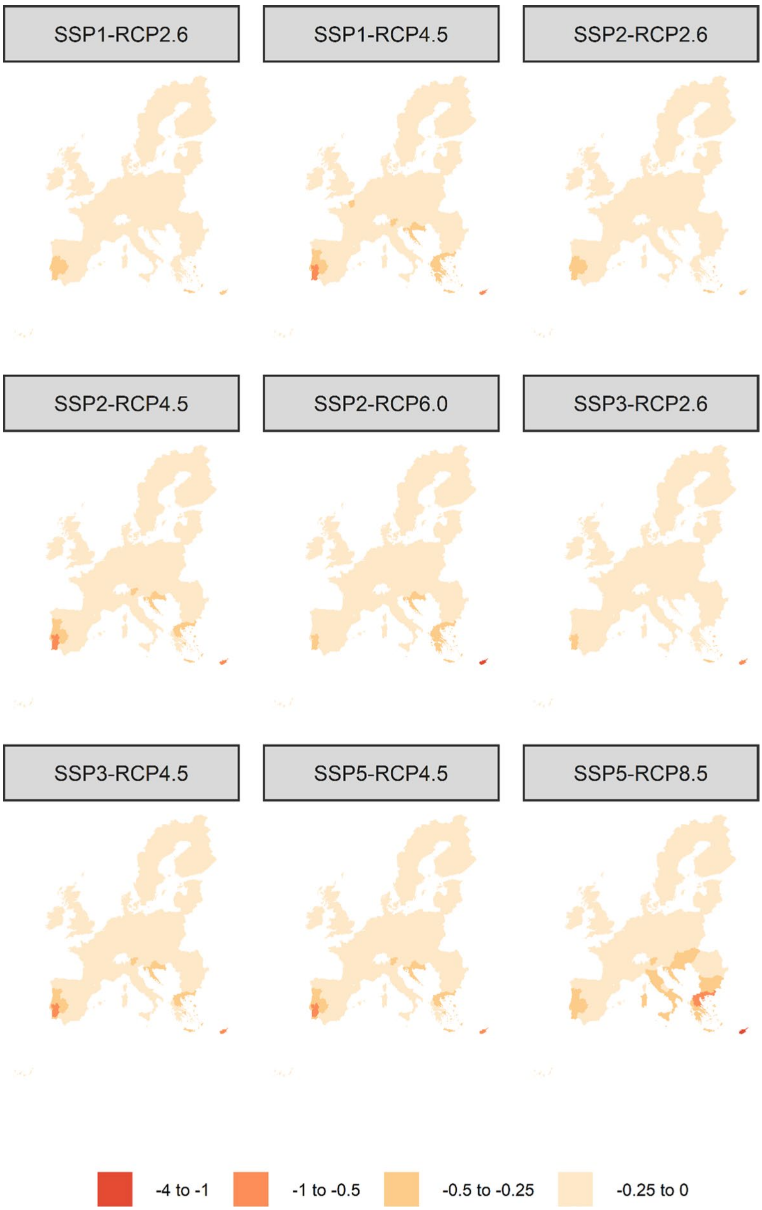

Fig. 6 Climate change impacts on energy demand in EU regions: GDP effects by scenario combination for the year 2030. Values in % changes from the reference scenarios

two plausible reasons for such an outcome; the first one is climatic and is linked to the temporal evolution of temperature in each RCP. The temperature increases are relatively close until 2050 and only start to diverge after mid-century with higher increases under RCP6.0 and RCP8.5, lower increases in RCP4.5, and a stabilisation in RCP2.6. The second reason is socio-economic, and it is related to the accumulation of negative spillovers along the years caused by a limited trade openness under SSP3.

However, the key contribution of this study is detailing the macro-economic effects at the sub-national level. Figure 6 shows GDP effects in 2030 for all the SSP-RCP combinations. Consistent with the results at the EU aggregate level, the GDP impacts remain moderate and quite uniform across the NUTS regions. Nevertheless, some areas in Southern Europe (Cyprus, Greece, Croatia, and Portugal) already show substantial negative effects in 2030 under most of the scenarios.

It is also worth noticing that in 2030, all the regions are projected to experience negative economic impacts, but this is not the case in 2070 (Fig. 7) when gains are experienced by some of the Northern European regions in Ireland, Scotland, Czech Republic, Denmark, Finland, and Sweden especially under SSP2-RCP2.6. On the contrary, many Southern EU regions in Spain, Italy, Greece, Portugal, Malta, Cyprus, Romania, Bulgaria, and Croatia suffer higher macro-economic losses in 2070 especially under SSP3-RCP4.5 and SSP5-RCP8.5. These economic losses are larger than 1% of GDP with the highest decline, around 7.5%, in Cyprus (Fig. 8). These negative effects are the consequence of the higher demand for electricity and gas. This translates into an increase in the production costs for firms and implies an efficiency loss in the use of some energy inputs, e.g. the electricity to satisfy the cooling needs.

