Sensitivity of Modeling Results to Technological and Regional Details: The Case of Italy's Carbon Mitigation Policy

Gabriele Standardi[a,b,*], Yiyong Cai[c] and Sonia Yeh[d,e]

Abstract

Models' differences in technological and geographical scales are common, but their contributions to uncertainties have not been systematically quantified in the climate policy literature. This paper carries out a systematic assessment on the sensitivity of Computable General Equilibrium models to technological and geographical scales in evaluating the economic impacts of carbon mitigation policies. Taking Italy as an example, we find that the estimation for carbon price and economic cost of a de-carbonization pathway by a model with technological and regional details can be lower than a model without such details by up to 40%. Additionally, the effect of representing regional details appears to be several times more important than the effect of representing the details of electricity technology in both the estimated carbon prices and the estimated impacts on electricity production. Our results for Italy highlight the importance of modeling uncertainties of these two key assumptions, which should be appropriately acknowledged when applying CGE models for policy impact assessment. Our conclusions can be generalized to different countries and policy scenarios not in terms of magnitudes of results but in terms of economic explanation. In particular, intra-national trade and the sub-national sectoral/technological specialization are important variables to understand the economic dynamics behind these outcomes.

Keywords: Computable General Equilibrium, Carbon Mitigation Policy, Sensitivity, Technology, Sub-national regions

[a] CMCC – EuroMediterranean Center on Climate Change

[b] FEEM – Fondazione Eni Enrico Mattei

[c] CSIRO – Commonwealth Scientific and Industrial Research Organisation

[d] Institute of Transportation Studies, University of California, Davis

[e] Department of Energy and Environment, Chalmers University of Technology

[*] Corresponding author, Email: gabriele.standardi@feem.it

1. Introduction

The rapidly increasing concentration of greenhouse gases (GHG) in the atmosphere due to human activity is one of the key contributing factors to climate change (IPCC, 2014a). To further mitigate the potential negative impacts of climate change, the European Union (EU) has defined ambitious targets for emissions reduction, renewables development[1] and energy efficiency (European Council, 2014), aiming to achieve a 40% GHG emission reduction target compared to 1990 by the end of 2030. To achieve the target of 40% reduction commitment, the existing cap of 1.74% annual reduction 2015-2020 will need to be lowered by 2.2% per year from 2021 (European Council, 2014). The current price of EU ETS is around €5 per tons of CO2-equivalent (CO2e) since 2013. Various studies suggest that significant reforms are needed to ensure the effectiveness of EU-internal abatement as of 2030, including restoring a higher price path to the anticipated €30 or higher (Brink et al., 2014; Hu et al., 2015).

The European target is now part of the legally binding global agreement adopted at the Paris Conference (COP21) in December 2015 to limit global warming to well below 2°C (FCCC, 2015; Latvian Presidency of the Council of the European Union, 2015). 188 countries representing 98% of global emission have made their Intended Nationally Determined Contribution (INDC). Among these countries there are the most important economic players such as the United States, China, the European Union, Russia and India. The INDCs include both adaptation and mitigation actions. These actions will entail a reduction of GHG emissions at certain point in time, the transition toward green technologies and presumably some carbon pricing.

Imposing a higher carbon price will increase the overall cost of industrial production and household consumption of fossil-based energy and activities. As a result, producers will switch to less carbon intensive energy sources and technologies and practices such as energy conservation while consumers will shift to goods and services with lower embodied emissions or reduce demand. The transition requires investment in new infrastructure, altered patterns of resource use, and shifts in labor markets. High transition costs can be associated with an ambitious de-carbonization target such as those committed by the EU. The debate on the costs of climate change mitigation implies very sensitive political considerations on distributional impacts among regions and industries (Gough, 2013; Barrett et al., 2015), and such discussions need to be based on rigorous quantitative analyses. In this context, Computable General Equilibrium (CGE) modeling has been a popular tool

[1] The EU has established a mandatory target that at least 27% of energy consumption must come from renewables by the end of 2030.

for analyzing the economic impacts of national carbon mitigation policies. The modeling approach captures the interactions between supply, demand, prices, labor, capital and trade; and it therefore provides a rigorous and consistent evaluation framework to quantify the socioeconomic impacts of government policies on the energy production and consumption as well as other related economic activities. By identifying the winners and losers among affected regions, sectors, institutions and technologies, CGE models can help policy makers gain a balanced view about consequences of their decisions.

However, results from CGE models vary greatly, and sometimes even contradictory, even for a common scenario setting. For instance, five recent studies suggest that for the EU27 countries to achieve a 20% emission reduction target by 2020 compared to 1990 level, the carbon price can range from 19 €/tCO2 to 70 €/tCO2, while there could be gross domestic product (GDP) gains of around 0.1% or losses of up to 2% (Bohringer et al., 2009; Durand-Lasserve et al., 2010; Peterson et al., 2011; Bosello et al., 2013; Orecchia and Parrado, 2013). Similarly, Pearce (2012) find that for Australia to achieve a 15% reduction of the country's CO2 emission in 2020 from the 2000 level, the national carbon price is estimated to be from 25$ to 70$ per ton of CO2 according to a meta-analysis of different CGE models, including G-Cubed (McKibbin et al., 2010), GTEM (Commonwealth of Australia, 2008 and 2011), and the Tasman Global Model (ACIL Tasman, 2008), and the consequential GDP losses could range from 0.4% to 1.4% from the business as usual.

Large variations in modeling results are not surprising, and numerous modeling comparison efforts have been conducted since 1970s to explore the underlying factors contributing to the differences and to gain insights (e.g. some more recent efforts include Luderer, Bosetti et al. (2012), IPCC (2014b), and Fawcett et al. (2014)). Most of the differences in modeling results can be attributed to differences in (1) modeling mechanisms (e.g. macroeconomic "top-down" model vs. "bottom-up" technology-detailed optimization model); (2) assumptions about baseline scenarios, (3) assumptions on characteristics of available technologies, policy constraints, and expectations that shape decision behaviors (i.e. the modeling of market distortions and second best outcomes (Carraro et al., 2012); (4) the scope and the system boundary of the model; and (5) framing of policy questions (Pearce, 2012).

Among these factors, the models' differences in technological and geographical scales are particularly noticeable, even though their contributions to uncertainties have not been systematically quantified in the climate policy literature. As an example, studies examining 20% emission reduction target by 2020 in EU27 show different levels of sophistication in representing the electric sector and country-level details. The ICES model (Bosello et al. 2013; Orecchia and Parrado 2013) has four electricity technologies including hydro, solar, wind and others, whereas the models used in other studies have only one electricity sector without further technological details. Peterson et al. (2011) considers EU27 as a single economic unit, while the models in other studies account for each major country separately. In the Australian case study referenced above, while the GTEM model (Commonwealth of Australia, 2008 and 2011) and the Tasman Global model (ACIL Tasman, 2008) disaggregate the electricity sector into a menu of technologies with different cost structures and carbon intensities, the G-Cubed model (McKibbin et al., 2010) represents the production of electricity as a single technology. Similarly, the Tasman Global model considers each Australian state and territory as a single economic unit, whereas G-Cubed and GTEM do not account for the sub-national differences.

Given the large differences in the cost and emissions profiles of electricity generation technologies, there will be variations in the represented electricity sectors' responses to shocks such as policy changes. For example, the average levelized cost of electricity (LCOE) for a conventional coal power plant is much lower than that of a solar unit (EIA, 2014). Furthermore, nations with politico-economic union or administrative units within a nation are heterogeneous in their socioeconomic characteristics. Each region can be affected differently by a given policy shock. Whether or not models take into account these technological and regional details can affect models' ability and the degree of the response to policies such as a carbon tax, leading to large difference in the assessment of the economic impacts of policies. Nevertheless, the importance of model differences in the assumptions of technological and regional details have not been clearly communicated nor analytically examined, making it difficult to place results on a comparable basis and put forward insights and policy recommendations.

It is the aim of this paper to carry out a systematic assessment on the sensitivity of CGE models to the assumptions of technological and geographical scales. Using Italy, the fourth largest economy and third carbon emitter in EU, as a case study, we investigate the robustness of the model's results to a carbon mitigation policy given model's structure in technological and regional details. We start with a basic version of a global CGE model and database, which considers Italy as one single economic unit and has one technology in the electricity sector. We then disaggregate the electricity sector into a bundle of various generation technologies, and split Italy into 20 sub-national regions to create more spatially disaggregated versions of the model. The comparison across different model specifications enables us to quantify the importance of technological and regional disaggregation in response to a given policy by carefully laying out the causal inferences that drive the differences of results, and quantitatively assessing the impacts on the results within the realm of the climate policies that we examined in this study. To the best of our knowledge, this is the first study to quantify the importance of technological and regional details in CGE modeling of carbon mitigation policies.

