# GHG mitigation schemes and energy policies: A model-based assessment for the Italian economy[*]

Barbara Annicchiarico[†] Susan Battles[‡] Fabio Di Dio[§]
Pierfrancesco Molina[¶] Pietro Zoppoli[‖]

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**Abstract**

We build up a large scale dynamic general equilibrium model embodying a cap on pollutant emissions, an electricity sector and fuel consumption to analyse climate-energy policies for the Italian economy. Our results show how the trade-off between environmental quality and economic activity can be effectively overcome by recycling the revenues from the sales of emission permits in labour tax reductions. A tax combination aimed at reducing the consumption of fossil fuel, while simultaneously decreasing taxes on labour, is expansionary, but the final outcome is influenced by the underlying GHG emission policy. Tax incentives encouraging the use of clean energy sources, by discouraging the use of fossil fuel, produce a sizeable reallocation of emissions across sectors and are found to be expansionary. Overall the paper highlights the non-trivial interactions between the different fiscal tools in hand to meet the legally binding commitment on emission reduction, while limiting the potential negative fallout on the economy.

*Keywords*: Environmental Policy, GHG Emissions, Energy Policies, Dynamic General Equilibrium Model, Simulation Analysis, Italy.

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[†] *Corresponding author*: Università degli Studi di Roma "Tor Vergata", Dipartimento di Economia e Finanza, Via Columbia 2, 00133 Roma, Italy.

[‡] Ministero dell'Economia e delle Finanze, Dipartimento del Tesoro, Italy.

[§] Sogei S.p.a. - IT Economia - Modelli di Previsione ed Analisi Statistiche, Italy.

[¶] Sapienza Università di Roma, Dipartimento di Scienze Sociali ed Economiche, Piazzale Aldo Moro 5, 00185 Roma.

[‖] Ministero dell'Economia e delle Finanze, Dipartimento del Tesoro, Italy.

# 1 Introduction

What is the macroeconomic impact of the implementation of greenhouse gases (GHG) mitigation scheme? To what extent do short-run economic frictions influence the macroeconomic effects of the environmental policy regime put in place? What if the revenues from auctioned emission permits or from major taxes on consumption of fossil fuel were used for cuts in labour taxes such as income and payroll taxes? Which are the effects of combined fiscal policies aimed at promoting diffusion of renewable energy while reducing the use of fossil energy?

In this paper we address these questions by exploring the potential effects of mitigation-energy interventions by making use of GEEM (General Equilibrium Environmental Model), a large-scale macroeconomic model designed for the Italian economy. In particular, we build up a dynamic general equilibrium (DGE) model specifically designed to capture the non-trivial interactions between climate-energy policies and the macroeconomic system in a fully microfounded set-up. GEEM has four key features. First, the model embodies typical elements of the so-called New Neoclassical Synthesis, combining features at the heart of New Keynesian models, such as nominal rigidities in wages and prices, with features central to the Real Business Cycle (RBC) models, such as the systematic application of intertemporal optimization and of the rational expectations hypothesis in determining consumption, investment and factor supply decisions. Second, the model incorporates an electricity sector, distinguishing between fossil and renewable sources (RES). Third, the model presents a transportation sector represented by fuel consumption on the household side. Households, in turn are of two types, differing over their ability to access financial markets. Fourth, in GEEM GHG emissions and firms abatement activities depend on the type of environmental regime adopted, namely a cap (i.e. an exogenous limit on emissions) or a tax policy (i.e. a carbon tax). Clearly, the underlying environmental policy gives rise to non-trivial interactions between agents' choices as well as between economic policies acting in different domains. Given these features, GEEM can be used to analyze the response of the economy to a variety of policy interventions under specific environmental regimes encompassing several potential transmission channels.[1]