The positive effects in some regions of Northern Europe are induced by the relatively lower increases in energy demand, especially for electricity in the services, compared to the rest of the EU. In a long time horizon, this can trigger positive competitiveness effects through trade. Nevertheless, these positive effects are smaller than the losses in the regions where GDP declines (Fig. 9). Overall, by comparing Figs. 8 and 9, loser regions can be identified mostly in Southern Europe and winner regions in Northern Europe. Although the gap in terms of future macro-economic effects between North and South is not evident in 2030, it emerges clearly in 2070 (Figs. 6 and 7).

Moving from SSP1 to SSP5 and from RCP2.6 to RCP8.5, following all the SSP-RCP combinations in Fig. 7, it is evident that a lower emission profile is associated with lower macro-economic losses of energy demand impacts. At the aggregate EU level, mitigation reduces the adverse macro-economic effects for Europe by a factor of ten in 2070 from 0.4% of GDP in SSP5-RCP8.5 to 0.04% in SSP2-RCP2.6 (Table 4).

7 Discussion and Conclusions

In this study, we assessed the macro-economic consequences of climate change impacts on energy demand in the EU. A novelty with respect to previous analyses is that the EU economic system has been represented and accordingly impacts have been quantified with a sub-national detail of 138 administrative units. Inputs to the macro-economic assessment are temperature-induced demand projections for petroleum, gas, and electricity in agricultural, industry, services, and residential sectors under nine different combinations of socio-economic and climate scenarios.

Our findings show that negative macro-economic effects may be relevant in Southern Europe in the second half of the century. By 2070, GDP losses are projected to be higher than 1% of GDP in some regions, especially under SSP3-RCP4.5 and SSP5-RCP8.5 scenarios, with the highest impact of 7.5% in Cyprus. The main drivers of this outcome are

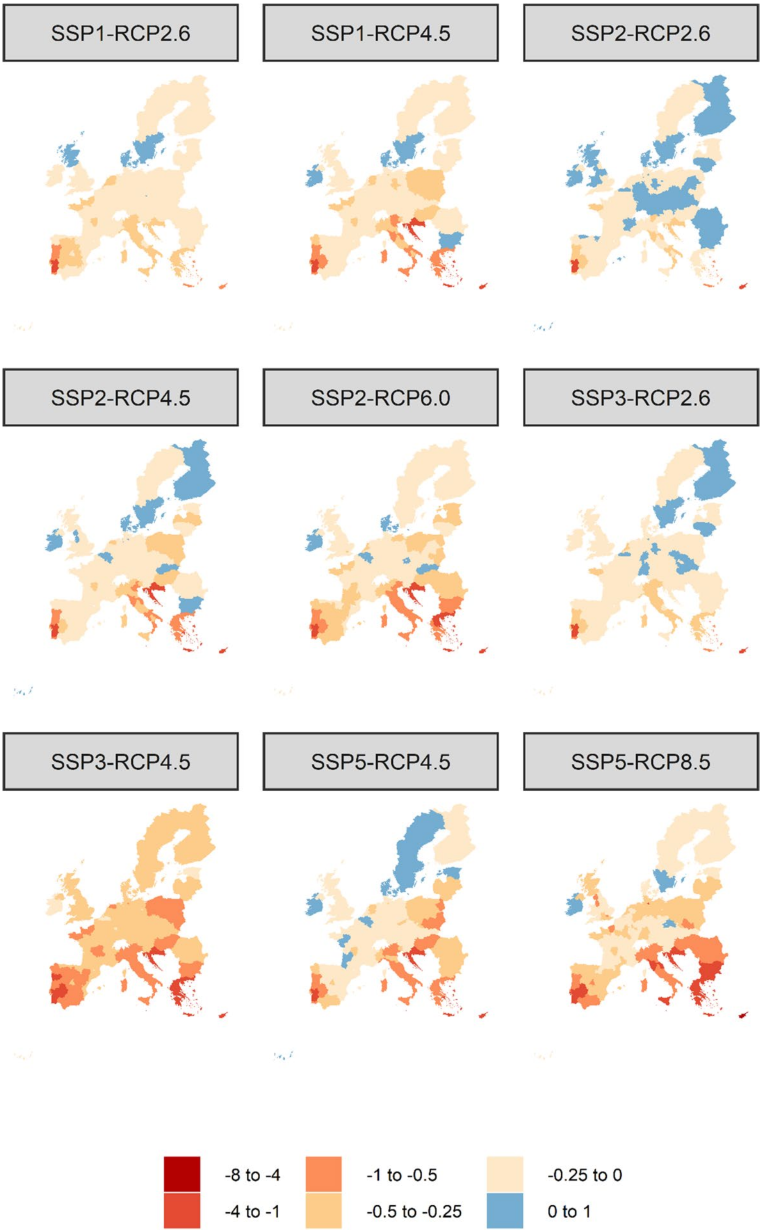

Fig. 7 Climate change impacts on energy demand in EU regions: GDP effects by scenario combination for the year 2070. Values in % changes from the reference scenarios

the increasing cooling needs of Southern European regions which boost the energy costs and penalise firms' production processes. Nonetheless, for symmetric motivations, some regions in North Europe may experience small economic gains especially in SSP2-RCP2.6.