The paper is organized as follows. In section 2 we present the economic and energy landscape of the Italian regions. In section 3 we describe the methodology for increasing the technological and geographical resolution of a CGE model, and set out the experiment design. In section 4 we discuss results and provide an economic interpretation. We conclude in Section 5 and offer our insights, caveats and suggestions for future studies.

2. The economic and energy landscape of the Italian regions

As already mentioned, the purpose of the paper is to carry out a systematic assessment on the sensitivity of CGE models to the assumptions of technological and geographical details. The Italian case study is particularly interesting as Italy is characterized by much heterogeneity at the socio-economic and technological-energy level. Overall, the country can be split into Northern, Central and Southern regions as displayed in Figure 1.

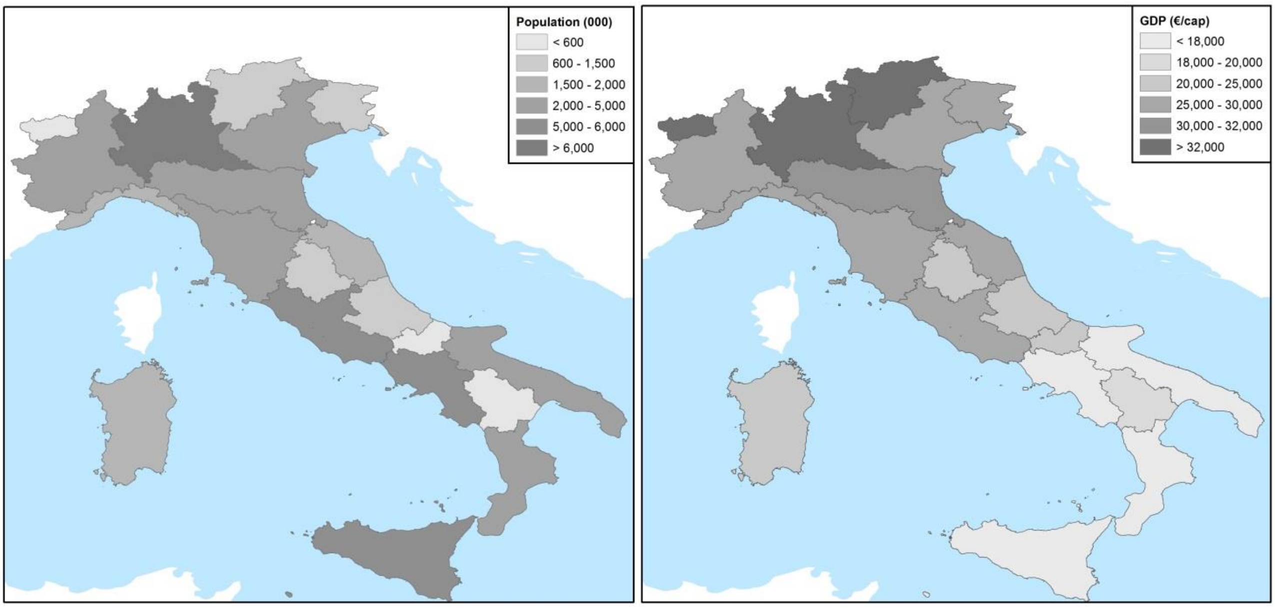
Figure 1: Map of Italian regions

Legend

Piedmont	Northern regions
Aosta Valley	
Lombardy	
Trentino Alto Adige	
Veneto	
Friuli Venezia Giulia	
Liguria	
Emilia-Romagna	
Tuscany	Central regions
Umbria	
Marche	
Lazio	
Abruzzo	Southern regions
Molise	
Campania	
Apulia	
Basilicata	
Calabria	
Sicily	
Sardinia	

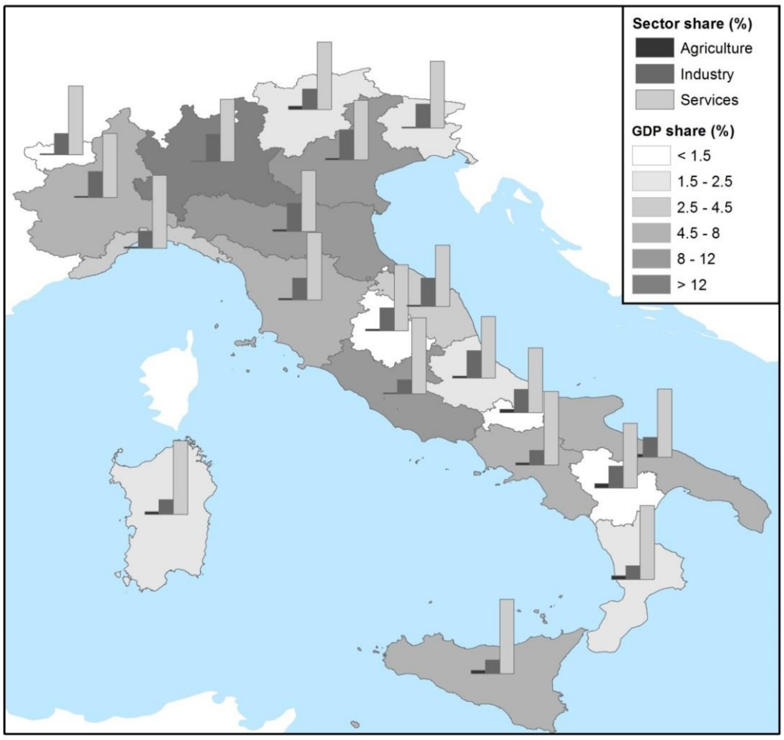
The demographic composition in Figure 2 shows that Lombardy in the North has the highest population. Campania and Sicily in the South and Lazio in the Center are also relatively populous, representing 9.6, 8.3 and 9.5% of the Italian population, respectively. Strong economic disparities can be observed within the Italian territory. The North is richer than the South in per capita terms (Figure 2). Despite a huge deindustrialization process occurring from 2008 after the global financial crisis, the North regions on average are still more specialized in manufactures (Figure 3). In contrast, the Southern regions are slightly more reliant on agriculture; and the central regions are mixed with Lazio exhibiting a strong specialization in services, in particular public services for its role as the region hosting the capital Rome.

Figure 2: Population and GDP per capita in 2011 of the Italian regions



Source: Italian Statistical Office (ISTAT).

Figure 3: GDP shares and sectoral shares in 2011 of the Italian regions

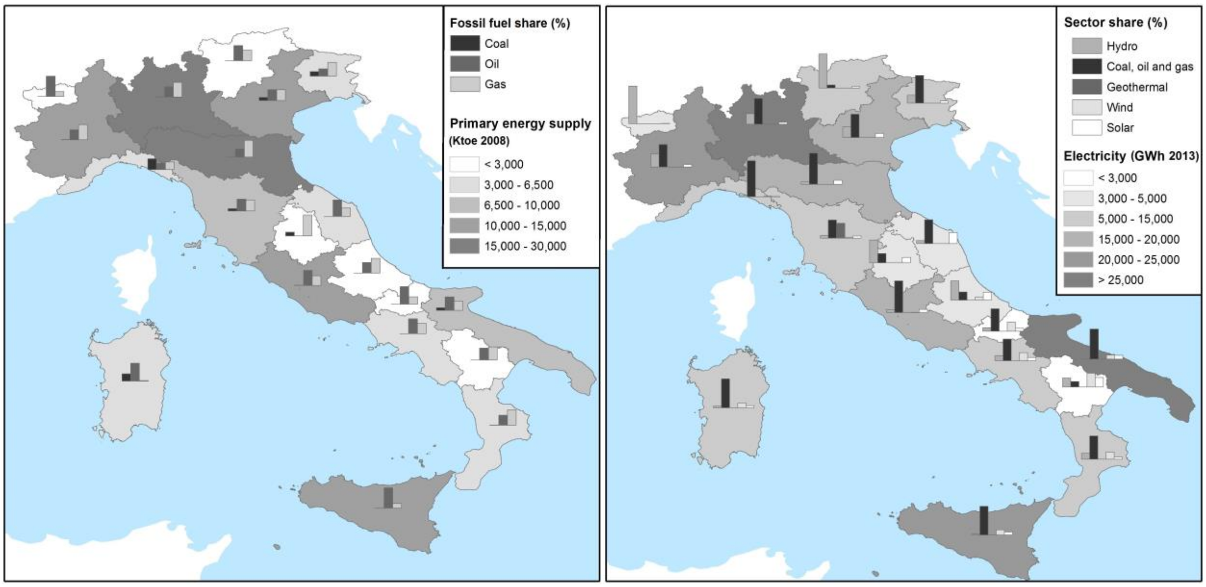


Source: Italian Statistical Office (ISTAT).