The detailed and intertemporal structure of GEEM allows us to explore several macroeconomic implications of climate-energy policies across sectors and over time. Our results show how GHG mitigation policies induce manufacturing firms either to limit the environmental impact of their production activity by undertaking abatement measures, or to reduce economic activity and, therefore, the use of labour inputs. The implementation of a gradual mitigation scheme, by changing the relative costs of the various energy sources, is also likely to induce large re-allocative effects in the electricity sector. In general, a major trade-off emerges between environmental quality and economic activity, especially along the transition path, where the presence of real and nominal frictions renders the adjustment towards a low carbon economy very costly. However, we show how this trade-off can be effectively overcome, mainly in the long run, by recycling the revenues from the GHG mitigation policy to reduce the burden of taxation on labour income. Further, from the analysis, it emerges a potentially strong case on distributional grounds between the two different types of households for recycling the revenues from auctioned emission permits or from the carbon tax in order to reduce

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[1] The structure of the model is general and can thus be used for the analysis of fiscal policy changes and tax reforms, along with the macroeconomic implications of greater competition in product and labour markets, as well as in the energy sector. From this perspective, GEEM can serve as a comprehensive tool for studying the macroeconomic implications of actual and hypothetical reform scenarios operating in different domains under alternative climate policy regimes. See the examples shown in Annicchiarico et al. (2016a).

taxes on labour income. In general, recycling carbon revenues with tax reductions alleviates the fiscal pressure on the budgets of the more vulnerable fraction of households with no access to the financial markets. Along the transition path, instead, the negative effects on the level of economic activity can be further alleviated by the implementation of a gradual mitigation scheme inducing small initial cuts of emissions and large cuts at later stages. In this way, in fact, forward looking agents are able to smooth the burden of adjustment more efficiently.

Tax shifts aimed at discouraging the consumption of fossil fuel and reducing the distortions of the tax system on labour are likely to increase the level of economic activity. Clearly, the existence of a cap on emissions is likely to condition and limit the expansionary effects on output and employment stemming from lower distortionary taxation on labour. However, important reallocation of GHG emissions across sectors is observed, whether the underlying environmental policy consists in a binding cap or in carbon tax.

Finally, a tax swap designed to promote the diffusion of clean energy sources and discourage the consumption of fossil fuel is shown to increase sharply investment in RES and the level of economic activity. Under an overall fixed cap the distribution of emissions across sectors changes substantially, while under a carbon tax emissions decline during the adjustment process and then revert back to their initial level in the long run.

The paper shares the unifying research agenda of many governmental and international organizations which have been refining their policy models to better account for the interaction between economic and climate-energy policies. This growing effort reflects basically two concerns. First, a major awareness that macroeconomic performance and mitigation policies are inherently intertwined, and that pursuing one objective without due consideration for the other may lead to achieving neither of the two. Second, given the close interrelationship between macroeconomic performance and energy policies, various macroeconomic policies, such as those falling in the area of taxation, may need to be used in conjunction with environmental policies to the achievement of mitigation targets. There is scope to better investigate how different policies interact, and what trade-offs they may give rise to, in order to better ascertain the appropriate policy mix required to reach environmental goals. In this respect, a full understanding of the impact of such policies through the use of fully-fledged models is highly desirable. Relevant models should include some realistic aspects, such as agents' expectations, imperfect price adjustments, real frictions, lack of perfect competition and an intertemporal dimension, in order to help us assess how general reform scenarios work under specific mitigation-energy constraints.

The remainder of the paper is structured as follows. Section 2 is devoted to a discussion on the related literature. Section 3 provides a description of the structure of the model. Section 4 describes the parametrization of the model and the solution strategy. Section 5 presents the mitigation hypotheses and the energy policy experiments, while Sections 6 reports the results. Finally, Section 7 concludes.