Our study allows us to disentangle the role of the socio-economic determinants from the climatic stressors. In particular, our results highlight that a lower trade openness, captured

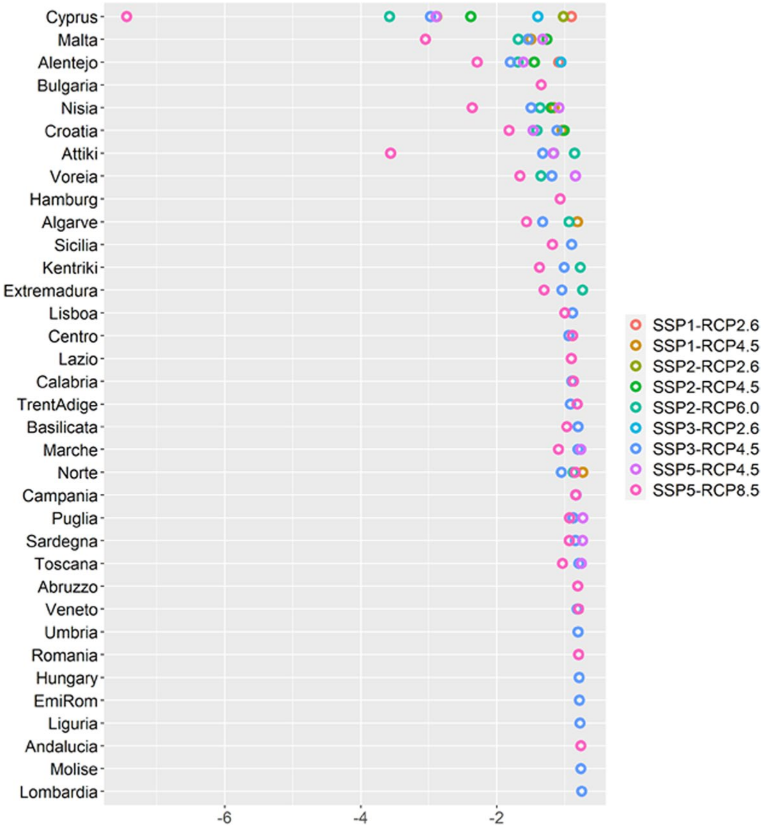

Fig. 8 The bottom 100 values for GDP impacts in EU regions across all scenario combinations in 2070 (loser regions). Values in % changes from the reference scenarios

by the parameterization of SSP3, shows the highest GDP losses at the EU aggregate level even if the climate signal is not the strongest.

Previous macro-economic CGE assessments have found smaller impacts on EU GDP (Aaheim et al. 2012; Dellink et al. 2019). The comparison is possible only for the highest emission scenarios (SSP2-RCP6.0 and SSP5-RCP8.5). The study by Aaheim et al. (2012) uses elasticities in De Cian et al. (2007) as a starting point to estimate the shock on the energy demand, while Dellink et al. (2019) rely on the International Energy Agency (IEA 2013) to compute input shocks for their CGE. However, in both studies the coverage of fuel/sector combinations is lower than that of our analysis and the geographical detail is coarser. Accordingly, a higher spatial (and sectoral) resolution is not only important to obtain a more granular picture of economic dynamics, but also to better represent results at the aggregate EU level. In our case, the more detailed modelling framework better captures the technological and regional constraints of the energy sector, which results in higher estimates of the overall economic loss compared to more spatially aggregated CGE models.

The study also emphasises that lower emission scenarios are associated with substantial reductions in the negative macro-economic consequences. These results confirm the importance of a leading EU role in implementing aggressive mitigation policies with upfront investment in more efficient and greener energy technologies. Nevertheless, noting

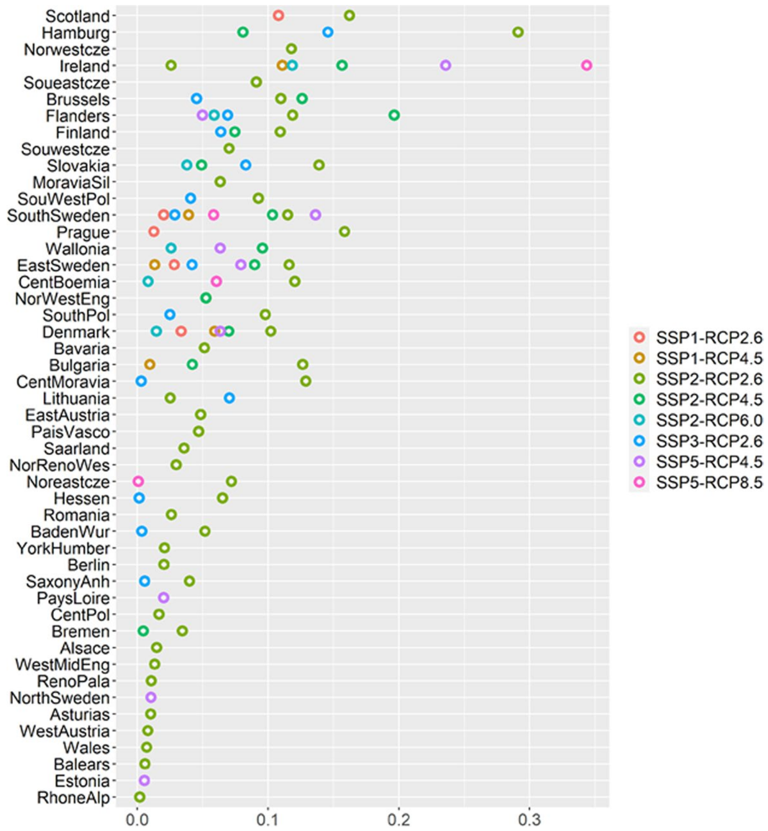

Fig. 9 The top 100 values for GDP impacts in EU regions across all scenario combinations in 2070 (winner regions). Values in % changes from the reference scenarios