The primary energy supply in Italy depends heavily on imports of coal, oil and gas from abroad[2]. Figure 4 shows how the supply is distributed across the regions. Oil and gas prevail in all the regions except Liguria where coal is still dominant. The energy intensive Northern economies of Lombardy, Emilia-Romagna, Piedmont and Veneto show the highest values of energy supply in million tons of oil equivalent (Mtoe). In the south Sicily also exhibits high numbers because of its important role in the refinery that imports oil.

[2] Source: https://www.eia.gov/beta/international/country.cfm?iso=ITA

Figure 4: Primary Energy Supply in 2008 and Power Generation in 2013 of the Italian Regions



Source: Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA) for the primary energy supply, and Trasmissione Elettrica Rete Nazionale (TERNA) for the electricity mix.

Figure 4 also shows the electricity generation mix[3]. Fossil fuels are prevailing in most Italian regions except the South regions (Abruzzo and Basilicata), Center (Toscana and Umbria) and the Alpine regions Trentino and Aosta Valley where there are large shares of hydro. In general, wind plays a non- negligible role in the South because of favorable climatic conditions. Solar is becoming more and more important in some regions of Center-South including Umbria, Marche, Abruzzo and Basilicata. It is worth noting that the situation is still evolving and the time-series data show a substantial variability. These sectors are relatively young and technology is likely to change rapidly in the next years.

Tuscany is unique in the Italian panorama for renewables. Taking advantage of its geothermal resources, this region has highly developed geothermal technology. In the South, Apulia, Sicily and Sardinia are fossil-fuel intensive. The scarcity of water basins makes hydro almost entirely absent in these regions. Solar and wind only partially compensate for this gap. Basilicata has the largest oil reserve in Europe but during the last decade it has seen a rapid growth of solar and wind, generating together with hydro more than three quarter of the electricity production.

[3] Figure 4 presents recent data from Trasmissione Elettrica Rete Nazionale (TERNA) on the electricity mix (http://download.terna.it/terna/0000/0113/40.pdf). TERNA does not provide information on biomass and waste. We use data from Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA) for the year 2008 to include these two technologies in the CGE model (Catoni and Iorio, 2011).

The gap between regions is even more pronounced for energy consumption (see Figure 5)[4]. This is largely driven by the sectoral specialization across regions as we have discussed above. Overall, energy consumption (electricity included) is greater in the Northern regions, which have more industries, than in the South regions. In absolute terms, Lombardy consumes the highest level of energy. However, some exceptions exist. For example, Apulia in the South has strong energy consumption in industry because of the presence of refineries and steelworks.

Transportation is also an important driver of energy consumption. For instance, Trentino Alto Adige, Aosta Valley and Liguria in the North consume higher share of energy from transport. Similarly, Lazio, Campania, Sicily and Sardinia in the Center and the South also see a large share of energy consumption (38-47 %) by the transportation sector.

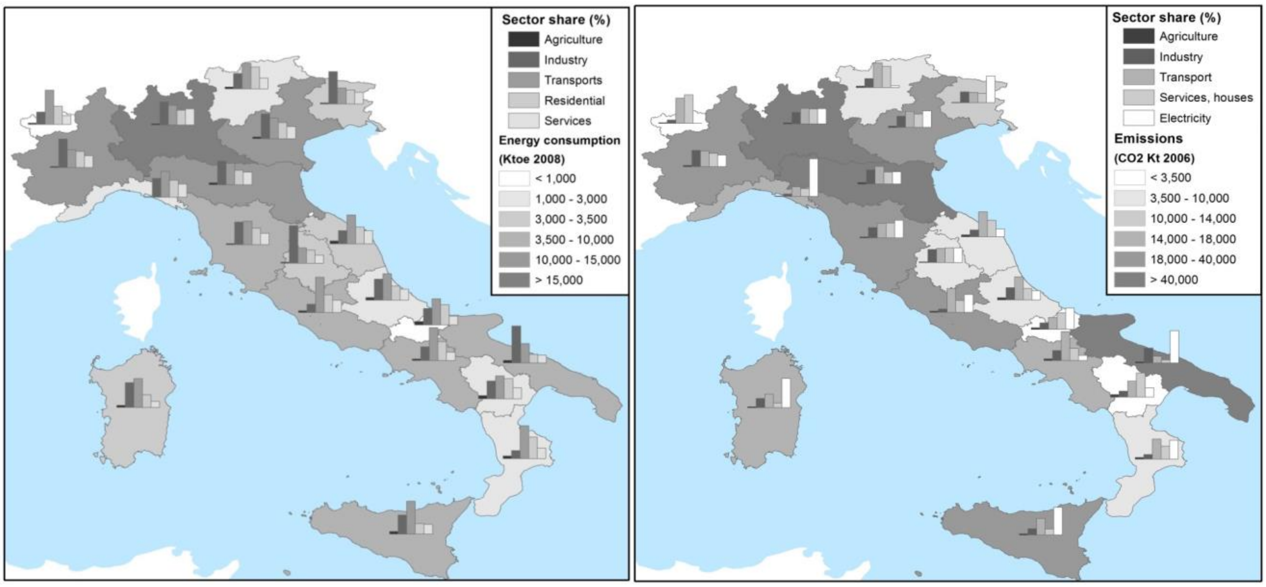
Energy consumption in residential sector is a combination of economic, technological and geographical factors, all of which interact and contribute to the total consumption. For example, the colder Northern regions consume more energy during the winter for heating and the warmer Southern regions consume more energy during the summer for air-conditioning. The physical morphology also matters (mountainous or flat regions) together with different levels of energy efficiency. Figure 4 shows that the Alpine Northern region Trentino Alto Adige and Southern flat region Apulia have the highest and lowest shares of their energy consumption in the residential sector.

Ultimately, emissions (Figure 5) reflect the pattern of energy supply and demand profiles discussed above. The hydropower covers a very high share of the electricity in the Alpine regions Trentino Alto Adige and Aosta Valley. This explains the very low shares of these two regions for emissions in the electric sector. Conversely, Liguria is fossil-fuels intensive and shows the highest share of emissions.

Because of these technological and socio-economic differences, it is reasonable to anticipate variations in the responses of different Italian regions to a carbon tax.

[4] Both data for energy consumption and emissions at the regional level stem from ENEA, Catoni and Iorio (2011) and Mancuso (2010), respectively.

Figure 5: Energy Consumption in 2008 and CO2 Emissions in 2006 of the Italian Regions



Source: Ente per le Nuove tecnologie, l'Energia e l'Ambiente (ENEA)

3. Methodology for detailing the technological and geographical characteristics in CGE modeling

3.1 General characteristics of the CGE model

Our CGE model has a neo-classical economic structure. This means that investments are saving driven and perfect competition holds in all the good markets. In each country or region a representative household maximizes the consumption utility flow subject to a budget constraint. In each country or region and each sector a representative firm minimizes costs subject to a technological constraint. Labor and capital are perfectly mobile between sectors of the economy but immobile within the country. Their remunerations accrue to the representative household. Countries or regions interact through trade (exports and imports) and investment flows. The CGE is a market-based tool and the introduction of a tax is equivalent to create a market distortion and a consequent welfare loss[5].

Our starting point is the CTAP model developed by Cai and Arora (2015), which is a variant of the neo-classical CGE model Global Trade Analysis Project (GTAP) (Hertel, 1997). GTAP is calibrated to the GTAP 8 database (Narayanan et al., 2012), a series of SAMs (Social Accounting Matrixes) for a maximum number of 129 countries or groups of countries (among them Italy) and

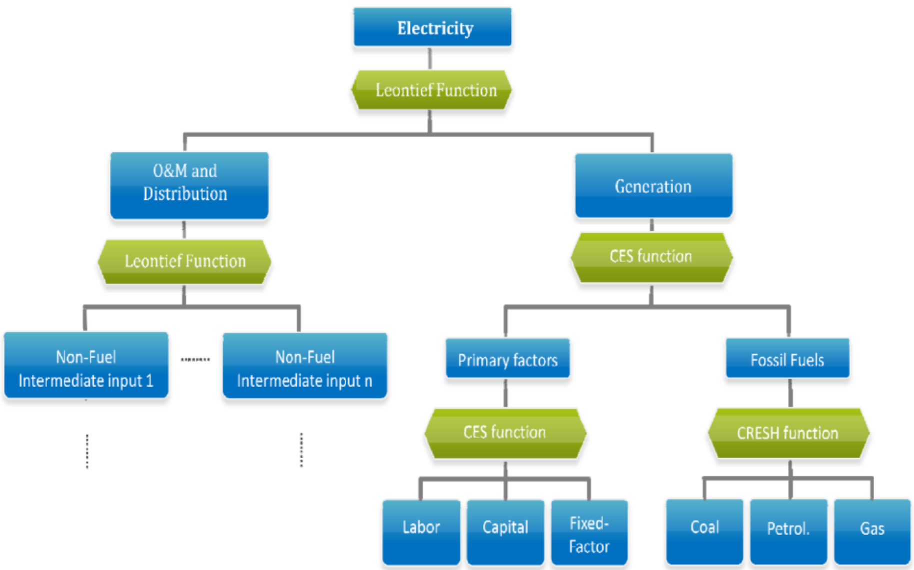
[5] Traditional CGE models do not account for the environmental benefits of climate change mitigation due to a carbon price or equivalently a carbon tax. When these benefits are internalized in an integrated modeling framework, a carbon price/tax can lead to welfare gains (see, e.g., Cai et al. (2015)).