## 2 Related literature

The methodology used in this model draws on the recent macro-environmental literature that makes use of the DGE framework to assess the impact of different climate and energy policies on economic activity.[2] In this respect, only recently large-scale DGE models have been used for environmental policy analysis. Environmental policy papers have been increasingly approaching the issue from a macroeconomic perspective, on the grounds that models abstracting from the interaction between environmental policies and macroeconomic variables run the risk of overlooking important feedback effects in the economy.[3] Some relevant examples in this direction include Bartocci and Pisani (2013), Conte et al. (2010), Bukowski and Kowal (2010) and Bukowski (2014).

In particular, Bartocci and Pisani (2013) build a DGE model for France, Germany, Italy and Spain. With this tool in hand they evaluate the macroeconomic implications of budget-neutral fiscal experiments, such as tax cuts on electricity consumption and higher subsidies to renewable sources of electricity generation financed by higher taxes on fuel for private transportation. Their findings show that such fiscal measures are likely to mitigate emissions in the transportation sector and induce a shift of electricity generation towards renewable sources, further limiting emission expansion. However, no major negative economic effects are recorded as a result of the fiscal change. Similarly to this contribution, GEEM presents a very detailed energy sector. However, our model incorporates a lot of nominal and real rigidities in order to mimic the slow adjustment of the economy in the short run. This makes it possible to look into the effects of environmental policy interventions incorporating the dynamic linkages between different rigidities and the main macroeconomic variables. In addition, in GEEM we conduct our economic policy experiments under different wide emission regulation regimes (cap on emissions or carbon tax) showing how these may condition the response of firms and households to more specific interventions, such as those aimed at promoting the use of energy from renewable source and at reducing energy consumption.

Conte et al. (2010) construct a multi-sector DGE model with endogenous technological change and explore the growth potential for the EU stemming from a set of comprehensive environmental and innovation policy interventions. In particular, this model represents an environmental-energy variant of the QUEST III model (see Ratto et al. 2009). Their simulation results highlight how the medium and the long run costs associated with mitigation policies can be substantially alleviated by recycling schemes. In addition, an appropriate policy mix may stimulate investment in green sectors already in the short term, yet providing all sectors with benefits in the medium-long term.[4] What GEEM has in common with this environmental variant of QUEST is the presence of real and nominal rigidities that strongly condition the short-run adjustments of the economy to policy shifts. Unlike the QUEST model, GEEM is able to assess environmental and energy policies under two different regimes, namely cap on emissions or carbon tax on emissions. This represents a significant strength of the model and highlights its flexibility. Furthermore, with this simulation tool we are able to conduct a comprehensive analysis of the macroeconomic impact of climate and energy policies designed to reduce emissions directly or indirectly and to induce a major use of clean energy sources.

Bukowski and Kowal (2010) and Bukowski (2014) develop a multi-sector DGE model to assess climate-energy policies for Poland. Their results show that mitigation policies are highly costly and

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[2] For an overview of the macroeconomic approach to the study of environmental policy issues, see the survey by Fischer and Heutel (2013).

[3] The dynamic general equilibrium approach has been recently used to study the short-run implications of environmental policies in the presence of economic uncertainty. See Ganelli and Tervala (2011), Fischer and Springborn (2011), Heutel (2012), Angelopoulos et al. (2013), Annicchiarico and Di Dio (2015), Dissou and Karnizova (2016), Annicchiarico et al. (2016b).

[4] Their simulation results are comparable in size with those contained in the impact assessment Climate and Energy package. See European Commission (2014).

that the use of emission revenues for subsiding green technology might reduce the trade-off between environmental and economic objectives. Moreover, reducing labour taxes is expected to be the best option to earmark the revenues from green taxes. While the Bukowski and Kowal model is more detailed in terms of number of economic sectors considered, GEEM includes abatement costs in a way that firms can decide to sustain the cost of emission abatement without lowering the level of output. The decision on abatement effort, in turn, depends on the level of emission taxes or the price of emission permits. We argue that this element raises the degree of complexity of the model making the analysis of mitigation policies more complete.