that some EU regions experience substantial negative economic effects already in 2030, it is clear that unavoidable impacts in the short-term need to be addressed with appropriate adaptation action. In the energy sectors this might include developing an efficient and decarbonized cooling technology, particularly in the Southern EU regions.

Finally, we acknowledge the limitations of the present research and indicate avenues for future research. Firstly, the database and basic parameterization of our model are those from GTAP 8 (Narayanan et al. 2012) that uses 2007 as a reference year and is linked to the country-specified GTAP model (Hertel 1997). Although some of these parameters have been modified in order to calibrate the reference scenarios, future work can focus on updating the database to a more recent year and conducting a sensitivity analysis on some key behavioural parameters to test the robustness of our findings. Further, it would be good to update the database moving away from the assumption of a uniform Transmission and Distribution share over total electricity within the country. This requires a data searching effort to calibrate Transmission and Distribution at the sub-national level.

The exogenous representation of technological progress is another limitation of the study. Technological features in the model are driven by the elasticity of substitution between different technologies and by the sector and factor-specific productivity parameters. The exogenous modelling of technological change, thus, does not capture discontinuities deriving from new emerging technologies or processes. In this case, the model can be too pessimistic in representing adaptation processes and the related costs. However, predicting trends in technological progress is a very uncertain exercise.

The study has shown the importance of the regional trade. In the current work, we use the GTAP Armington elasticities and we increase them to model intranational trade. Further research can improve the calibration of elasticities at the sub-national level. Our model also assumes a perfectly competitive market structure, which can be rather unrealistic especially in the analysis of energy sectors where the oligopolistic market structure could be more representative. This could be another robustness check of our findings.

Assumptions about labour mobility within member states and across Europe may play an important role. Indeed, increasing levels of labour mobility could influence the results of the study but we assume here that workers cannot move outside the sub-national region.

Finally, we note that it could be interesting to apply this framework to other large countries such as the USA or China to test if the regionalization may have a similar importance in shaping the macro-economic effects. Climate change impacts on energy demand can be easily re-scaled according to the new regional scope, but sub-national CGE models should be available for those economies.

Appendix

A.1: Regionalizing the GTAP Database

In the following sections, we summarise how the sub-national SAMs have been obtained starting from the GTAP 8 database (Narayanan et al. 2012). Concerning the number of regions in each country, we should keep in mind that the regionalization process is very time-consuming. The process requires to specify all the variables in the original GTAP database at the sub-national level, to balance the sub-national Social Accounting Matrices and to compute the intranational bi-lateral trade flows. Therefore, we adopt a sub-national detail (NUT2 or NUTS1) for the larger economies, such as Germany, France, UK, Italy, and Spain. Small countries such as the Baltic countries, Luxembourg, Slovenia, and Croatia are kept at the national NUTS0 level. Some medium-sized countries like Netherlands, Sweden, Belgium, Poland, and Czech Republic are also regionalised to better represent Eastern Europe, Scandinavia, and Benelux.

It is worth noting that our downscaling method is applied to a global database. Therefore, the database includes information also for 18 regions in the rest of the world; Latin America, USA, Rest of North America, North Africa, Sub Saharan Africa, South Africa, Middle East, India, South Asia, South East Asia, East Asia, China, Japan, Former Soviet Union, Rest of Europe, EFTA, Australia, and New Zealand. For these macro-regions as well, we compute impacts on energy demand in the different RCPs.

A.1.1: Creating and Balancing the Sub-national EU SAMs

The collection of the sub-national information is only a preliminary step to obtain the final database. We use the methodology in Bosello and Standardi (2018) to compute and balance the regionalised SAMs. The methodology is applied in the following steps. In the CGE model, the value added is the sum of primary factors remuneration (labour, capital, land, natural resources). Therefore, the first step of the process consists in disaggregating the value added, originally available at the country level in the GTAP 8 database, to the new regional scale. To do this, first, we match the GTAP sectors with those of our data sources from Eurostat. Then, in each sector the regional shares of labour, capital, land, and natural resources are computed from the sub-national data and used to distribute the respective GTAP data across the sub-national units.