57 sectors covering all the economic system for the year 2007. A SAM is a description of a country's supply and use table, containing details of sectors, activities, commodities, institutions and capital account (Miller and Blair, 2009). It is the key matrix that measures distributional impacts of policy stimulations.

3.2 Disaggregating electricity technologies: from CTAP-1 to CTEM-1

The CTAP model considers the electricity sector as characterized by a unique technology. This technology (Figure 6) is a Leontief function between power generation and non-fuel intermediates inputs involved in the O&M and distribution activities. In addition the generation technology allows substitution by the means of a CES (Constant Elasticity Substitution) function between the bundle of primary factors (capital, labor and a fixed factor specific to the technology) and the bundle of fossil fuel intermediates (oil, coal and gas). As seen in the figure, imposing a carbon price will result in a shift toward higher share costs of labor and capital and less oil, coal and gas, mimicking the uptake of renewable power technologies.

Figure 6: Electricity generation in CTAP



The CTEM model[6] (Cai and Arora, 2015; Cai et al, 2015) is otherwise identical to CTAP but uses an electricity technology bundle (Figure 7). The CTEM model features disaggregated modeling of

[6] In the paper of Cai et al. (2015) CTEM is referred to as GTEM-C. GTEM (Global Trade and Environment Model) was developed by Pant (2007). GTEM-C has added new features in both model and database. The letter C refers to the Australian research institute CSIRO (Commonwealth Scientific and Industrial Research Organization) whose team has upgraded the original GTEM model.

the electricity sector into a bundle of 13 generation technologies (Coal, Oil, Gas, Nuclear, Hydro, Wind, Solar, Biomass, Waste, Geothermal, Coal plus CCS, Oil plus CCS, Gas plus CCS). Competing electricity technologies are combined through the CRESH (Constant Ratios of Elasticities of Substitution, Homothetic) function (see Hanoch, 1971; Pant, 2007; Cai and Arora, 2015), which allows for differing levels of substitution between any two technologies.

In both models, commodity-embedded flows of energies and GHG emissions (CO_2, N_2O, CH_4 and F-gases) are calculated based on the economic values of the SAM. To build these SAMs, both CTEM and CTAP are calibrated to the GTAP 8 database and other available data from the IEA (International Energy Agency) and EIA (Energy Information Administration) (EIA, 2012 and 2013).

In this first step of our methodology we create two basic models, CTAP-1 and CTEM-1, each is represented with 3 regions (Italy, Rest of Europe and Rest of the World) and 19 sectors (among them the electricity sector) (Table 1). The reference year is 2007. CTEM-1 has greater technology details of the electricity sector (as shown in Figure 7) otherwise is identical to CTAP-1. The comparisons between the CTAP-1 and CTEM-1 models allow us to investigate the impacts of modeling electricity production as a single production technology (Figure 6) vs. 13 generation technologies (Figure 7).

Figure 7: Electricity generation in CTEM

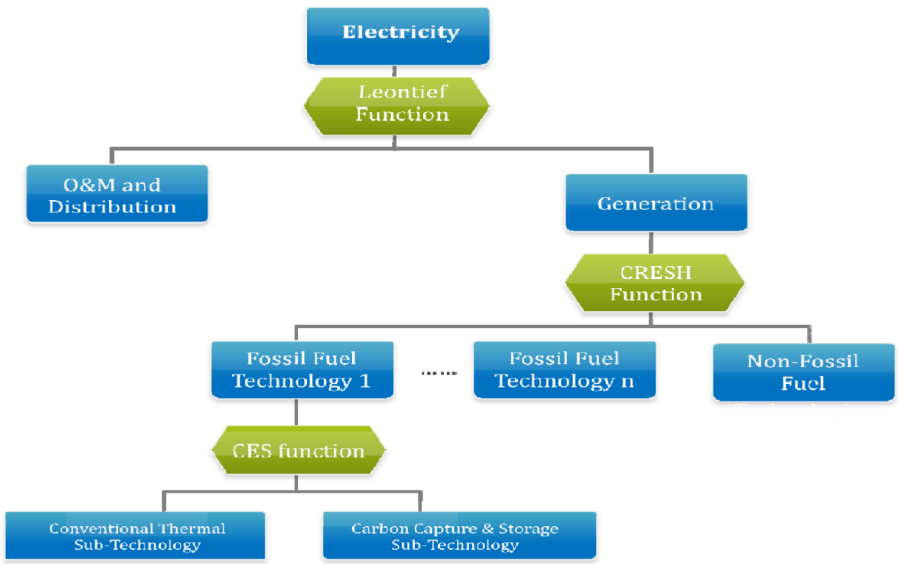


Table 1: Sectors in CTAP and CTEM

COL	coal	MANU	Manufactures
OIL	oil	OTP	Land transport
GAS	gas	WTP	Water Transport
P_C	coal and oil products	ATP	Air transport
ELY	electricity	CROPS	Crops
I_S	Iron and Steel	LSTK	Livestock
NFM	Nonferrous metals	FISHFOR	Fishing and Forestry
CRP	Chemical, rubber, plastic products	FOOD	Processed Food
OMN	Other mining	SVCE	Services
NMM	Nonmetallic minerals		

3.3 Creating the sub-national database: from CTAP-1 to CTAP-20

To further investigate the impacts of modeling sub-national details, we disaggregate Italy in 20 sub-national regions, moving from CTAP-1 to CTAP-20. To achieve this goal we need to split Italy in the GTAP 8 database into 20 regions, keeping the consistency of all economic accounts in the SAM.

The first step consists of disaggregating the SAM, originally available at the country level, to the regional scale. First, we match the ISTAT (Italian Statistical Office) sectors with the 57 GTAP sectors. Then, the regional shares of value added, labor and land computed from ISTAT data are used to distribute the respective GTAP Italian data across the 20 Italian regions (ISTAT Agricoltura e Zootecnia, ISTAT Conti Economici Regionali, ISTAT Valore Aggiunto ai Prezzi di Base dell'Agricoltura per Regione). Note that two more primary factors appear in the GTAP database: capital and natural resources. The respective regional shares are not retrievable from ISTAT. Those of capital are then computed as a difference between value added and labor, while those of natural resources are proxied by the sub-national share of value added in fishery, forestry and mining sectors.

The second step, consisting in the determination of domestic regional demand and bilateral trade flows between sub-national regions, is the most challenging. These data are very often missing. To overcome the problem the procedure usually adopted is the so-called gravitational approach as in Wittwer and Horridge (2010) and Dixon et al. (2012). By this method, the bilateral intra-country trade flows are estimated using a gravity equation as in the Newtonian physics. It accounts for the sectoral production in the origin region and sectoral demand in the destination region as attractors and the distance between them as friction. Some alternative approaches exist. For example, Chintrakarn and Millimet (2006) and Canning and Tsigas (2000) use transport data for the United States to obtain trade flows across member States. Dubé and Lemelin (2005) also use transport data to estimate the trade flows across the three sub-national regions of Quebec. In addition, they integrate this information with economic data about aggregate sub-national exports and imports and apply a cross-entropy optimization method to make the two types of information consistent.

Following Dubé and Lemelin (2005), we derive the domestic regional demand and the trade flows across sub-national regions using the already cited ISTAT economic production data and ISTAT transportation data (ISTAT Trasporto Merci su Strada 2008-2009, ISTAT Trasporto Aereo 2003-2009, ISTAT Trasporto Marittimo 2005-2008, ISTAT Trasporto Ferroviario 2004-2009). Then to create consistency between transportation and the economic information we implement the RAS statistical method (Deming and Stephan, 1940; Bacharach, 1970). For a detailed description of the methodology reader can refer to Standardi et al. (2014) and Carrera et al. (2015).

To obtain the emissions, we assume that all Italian regions have the same emissions intensity for the same energy input in the same sector. As a result, emissions are proportional to the economic variables in the database. Specially, we use the ratio of a regional variable to the sum of all Italian regions multiplied by the corresponding variable for Italy as a whole in the GTAP CO2 and non CO2 databases.

It is worth noting that CTAP-1 and CTAP-20 models have exactly the same model specifications. This means that we have the same equations, variables and parameters. The only difference is the database. CTAP-20 considers 20 Italian regions in place of considering Italy as a whole in CTAP-1.