Another important strand of literature in this domain is represented by the CGE modelling approach. CGE models are frequently used to study the economic cost of GHG emission mitigation policies and evaluate the effects of emission taxes and other environmental policy instruments. For a comprehensive overview, see Bergman (2005). A recent contribution in this direction, among others, is the paper by Vrontisi et al. (2016), who evaluate the macroeconomic impact of the Clean Air Policy Package at EU level making use of a multi-sector and multi-region CGE model.[5] The paper shows that, despite the fact pollution abatement is costly for producers, it also generates a positive spillover on the sectors that produce the goods required for pollution abatement. As a result, they find that positive feedback effects can offset the resource costs associated to the Clean Air Policy and result in positive a impact for the economy of the European Union. A similar mechanism is at work in our model, since abatement effort is costly and requires the use of extra units of output, thus preventing aggregate demand to shrink in response to mitigation policies. Unlike that contribution, however, GEEM is fully dynamic and embodies forward looking and optimizing agents. This allows us to draw the adjustment path of the main macroeconomic variables over the relevant simulation time and overcome the Lucas critique.

## 3 The model set-up

GEEM is a large-scale small open-economy DGE model. Consistently with the conventional New Keynesian models and in the spirit of the so-called New Neoclassical Synthesis, the model integrates a large variety of nominal and real frictions shaping the short- and the medium-run behaviour of the economy, while neoclassical features tend to prevail in the long run.

The model embodies three key features: (i) an electricity sector, where electricity is generated by fossil fuels imported from abroad (coal, natural gas and crude oil) and renewable sources which require the use of capital (solar panels, wind turbines, biomass and hydroelectric plants), while the share of electricity generated from nuclear energy is imported; (ii) a transportation sector represented by the consumption of fuel on the part of households; (iii) a climate policy according to which the overall GHG emissions of the economy may be subject to a cap. The government is assumed to allocate emission permits among sectors (firms and households), according to a specific allocation rule. Households are assumed to receive emission permits for free, while firms are assumed to buy allowances through an auction process and have access to an abatement technology. Nonetheless, firms are neither allowed to trade their permits in a secondary market nor accumulate them.

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[5] Other recent examples of CGE analysis include Böhringer and Rutherford (2010) who, in a large scale CGE model, study the economic implications of climate action for Canada, while Arif and Dissou (2016) conduct an analysis in a multi-region CGE to evaluate the non-trivial implications arising from different burden sharing rules across regions of a hypothetical economy embarked on a GHG emission mitigation policy.

More specifically the model economy features six types of agents: (i) electricity producers; (ii) intermediate good producers employing labour, capital and electricity; (iii) importing and exporting firms; (iv) final good producers combining domestically produced intermediate goods with imported intermediate goods; (v) households consuming final goods and fuel, deciding over saving and supplying labour; (vi) public sector deciding over monetary, fiscal and environmental policy.

In what follows we describe the main features of GEEM, presenting the structure of the model and emphasizing the key policy variables to be used in our simulation exercises.[6]

## 3.1 Electricity sector

The electricity sector is made up of a continuum of monopolistically competitive producers which, in turn, in order to provide the amount of electricity demanded by the intermediate good producers, combine electricity produced with fossil fuels (coal, $COA_t$, natural gas, $GAS_t$, and crude oil, $OIL_t$), electricity generated from nuclear energy and electricity generated from RES. Furthermore, we assume that fossil fuels and electricity generated from nuclear energy are purchased from importing firms, whereas the electricity generated from RES is supplied by domestic producers.

Following Bartocci and Pisani (2013), the electricity production technology is modelled according to a system of nested CES functions. Total electricity is produced by combining the electricity generated from conventional sources, $EL_{CON,t}$, (fossil fuels and nuclear energy) with the electricity generated from RES, $EL_{RES,t}$:

$$EL_t = \left[ \rho_{EL_{CON}}^{\frac{1}{\theta}} EL_{CON,t}^{\frac{\theta-1}{\theta}} + (1-\rho_{EL_{CON}})^{\frac{1}{\theta}} EL_{RES,t}^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}, \tag{1}$$

where $\theta$ is the elasticity of substitution between electricity generated from conventional sources and RES and $\rho_{EL_{CON}}$ represents the share of electricity generated from conventional sources over the total production of electricity.