The second step is more challenging as we need to compute intranational trade. This is equivalent to compute the sub-national domestic and imported consumption from the Eurostat information we collected. Indeed, sub-national data on intranational trade is often missing and needs to be reconstructed using different techniques. In our case we rely on the so-called Simple Locations Quotients (SLQs) (Miller and Blair 1985; Bonfiglio and Chelli 2008; Bonfiglio 2008). The formula for the SLQs is the following:

$$SLQ_{i,r} = \frac{X_{i,r}/X_r}{X_{i,c}/X_c} \tag{1}$$

where i is the sector and X the value added, r and c represent the regional and national indexes, respectively. SLQ gives a measure of the regional specialisation in the economic activity. When SLQ is equal to zero, the region needs to import intermediate and final goods from other regions. In the other extreme case, the sectoral value added in the region is equal to the national one and this means that the region tends to export those goods for intermediate or final consumption. Clearly in almost all the cases the SLQ values are in between the two extreme cases. The sub-national shares of domestic and imported demand are obtained by multiplying the national shares times SLQs and then normalising these shares.

The final step consists in the determination of the bilateral trade flows across the sub-national regions. The procedure usually adopted is based on gravitational approaches as in Horridge and Wittwer (2010) and Dixon et al. (2012). By this method, the bilateral intra-country trade flows are estimated using a gravity equation. We also follow a gravitational approach based on the kilometric road distance between each couple of capital cities for the regions within the country. We adjust the trade flows across sub-national regions by using the RAS statistical method (Bacharach 1970) to make them consistent with the aggregate intranational exports and imports obtained through the SLQs.

A.1.2: Splitting the Electricity Sector at the Sub-national Level

In the construction of the SSP-RCP combinations, it is important to represent the electricity sector in a sophisticated manner because the energy sector develops differently according to each scenario, and this has relevant economic implications for the macro-economic assessment. For example, in SSP1 we may expect a strong development of the renewables-based power generation sector and a progressive electrification of the economy while in SSP5 fossil fuels remain important sources for both the electricity sector and the overall economy. Therefore, we have increased the detail of the electricity sector at the sub-national level in the reference year 2007. We use information from the World Electric Power Plants Database (WEPP) (PLATTS 2014) to increase the technological detail in the electricity sector at the NUTS1/2 level. WEPP is a global inventory of electric power generating units managed by S&P Global. It provides information on more than 107,500 plant sites in more than 230 countries and territories and details on plant operators, geographic location, capacity (MW), age, technology, fuels, and boiler, turbine, and generator manufacturers, emissions control equipment, renewable energy units and more. Using the WEPP information, we are able to include in the electricity sector six more technologies at the sub-national EU level: nuclear, fossil power generation, wind, hydropower, solar, and other renewables.

See Tables 5, 6 and Figs. 10, 11, 12, 13.

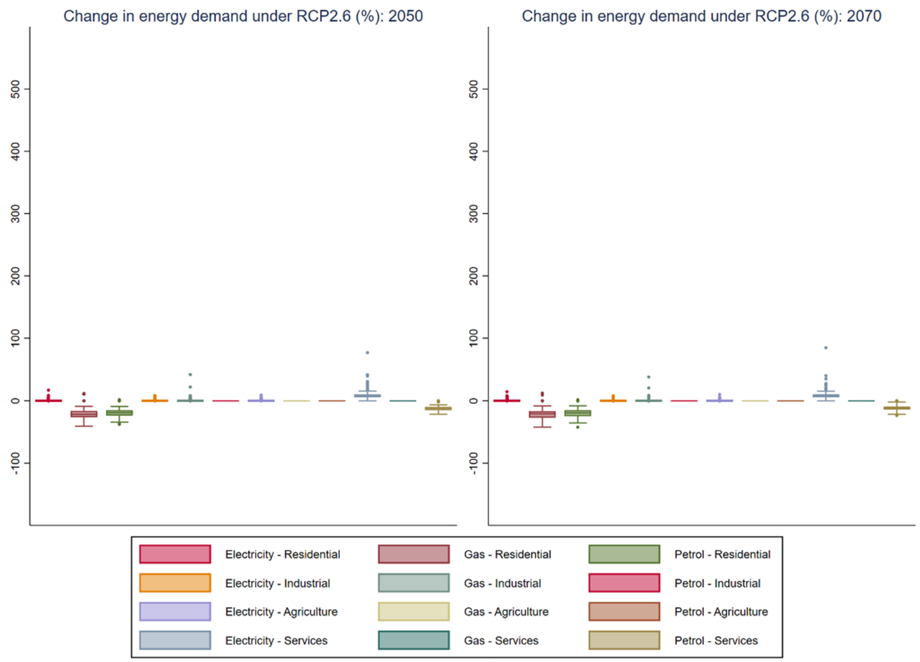

Fig. 10 Box-plot of climate-induced energy demand trends in EU regions and RCP2.6 (2015–2050% changes left, 2015–2070% changes right)