3.4 Combining the technological and regional details: from CTAP-20 to CTEM-20

This step of the process we include both the technological and geographical details into the model. We construct a regional database of power generation from fossil fuels and renewable resources in Italy that is consistent with the IEA World Energy Balance Table (2013). We also use further information from TERNA[7] and ENEA (Catoni and Iorio, 2011) to integrate the national and sub-national data for electricity in Italy. In particular, the information from ENEA allows us to build a

[7] Source: http://download.terna.it/terna/0000/0113/50.pdf

more detailed database for renewables in each one of the Italian regions. Solar, wind, geothermal, waste, biomass and hydro power technologies are considered.

These steps create a model with technology bundle in the electricity sector within each Italian region. The model, which we now call CTEM-20, has the same technologies as CTEM-1 for the electricity sector. Like CTAP-1 and CTAP-20, CTEM-1 and CTEM-20 have exactly the same model specifications but use a different database.

3.5 Accounting for labor mobility within Italy: CTEM-20Lab

When constructing CTAP-20 and CTEM-20, we have followed standard country-level CGE models which exclude the possibility for inter-national migration (e.g., Hertel (1997)). This corresponds to rule out inter-regional migration in CTAP-20 and CTEM-20. However, we note that workers are more likely to move between regions of the country. To further test the importance of labor mobility in modeling, we have created an extension of CTEM-20, which is called CTEM-20Lab. The model allows for labor mobility within Italy, by using a CET (Constant Elasticity Transformation) function to determine the endogenous supply of labor at the regional level. Workers migrate according to the relative differentials of wage between the Italian regions, while respecting the national constraint of labor supply. The degree of intra-national labor mobility is regulated by the elasticity of substitution in the CET function. When its value is zero workers cannot move outside the region; and when its value tends to infinite we have perfect labor mobility within Italy. In this exercise, we have set an intermediate value (2.0) which corresponds to an imperfect labor mobility between the Italian regions (see Standardi et al. (2014) and Carrera et al. (2015).).

4. Results

With the five versions of the CGE model, we have carried out a simple comparative static exercise. We use the data in 2007 as our baseline, and simulate a counter-factual scenario in which a 20% CO2 emission reduction target in Italy is achieved by a uniform national carbon tax. Even if this target is consistent with the five recent studies for EU27 (Bohringer et al., 2009; Durand-Lasserve et al., 2010; Peterson et al., 2011, Bosello et al, 2013, Orecchia and Parrado, 2013), a comparison is not possible. First of all, unlike the five previously cited studies, no permits trade or technological advancement in energy saving is assumed in this paper. In addition, the climate policy is implemented only in Italy. Therefore, our exercise will lead to higher estimations of carbon prices for the 20% mitigation target. Reader should not take our results as a prediction for future policies and economic consequences.

Our primary objective is to test the sensitivity of the model. By moving from CTAP-1 to CTEM-20Lab we are able to test how the different assumptions introduced step by step in the model affect the results for the mitigation costs, and to keep track of all changes in a systematic and controlled way. In particular, we can disentangle the technological and spatial component and look at their interaction. We start with the one-region and one-electric-technology model (CTAP-1), to the disaggregated 20-region and 13-electric-technology model (CTEM-20), and finally one that accounts for labor mobility between regions (CTEM-20Lab). We report the results below.

4.1 Carbon price and the overall economy

Tables 2 shows the simulation results for carbon price of the five models. We find that, as more details of technological and spatial dimension are added to the modeling, the estimates for carbon price in Italy are monotonically decreasing. However, the effect of representing regional details (-28.8%) appears to be twice as large as the effect of representing the details of electricity technology (-14.9%). Including both regional and technological details together will lower the estimate for carbon price by -40.4%; but further adding labor mobility appears to have only a marginal effect on reducing the estimate.

Table 2: Carbon price to achieve a 20% national CO2 emission reduction in Italy and the estimated effects of disaggregating regions and electric technologies

<table>
<tr><th></th><th>$ per ton of CO2</th><th>Effect of tech disaggregation</th><th>Effect of regional disaggregation</th><th>Effect of adding labor mobility</th></tr>
<tr><td>CTAP-1</td><td>208</td><td></td><td></td><td></td></tr>
<tr><td>CTEM-1</td><td>177</td><td>-14.9%</td><td></td><td></td></tr>
<tr><td>CTAP-20</td><td>148</td><td></td><td>-28.8%</td><td></td></tr>
<tr><td>CTEM-20</td><td>124</td><td colspan="2">-40.4%</td><td></td></tr>
<tr><td>CTEM-20Lab</td><td>123</td><td colspan="3">-40.9%</td></tr>
</table>

As a result of the different estimates for carbon price, the five models arrive at different predictions for mitigation costs as measured by GDP loss from the 2007 level (Table 3). Overall, the model that entails the most regional and technological details plus assumptions of labor movement between regions (CTEM-20Lab) shows much lower estimate of abatement cost (approximately -41%) than the one that does not account for the regional and technological differences (CTAP-1). While the impact of representing electric technological details is less significant (-1.3%) than that of representing regional details (-22.6%) when considered separately, the interaction of them are substantial leading to 33.7% reduction in the estimate of mitigation cost. Taking account of labor mobility among regions will further reduce the estimated cost by 41.2%. The regional details are also reported in Table A.1 of the appendix.

Table 3: Mitigation cost to achieve a 20% national CO2 emission reduction in Italy and the estimated effects of disaggregating regions and electric technologies

	GDP loss (in 2007 billion US$)	Effect of tech disaggregation	Effect of regional disaggregation	Effect of adding labor mobility
CTAP-1	32.31			
CTEM-1	31.90	-1.3%		
CTAP-20	25.00		-22.6%	
CTEM-20	21.41	-33.7%		
CTEM-20Lab	18.99	-41.2%		

Figures 8 and 9 allow us to further investigate the regional mitigation costs and CO2 reductions across the three sub-national specifications, CTAP-20, CTEM-20 and CTEM-20Lab. Red and green numbers represent respectively the highest reductions and gains in the most significant regions. The results for all regions are reported in Tables A.2 and A.3 of the Appendix.

Despite the fact that the Southern regions Apulia, Sardinia and Sicily have recently developed wind and solar, they still remain amongst the most fossil-fuel intensive economies and experience the highest relative GDP losses. A relatively larger reduction in GDP can be observed also in Liguria in the North and Lazio in the Center for the same reason. Conversely, Aosta Valley, Piedmont, Trentino Alto Adige and Emilia-Romagna in the North, and Calabria, Abruzzo and Molise in the South see GDP gains in this experiment[8]. Trentino Alto Adige, Emilia Romagna and Abruzzo have the lowest emission intensities in Italy relative to GDP (Table A.4 of the Appendix). The emission reductions follow the same ranking of the GDP changes, but they tend to be more evenly distributed across the regions (Figure 9). This is largely driven by the growth of renewable technologies and/or

[8] Molise attracts investment as it is less abundant in capital relative to the other regions and this pushes up the yield of capital. This huge inflow can bias the results of the policy for this very small region because investment is assumed to be perfectly mobile within Italy.

the regional reshuffling of fossil-fuel power generations as captured in CTAP-20, CTEM-20 and CTEM-20Lab, which is to be investigated in the next sub-sections.

Figure 8: GDP changes (%) due to carbon price (tax) to achieve a 20% national CO2 emission reduction in Italy. Red and green numbers represent the highest reductions and gains, respectively, in the most significant regions.