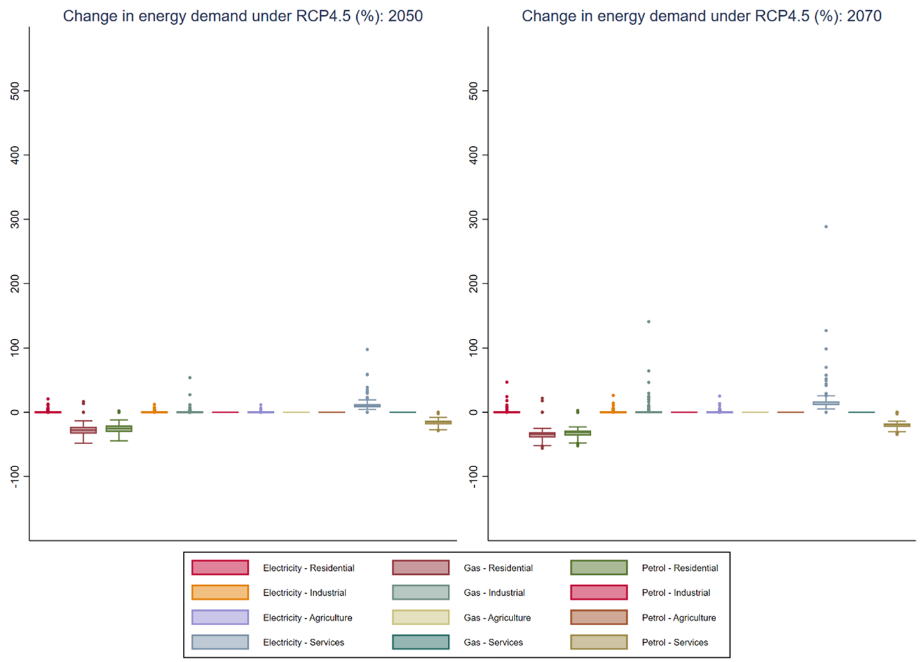

Fig. 11 Box-plot of climate-induced energy demand trends in EU regions and RCP4.5 (2015–2050% changes left, 2015–2070% changes right)

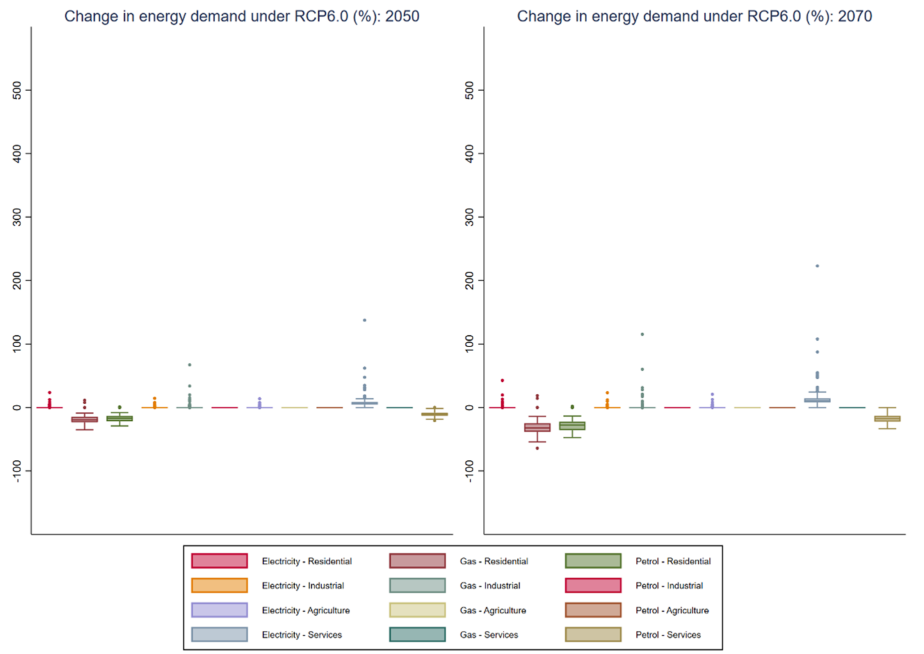

Fig. 12 Box-plot of climate-induced energy demand trends in EU regions and RCP6.0 (2015–2050% changes left, 2015–2070% changes right)

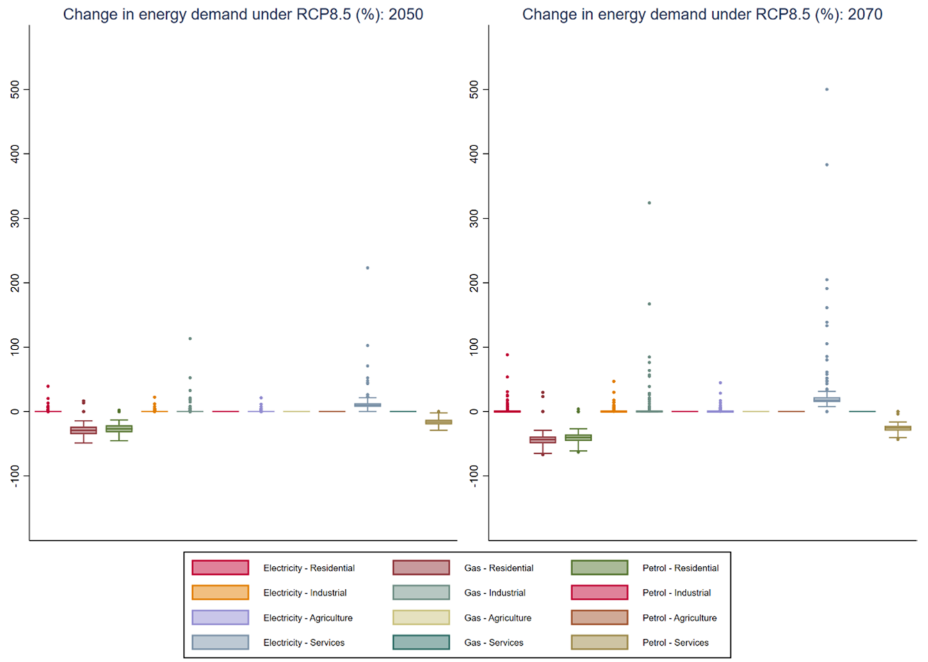

Fig. 13 Box-plot of climate-induced energy demand trends in EU regions and RCP8.5 (2015–2050% changes left, 2015–2070% changes right)

Table 5 Mapping between EU regions of the ICES model and NUTS 2013 EU code

No	ICES EU regions	NUTS Level (from level 0 country to level 2)	NUTS 2013 code	Country
1	East Austria	NUTS1	AT1	Austria
2	South Austria	NUTS1	AT2	Austria
3	West Austria	NUTS1	AT3	Austria
4	Brussels	NUTS1	BE1	Belgium
5	Flanders	NUTS1	BE2	Belgium
6	Wallonia	NUTS1	BE3	Belgium
7	Cyprus	NUTS0	CY	Cyprus
8	Prague	NUTS2	CZ01	Czech Rep
9	CentBoemia	NUTS2	CZ02	Czech Rep
10	Souwestcze	NUTS2	CZ03	Czech Rep
11	Norwestcze	NUTS2	CZ04	Czech Rep
12	Noreastcze	NUTS2	CZ05	Czech Rep
13	Soueastcze	NUTS2	CZ06	Czech Rep
14	CentMoravia	NUTS2	CZ07	Czech Rep
15	MoraviaSil	NUTS2	CZ08	Czech Rep
16	Denmark	NUTS0	DK	Denmark
17	Estonia	NUTS0	EE	Estonia
18	Finland	NUTS0	FI	Finland
19	IleFrance	NUTS2	FR10	France
20	ChamArde	NUTS2	FR21	France
21	Picardie	NUTS2	FR22	France
22	HautNorm	NUTS2	FR23	France
23	Centre	NUTS2	FR24	France
24	BasseNorm	NUTS2	FR25	France
25	Bourgogne	NUTS2	FR26	France
26	NordPCalais	NUTS2	FR30	France
27	Lorraine	NUTS2	FR41	France
28	Alsace	NUTS2	FR42	France
29	FranComte	NUTS2	FR43	France
30	PaysLoire	NUTS2	FR51	France
31	Bretagne	NUTS2	FR52	France
32	PoitouChar	NUTS2	FR53	France
33	Aquitaine	NUTS2	FR61	France
34	MidiPyren	NUTS2	FR62	France
35	Limousin	NUTS2	FR63	France
36	RhoneAlp	NUTS2	FR71	France
37	Auvergne	NUTS2	FR72	France
38	LangRouss	NUTS2	FR81	France
39	Provence	NUTS2	FR82	France
40	Corse	NUTS2	FR83	France
41	BadenWur	NUTS1	DE1	Germany
42	Bavaria	NUTS1	DE2	Germany
43	Berlin	NUTS1	DE3	Germany
44	Branden	NUTS1	DE4	Germany

Table 5 (continued)

No	ICES EU regions	NUTS Level (from level 0 country to level 2)	NUTS 2013 code	Country
45	Bremen	NUTS1	DE5	Germany
46	Hamburg	NUTS1	DE6	Germany
47	Hessen	NUTS1	DE7	Germany
48	MeklenVor	NUTS1	DE8	Germany
49	LowSaxony	NUTS1	DE9	Germany
50	NorRenoWes	NUTS1	DEA	Germany
51	RenoPala	NUTS1	DEB	Germany
52	Saarland	NUTS1	DEC	Germany
53	Saxony	NUTS1	DED	Germany
54	SaxonyAnh	NUTS1	DEE	Germany
55	SchHol	NUTS1	DEF	Germany
56	Turingia	NUTS1	DEG	Germany
57	Voreia	NUTS1	EL1 (NUTS 2010 code)	Greece
58	Kentriki	NUTS1	EL2 (NUTS 2010 code)	Greece
59	Attiki	NUTS1	EL3	Greece
60	Nisia	NUTS1	EL4	Greece
61	Hungary	NUTS0	HU	Hungary
62	Ireland	NUTS0	IE	Ireland
63	Piemonte	NUTS2	ITC1	Italy
64	ValAosta	NUTS2	ITC2	Italy
65	Lombardia	NUTS2	ITC4	Italy
66	TrentAdige*	NUTS2	ITH1-ITH2	Italy
67	Veneto	NUTS2	ITH3	Italy
68	FriuliGiulia	NUTS2	ITH4	Italy
69	Liguria	NUTS2	ITC3	Italy
70	EmiRom	NUTS2	ITH5	Italy
71	Toscana	NUTS2	ITI1	Italy
72	Umbria	NUTS2	ITI2	Italy
73	Marche	NUTS2	ITI3	Italy
74	Lazio	NUTS2	ITI4	Italy
75	Abruzzo	NUTS2	ITF1	Italy
76	Molise	NUTS2	ITF2	Italy
77	Campania	NUTS2	ITF3	Italy
78	Puglia	NUTS2	ITF4	Italy
79	Basilicata	NUTS2	ITF5	Italy
80	Calabria	NUTS2	ITF6	Italy
81	Sicilia	NUTS2	ITG1	Italy
82	Sardegna	NUTS2	ITG2	Italy
83	Latvia	NUTS0	LV	Latvia
84	Lithuania	NUTS0	LT	Lithuania
85	Luxembourg	NUTS0	LU	Luxembourg
86	Malta	NUTS0	MT	Malta
87	NorthNether	NUTS1	NL1	Netherlands
88	EastNether	NUTS1	NL2	Netherlands