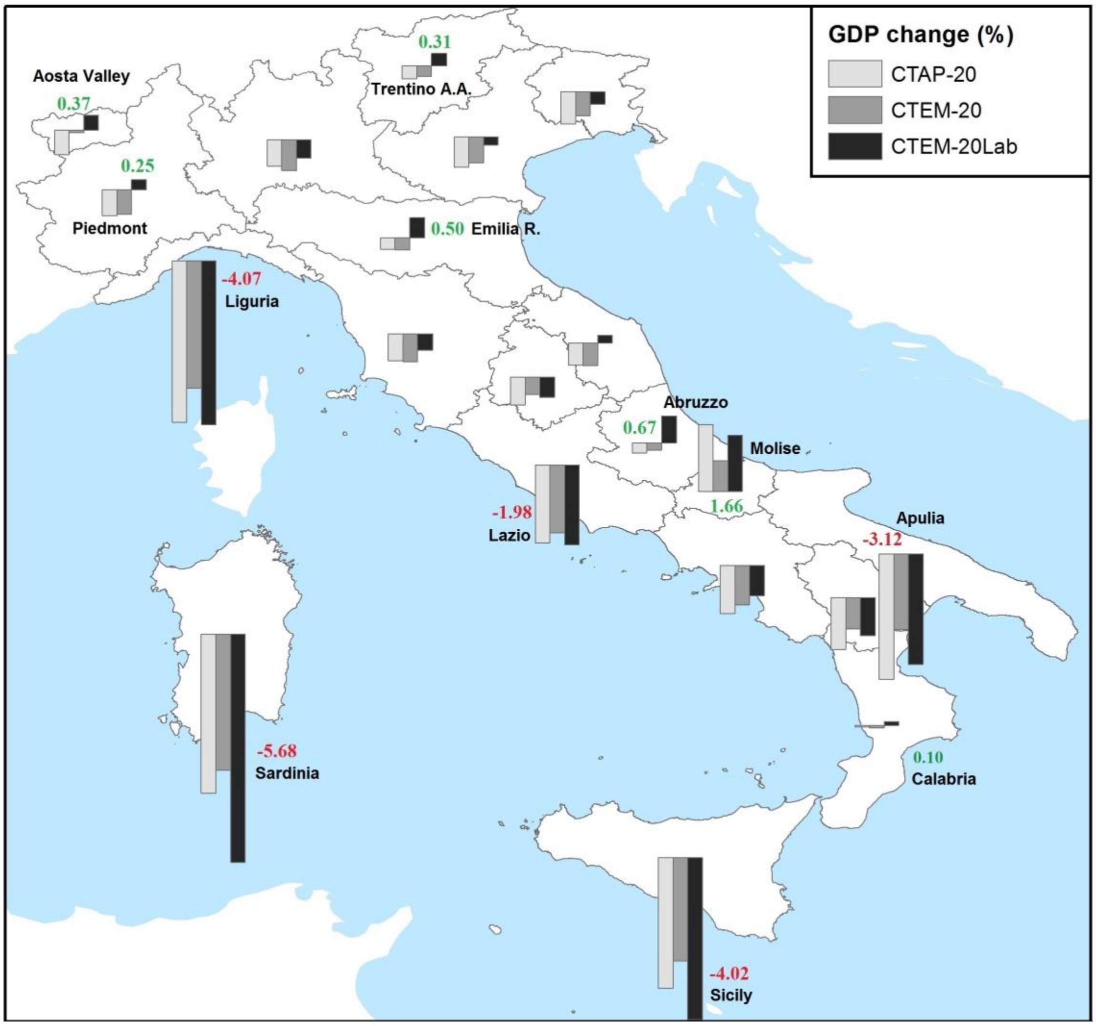
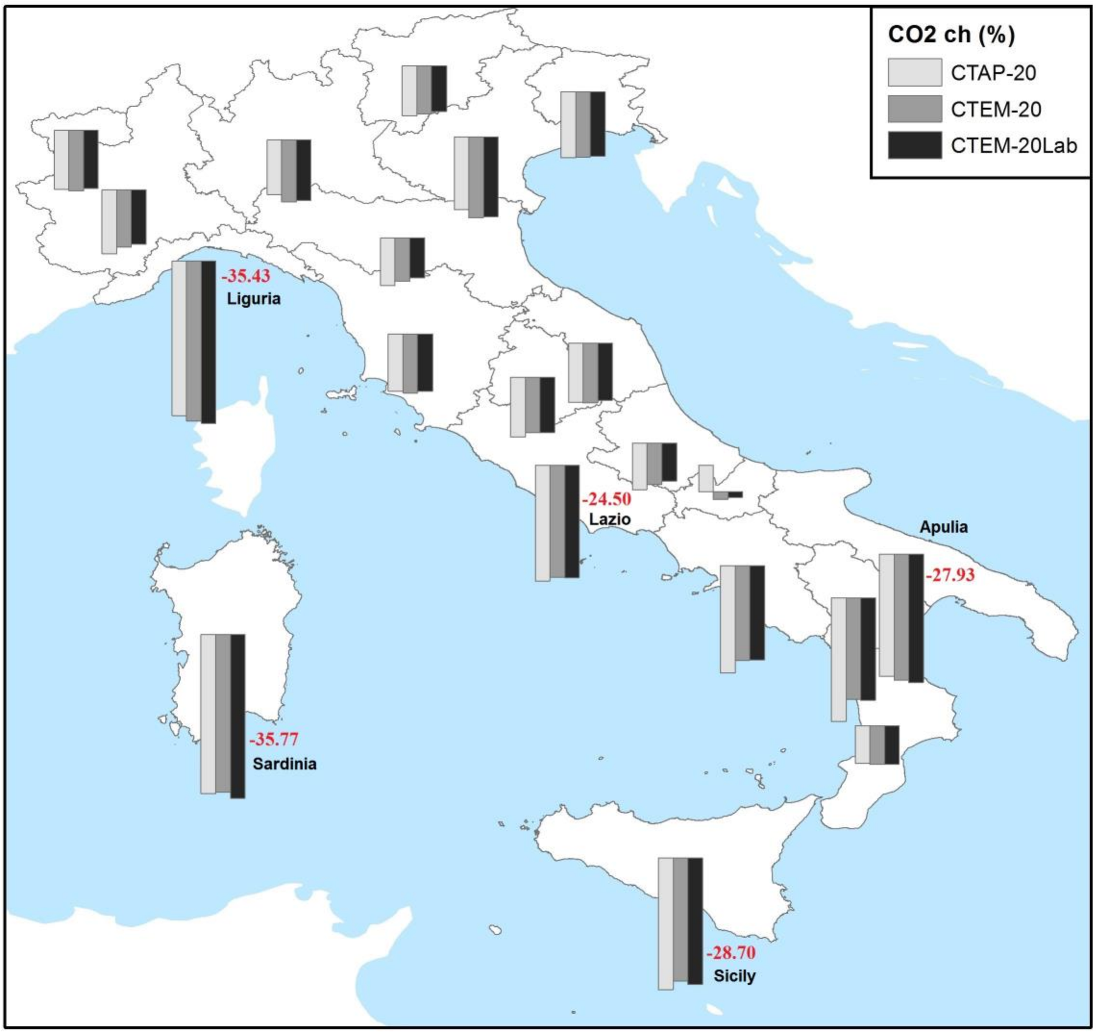


Figure 9: CO2 Emissions reduction (%) due to carbon price (tax) to achieve a 20% national CO2 emission reduction in Italy. Red numbers represent the highest reductions in the most significant regions.



4.2 Power generation

In general, either technological or regional disaggregation of the model will lower the predictions for reduction of power generation (Table 4) due to a 20% national CO2 emission reduction in Italy. Specifically, adding electric technology details allows for the shift of electricity production from fossil fuels to renewable technologies; while adding the regional details allows for the shift of fossil-fuel electricity production from less energy efficient regions to the more energy efficient regions. Our simulation results suggest that the second factor (35.4% less reduction in power generation) appears to be seven times more important than the first (5.0% less reduction in power generation). However, the interaction between the two factors is strong, leading to 44.2% less reduction in power generation. Both of the two factors allow Italy to decarbonize the power sector (Table 5) and achieve the national mitigation target while giving up less electricity consumption.

Table 4: Reduction of power generation due to a 20% national CO2 emission reduction in Italy and the estimated effects of disaggregating regions and electric technologies

<table>
<tr><th></th><th>Power generation (% reduction from 2007)</th><th>Effect of regional disaggregation</th><th>Effect of tech disaggregation</th><th>Effect of adding labor mobility</th></tr>
<tr><td>CTAP-1</td><td>18.1</td><td></td><td></td><td></td></tr>
<tr><td>CTEM-1</td><td>17.2</td><td></td><td>-5.0%</td><td></td></tr>
<tr><td>CTAP-20</td><td>11.7</td><td>-35.4%</td><td></td><td></td></tr>
<tr><td>CTEM-20</td><td>10.1</td><td colspan="2">-44.2%</td><td></td></tr>
<tr><td>CTEM-20Lab</td><td>10.2</td><td colspan="3">-43.6%</td></tr>
</table>

Table 5: Change of electric sector CO2 emissions due to a 20% national CO2 emission reduction in Italy (% change from the 2007 level)

	CTAP-1	**CTEM-1**	**CTAP-20**	**CTEM-20**	**CTEM-20Lab**
Piedmont	n.a	n.a	5.7	-0.1	0.6
Aosta Valley	n.a	n.a	14.6	4.6	5.0
Lombardy	n.a	n.a	-9.5	-21.7	-21.4
Trentino AA	n.a	n.a	12.6	2.6	3.1
Veneto	n.a	n.a	-23.2	-36.6	-36.2
Friuli VG	n.a	n.a	-11.5	-18.6	-18.3
Liguria	n.a	n.a	-38.0	-46.3	-46.7
Emilia-Romagna	n.a	n.a	6.4	2.5	3.2
Tuscany	n.a	n.a	-4.8	-17.5	-17.1
Umbria	n.a	n.a	-11.6	-14.6	-14.6
Marche	n.a	n.a	-22.8	-29.9	-29.2
Lazio	n.a	n.a	-31.5	-41.7	-41.8
Abruzzo	n.a	n.a	14.3	11.1	11.7
Molise	n.a	n.a	89.2	43.5	43.4
Campania	n.a	n.a	9.4	6.8	7.1
Apulia	n.a	n.a	-26.7	-34.1	-34.5
Basilicata	n.a	n.a	-60.9	-49.4	-49.0
Calabria	n.a	n.a	76.0	52.7	52.3
Sicily	n.a	n.a	-40.6	-42.1	-42.7
Sardinia	n.a	n.a	-48.4	-51.1	-51.9
Italy	**-21.2**	**-27.9**	**-25.7**	**-33.8**	**-33.9**

We can appreciate better the regional specialization looking at Tables 6 and 7. Noticeably, the fossil-fuel-intensive regions, such as Liguria, Lazio, Apulia, Sicily and Sardinia, strongly decrease their electric production (Table 6) but are able to add large shares of renewables into their power generation (Table 7). On the other hand regions like Emilia Romagna, Abruzzo, Molise, Campania and Calabria see the growth in both fossil-fuel and renewable power technologies (Table 7) and this results in an increase of the electric production (Table 6). These outcomes describe very well the economic efficiency gains linked to the two factors already mentioned.

Table 6: Change of electricity production due to a 20% national CO2 emission reduction in Italy (% change from the 2007 level)

	CTAP-1	**CTEM-1**	**CTAP-20**	**CTEM-20**	**CTEM-20Lab**
Piedmont	n.a.	n.a.	8.3	3.3	3.9
Aosta Valley	n.a.	n.a.	17.7	25.2	25.5
Lombardy	n.a.	n.a.	-7.2	-7.2	-7.0
Trentino AA	n.a.	n.a.	15.8	13.9	14.2
Veneto	n.a.	n.a.	-20.0	-16.9	-16.5
Friuli VG	n.a.	n.a.	-8.0	-6.1	-5.9
Liguria	n.a.	n.a.	-35.7	-30.8	-31.4
Emilia-Romagna	n.a.	n.a.	9.1	5.2	5.9
Tuscany	n.a.	n.a.	-2.2	-4.3	-4.0
Umbria	n.a.	n.a.	-7.7	1.1	1.0
Marche	n.a.	n.a.	-21.0	-21.9	-21.3
Lazio	n.a.	n.a.	-28.7	-26.9	-27.1
Abruzzo	n.a.	n.a.	17.0	17.9	18.5
Molise	n.a.	n.a.	94.8	55.1	54.8
Campania	n.a.	n.a.	12.0	14.9	15.1
Apulia	n.a.	n.a.	-23.8	-12.7	-13.4
Basilicata	n.a.	n.a.	-59.8	-30.5	-30.2
Calabria	n.a.	n.a.	81.1	63.7	63.3
Sicily	n.a.	n.a.	-39.1	-32.9	-33.6
Sardinia	n.a.	n.a.	-47.2	-44.3	-45.3
Italy	**-18.1**	**-17.2**	**-11.7**	**-10.1**	**-10.2**

Table 7: Change of power technology in the electricity sector in CTEM-20
(% change from the 2007 level)

	Coal	Oil	Gas	Hydro	Wind	Solar	Biomass	Waste	Geoth.
Piedmont	9.9	1.8	-2.1	10.3	0.0	19.9	23.9	23.6	0.0
Aosta Valley	26.4	12.7	-31.3	25.3	0.0	0.0	0.0	0.0	0.0
Lombardy	9.9	-2.3	-24.8	18.0	0.0	61.4	72.1	72.3	0.0
Trentino AA	16.5	5.5	-11.0	15.6	24.7	22.9	28.8	28.7	0.0
Veneto	-45.8	-17.6	-17.9	6.8	0.0	59.8	63.3	63.0	0.0
Friuli VG	-24.9	-11.7	-2.2	2.9	0.0	22.9	23.9	23.7	0.0
Liguria	-56.1	-30.2	-27.6	7.6	129.8	0.0	0.0	140.9	0.0
Emilia-Romagna	9.8	2.0	3.9	9.2	15.2	14.6	18.6	18.4	0.0
Tuscany	5.9	-4.0	-23.6	5.7	21.7	20.4	29.1	29.1	20.9
Umbria	-21.4	-6.1	5.4	8.3	28.1	27.2	31.2	31.2	0.0
Marche	-4.0	-17.6	-31.7	5.2	0.0	54.6	0.0	56.6	0.0
Lazio	-50.5	-23.4	-27.4	3.4	65.1	64.7	66.6	67.2	0.0
Abruzzo	19.4	10.4	19.3	16.8	22.4	20.8	27.9	27.8	0.0
Molise	55.9	44.5	57.4	44.1	44.8	0.0	63.0	63.5	0.0
Campania	15.6	6.3	16.5	13.6	18.9	17.5	0.0	23.5	0.0
Apulia	-43.5	-19.8	-7.3	0.0	39.2	35.5	51.8	52.1	0.0
Basilicata	-24.7	-36.6	-51.0	-16.9	19.5	0.0	19.1	19.2	0.0
Calabria	64.9	52.5	66.2	51.0	53.2	47.4	74.3	74.4	0.0
Sicily	-17.1	-32.5	-43.1	-7.8	62.9	59.7	72.0	73.3	0.0
Sardinia	-56.2	-44.1	-50.3	-18.3	49.9	48.5	52.5	54.2	0.0
Italy CTEM-20	**-15.6**	**-12.5**	**-16.6**	**13.4**	**41.6**	**36.8**	**50.4**	**58.4**	**20.9**
Italy CTEM-1	**-33.5**	**-14.0**	**-28.6**	**12.7**	**74.8**	**71.6**	**86.5**	**86.5**	**71.4**

4.3 Labor movement

In CTEM-20Lab workers migrate mainly from South (Sicily, Sardinia, Apulia and Basilicata) to North (Piedmont, Lombardy, Veneto and Emilia-Romagna). This results in changing the magnitude and sign of the cost impacts in many regions (Table A.1 in the Appendix). In particular, Lazio in the Central region and Apulia, Sicily and Sardinia in the Southern see greater costs impacts, whereas Piedmont and Emilia Romagna in the North show GDP gains rather losses, and Lombardy, Veneto, and Liguria in the North and Tuscany in the Central show smaller GDP losses after accounting for labor mobility.

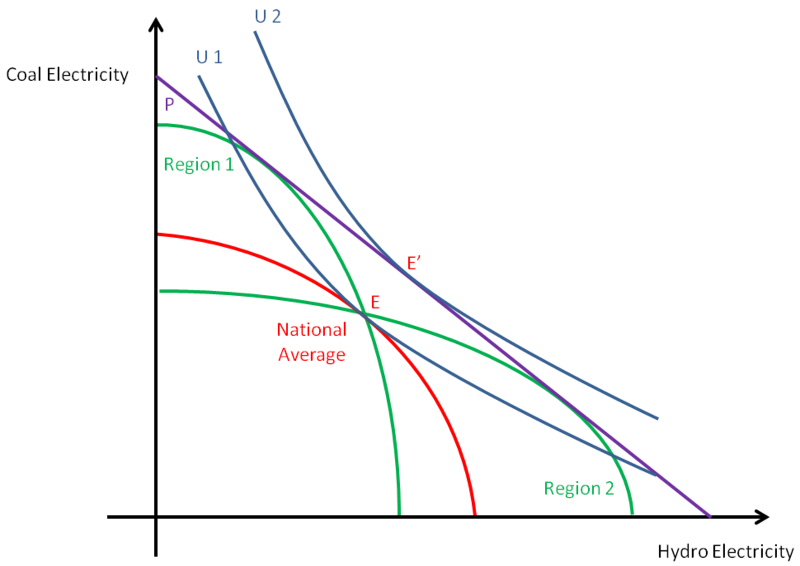
This outcome is consistent with the fact that Southern regions are relatively more labor abundant while Northern regions are more capital abundant. When labor mobility is introduced within Italy Southern workers can move toward North where the labor supply is smaller relative to the demand and wages are higher. The increase in labor supply translates in a GDP increase or smaller GDP losses of the above-mentioned Northern regions. Conversely, the Southern regions (Sicily, Sardinia, Apulia and Basilicata) decrease their labor force and experience greater GDP reductions. It is worth noting that increasing the flexibility in the labor market decreases the overall cost of the policy for Italy (Table A.1). This is not surprising given the theoretical structure of the model based on competitive markets.

4.4 Economic interpretation of the results

The key intuition behind our modeling results is the benefit of the sub-national sectoral/technological specialization and intra-national trade. In fact, the results are a natural consequence of the well known Heckscher-Ohlin theorem (Feenstra, 2013) applied to sub-national entities. The theorem states that countries can gain from trade by specializing in producing the good, which uses more intensively the relative abundant/cheap input. In the context of modeling a climate policy, the disaggregation of regional and electric technological details allows the market to explore the regional comparative advantages in either renewable energy source or energy efficiency, and to arrive at a cost-minimizing mitigation profile. In contrast, overlooking the sub-national technological and socio-economic differences in energy production and consumption tends to lead to overestimation of the carbon price and the consequential economic losses.