Table 5 (continued)

No	ICES EU regions	NUTS Level (from level 0 country to level 2)	NUTS 2013 code	Country
89	WestNether	NUTS1	NL3	Netherlands
90	SouthNether	NUTS1	NL4	Netherlands
91	CentPol	NUTS1	PL1	Poland
92	SouthPol	NUTS1	PL2	Poland
93	EastPol	NUTS1	PL3	Poland
94	NorWestPol	NUTS1	PL4	Poland
95	SouWestPol	NUTS1	PL5	Poland
96	NorthPol	NUTS1	PL6	Poland
97	Norte	NUTS2	PT11	Portugal
98	Algarve	NUTS2	PT15	Portugal
99	Centro	NUTS2	PT16	Portugal
100	Lisboa	NUTS2	PT17	Portugal
101	Alentejo	NUTS2	PT18	Portugal
102	Slovakia	NUTS0	SK	Slovakia
103	Slovenia	NUTS0	SI	Slovenia
104	Galicia	NUTS2	ES11	Spain
105	Asturias	NUTS2	ES12	Spain
106	Cantabria	NUTS2	ES13	Spain
107	PaisVasco	NUTS2	ES21	Spain
108	Navarra	NUTS2	ES22	Spain
109	LaRioja	NUTS2	ES23	Spain
110	Aragon	NUTS2	ES24	Spain
111	Madrid	NUTS2	ES30	Spain
112	CastLeon	NUTS2	ES41	Spain
113	CastMancha	NUTS2	ES42	Spain
114	Extremadura	NUTS2	ES43	Spain
115	Cataluna	NUTS2	ES51	Spain
116	Valencia	NUTS2	ES52	Spain
117	Balears	NUTS2	ES53	Spain
118	Andalucia**	NUTS2	ES61–ES63–ES64	Spain
119	Murcia	NUTS2	ES62	Spain
120	Canarias	NUTS2	ES70	Spain
121	EastSweden	NUTS1	SE1	Sweden
122	SouthSweden	NUTS1	SE2	Sweden
123	NorthSweden	NUTS1	SE3	Sweden
124	NorEastEng	NUTS1	UKC	UK
125	NorWestEng	NUTS1	UKD	UK
126	YorkHumber	NUTS1	UKE	UK
127	EastMidEng	NUTS1	UKF	UK
128	WestMidEng	NUTS1	UKG	UK
129	EastofEng	NUTS1	UKH	UK
130	London	NUTS1	UKI	UK
131	SouEastEng	NUTS1	UKJ	UK
132	SouWestEng	NUTS1	UKK	UK

Table 5 (continued)

No	ICES EU regions	NUTS Level (from level 0 country to level 2)	NUTS 2013 code	Country
133	Wales	NUTS1	UKL	UK
134	Scotland	NUTS1	UKM	UK
135	NorthIre	NUTS1	UKN	UK
136	Bulgaria	NUTS0	BG	Bulgaria
137	Croatia	NUTS0	HR	Croatia
138	Romania	NUTS0	RO	Romania

*It includes two Italian Nuts2 regions: Provincia Autonoma di Bolzano (ITH1) and Provincia Autonoma di Trento (ITH2)

**It includes three Nuts2 Spanish regions: Andalucia (ES61), Ceuta (ES63) and Melilla (ES64)

Table 6 Transmission and distribution (Tr&D) share in the value added of the electricity sector. Source: GTAP-Power database for the year 2007 (Peters 2016)

	Tr&D share (%)		Tr&D share (%)
Austria	21.27	Latvia	24.15
Belgium	21.42	Lithuania	27.42
Bulgaria	25.96	Luxembourg	26.18
Croatia	67.96	Malta	84.05
Cyprus	79.94	Netherlands	29.59
Czech Republic	19.32	Poland	24.70
Denmark	21.65	Portugal	23.17
Estonia	45.61	Romania	26.54
Finland	22.77	Slovakia	20.95
France	20.55	Slovenia	21.60
Germany	26.63	Spain	25.03
Greece	43.90	Sweden	16.11
Hungary	26.00	United Kingdom	24.70
Ireland	22.83	EU28	24.66
Italy	28.73		

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Declarations

Conflict of interest All authors declare that they have no conflicts of interest to disclose.

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