In Figure 10, we demonstrate graphically the application of the Heckscher-Ohlin theorem to an emission target policy. Let us consider a country that is made up of two regions and two goods (coal power and hydro power). The two green curves represent the frontiers of productive possibilities (FPP) of the two regions, respectively. Region 1 is rich in coal reserve while Region 2 has more hydro resources. When these regional differences are overlooked in an aggregated CGE model, the national average FPP is represented by the red curve. The economic equilibrium takes place in E, where the FPP is tangent to utility level curve (U1). When sub-national details are introduced into the modeling, the equilibrium moves from E to E'. The two regions take advantage of their different endowment composition in electricity generation. They specialize in an efficient way according to their FPPs and supply electricity to the national grid as guided by the price curve P in purple color. Overall, the country will be economically better off due to increased consumption of electricity[9].

Figure 10: Welfare improvement as a result of inter-regional trade



Our arguments are consistent with the trade literature pointing out the underestimation of welfare gains following trade liberalization using aggregated general equilibrium models and average aggregated tariff (Narayanan et al., 2010; Anderson and van Wincoop, 2004; Hillberry, 2002; Pomfret, 1985; Trefler, 1993, Gaston and Trefler, 1994, 1997; Beghin and Kherallah, 1994; Goldberg, 1995; Olarreaga and Soloaga, 1998; Beghin and Fang, 2002).

While our simulation results are limited to the Italian case, our conclusions can be generalized to different countries and policy scenarios not in terms of magnitudes of results but in terms of economic explanation. This is because intra-national trade exists in every country and sub-national entities are different in terms of sectoral or technological specialization.

5. Concluding remarks

Very few studies exist today to explore the importance of model uncertainty, particularly in the area of climate abatement policies. CGE models as other macro-economic models with similar characteristics represent a popular tool to estimate mitigations costs of climate abatement policies, identify the distributional impacts and guide policy decisions. In this work we systematically

[9] Figure 10 is a graphical simplification. The new equilibrium E' sees an increase of consumption in both hydro and coal electricity. The increase of coal electricity can be interpreted as the result of improved energy efficiency in the use of coal. In addition in the CGE model the welfare gains also stem from sectoral specialization in the non- electric sectors of the whole economy.

analyze the role that technological and regional aggregations have in CGE models applied to a climate policy simulation. A deeper and clearer understanding on the underlying economic dynamics affected by the two fundamental model structure assumptions is critical to the understanding of the robustness of the results generated by these types of models.

Our results clearly show that abatement costs change substantially according to different geographical and technological scales. This work also underlines the importance to consider intra-national trade and technological/sectoral specialization at the sub-national level as potential drivers to lower the mitigation costs of a carbon policy. The insights we provide here can be useful not only for the Italian case but also for the other European countries involved in the de-carbonization pathways and potentially any other country in the world. Special attention should be paid on the largest countries such as USA, China, Russia, India, Brazil where much greater degree of heterogeneity can be observed within the borders both from an energy-technological and socio-economic point of view.

As a caveat, it is worth noting that the economic explanation behind is even more important than the results provided by CGE modeling, with rough numbers on GDP and emissions changes. This is because the magnitude of the economic effects also relies on large dataset. These data can always contain errors or omissions. Especially in the case of a large database at the sub-national level, a part of the relevant information cannot be retrieved directly from the regional accounts but must be derived indirectly by using different techniques. However, the identification of the economic causal link and key variables remains valid and robust.

Acknowledgements

The research leading to these results has received funding from the Italian Ministry of Education, University and Research and the Italian Ministry of Environment, Land and Sea under the GEMINA project. We thank Mattia Amadio for drawing maps. The authors are the only responsible for errors and omissions in this work.

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Appendix A

Table A1: Mitigation costs expressed as real GDP losses

(2007 billion US$)

	CTAP-1	CTEM-1	CTAP-20	CTEM-20	CTEM-20Lab
Piedmont	n.a.	n.a.	-1.11	-1.05	0.43
Aosta Valley	n.a.	n.a.	-0.03	0.00	0.02
Lombardy	n.a.	n.a.	-3.01	-3.46	-2.11
Trentino Alto Adige	n.a.	n.a.	-0.13	-0.10	0.12
Veneto	n.a.	n.a.	-1.51	-1.29	-0.40
Friuli Venezia Giulia	n.a.	n.a.	-0.38	-0.28	-0.14
Liguria	n.a.	n.a.	-2.34	-1.84	-2.38
Emilia Romagna	n.a.	n.a.	-0.56	-0.59	0.97
Tuscany	n.a.	n.a.	-0.94	-0.98	-0.57
Umbria	n.a.	n.a.	-0.20	-0.12	-0.15
Marche	n.a.	n.a.	-0.31	-0.31	0.11
Lazio	n.a.	n.a.	-4.17	-3.63	-4.28
Abruzzo	n.a.	n.a.	-0.10	-0.07	0.27
Molise	n.a.	n.a.	0.16	0.07	0.13
Campania	n.a.	n.a.	-1.52	-1.24	-0.96
Apulia	n.a.	n.a.	-3.03	-1.81	-2.66
Basilicata	n.a.	n.a.	-0.21	-0.13	-0.16
Calabria	n.a.	n.a.	-0.01	-0.03	0.04
Sicily	n.a.	n.a.	-3.79	-2.99	-4.69
Sardinia	n.a.	n.a.	-1.81	-1.55	-2.60
Italy	**-32.31**	**-31.90**	**-25.00**	**-21.41**	**-18.99**
Rest of Europe	3.33	2.89	2.30	1.95	1.95
Rest of the World	1.81	1.51	0.84	0.69	0.65
World	-27.17	-27.51	-21.86	-18.77	-16.38

Table A.2: Mitigation costs expressed as real GDP losses

(% change from the 2007 level)

	CTAP-20	**CTEM-20**	**CTEM-20Lab**
Piedmont	-0.64	-0.61	0.25
Aosta Valley	-0.62	-0.06	0.37
Lombardy	-0.66	-0.76	-0.46
Trentino Alto Adige	-0.32	-0.26	0.31
Veneto	-0.75	-0.64	-0.20
Friuli Venezia Giulia	-0.79	-0.58	-0.30
Liguria	-4.01	-3.16	-4.07
Emilia Romagna	-0.29	-0.30	0.50
Tuscany	-0.67	-0.70	-0.41
Umbria	-0.69	-0.43	-0.51
Marche	-0.55	-0.56	0.19
Lazio	-1.93	-1.68	-1.98
Abruzzo	-0.25	-0.18	0.67
Molise	1.66	0.77	1.40
Campania	-1.20	-0.98	-0.76
Apulia	-3.12	-1.87	-2.74
Basilicata	-1.29	-0.78	-0.95
Calabria	-0.03	-0.06	0.10
Sicily	-3.25	-2.57	-4.02
Sardinia	-3.95	-3.38	-5.68
Italy	-1.18	-1.01	-0.90

Source: Simulation results

Table A.3: CO_2 abatements

(% change from the 2007 level)

	CTAP-20	CTEM-20	CTEM-20Lab
Piedmont	-13.91	-12.47	-11.82
Aosta Valley	-12.91	-13.23	-12.76
Lombardy	-11.98	-13.54	-13.23
Trentino Alto Adige	-10.74	-10.33	-9.89
Veneto	-15.85	-17.64	-17.35
Friuli Venezia Giulia	-14.27	-14.16	-13.91
Liguria	-33.80	-34.92	-35.43
Emilia Romagna	-10.42	-9.46	-8.74
Tuscany	-12.56	-12.90	-12.57
Umbria	-13.08	-12.06	-12.05
Marche	-12.97	-13.06	-12.47
Lazio	-25.21	-24.42	-24.50
Abruzzo	-10.18	-8.98	-8.28
Molise	5.83	-1.60	-1.19
Campania	-23.41	-20.71	-20.58
Apulia	-26.59	-27.49	-27.93
Basilicata	-27.02	-22.20	-22.36
Calabria	-8.17	-8.36	-8.35
Sicily	-28.70	-26.86	-27.54
Sardinia	-34.71	-34.36	-35.77
Italy	-20	-20	-20

Source: Simulation results

Table A.4: CO_2 Emission Intensity Relative to GDP of the 20 Italian Regions

	Mt CO2 per 2007 billion US$
Piedmont	16.97
Aosta Valley	17.91
Lombardy	24.35
Trentino Alto Adige	15.18
Veneto	20.68
Friuli Venezia Giulia	20.72
Liguria	59.62
Emilia Romagna	15.54
Tuscany	19.63
Umbria	18.40
Marche	17.36
Lazio	33.18
Abruzzo	13.70
Molise	23.04
Campania	21.18
Apulia	43.14
Basilicata	22.85
Calabria	18.58
Sicily	50.13
Sardinia	62.72
Italy	26.19

Source: Authors' calculation from the database in the reference year (2007)