The electricity generated from conventional sources is, in turn, produced according to technology:

$$EL_{CON,t} = \left[ \rho_{EL_{FOS}}^{\frac{1}{\theta_{CON}}} EL_{FOS,t}^{\frac{\theta_{CON}-1}{\theta_{CON}}} + (1-\rho_{EL_{FOS}})^{\frac{1}{\theta_{CON}}} EL_{NUC,t}^{\frac{\theta_{CON}-1}{\theta_{CON}}} \right]^{\frac{\theta_{CON}}{\theta_{CON}-1}}, \tag{2}$$

where $\theta_{CON}$ is the elasticity of substitution between electricity generated from fossil fuels, $EL_{FOS,t}$, and nuclear energy, $EL_{NUC,t}$, and $\rho_{EL_{FOS}}$ represents the share of electricity generated from fossil fuels used in the production of electricity generated from conventional sources.

The electricity generated from fossil fuels is assumed to be produced by combining the electricity generated from coal and crude oil, $EL_{COAOIL,t}$, with natural gas, $GAS_t$:

$$EL_{FOS,t} = \left[ \rho_{EL_{COAOIL}}^{\frac{1}{\theta_{FOS}}} EL_{COAOIL,t}^{\frac{\theta_{FOS}-1}{\theta_{FOS}}} + (1-\rho_{EL_{COAOIL}})^{\frac{1}{\theta_{FOS}}} GAS_t^{\frac{\theta_{FOS}-1}{\theta_{FOS}}} \right]^{\frac{\theta_{FOS}}{\theta_{FOS}-1}}, \tag{3}$$

where $\theta_{FOS}$ is the elasticity of substitution between the electricity generated from coal-and-crude oil and natural gas, while $\rho_{EL_{COAOIL}}$ represents the share of coal and crude oil in the total production

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[6] The structure of the model is fully presented in the working paper version. See Annicchiarico et al. (2016a).

of electricity generated from fossil fuels. Finally, the electricity generated from coal and crude oil is produced combining coal, $COA_t$, with crude oil, $OIL_t$, according to:

$$EL_{COAOIL,t} = \left[ \rho_{COA}^{\frac{1}{\theta_{COAOIL}}} COA_t^{\frac{\theta_{COAOIL}-1}{\theta_{COAOIL}}} + (1-\rho_{COA})^{\frac{1}{\theta_{COAOIL}}} OIL_t^{\frac{\theta_{COAOIL}-1}{\theta_{COAOIL}}} \right]^{\frac{\theta_{COAOIL}}{\theta_{COAOIL}-1}}, \tag{4}$$

where $\theta_{COAOIL}$ is the elasticity of substitution between coal and crude oil, while $\rho_{COA}$ represents the share of coal over total production of electricity generated from coal and oil.

We now turn our attention to the production of electricity from renewable sources. In particular, the electricity generated from RES is produced according to the following technology:

$$EL_{RES,t} = \left[ \begin{array}{c} \rho_{EL_{SOL}}^{\frac{1}{\theta_{RES}}} EL_{SOL,t}^{\frac{\theta_{RES}-1}{\theta_{RES}}} + \rho_{EL_{WIN}}^{\frac{1}{\theta_{RES}}} EL_{WIN,t}^{\frac{\theta_{RES}-1}{\theta_{RES}}} + \rho_{EL_{BIO}}^{\frac{1}{\theta_{RES}}} EL_{BIO,t}^{\frac{\theta_{RES}-1}{\theta_{RES}}} \\ +(1-\rho_{EL_{SOL}}-\rho_{EL_{WIN}}-\rho_{EL_{BIO}})^{\frac{1}{\theta_{RES}}} EL_{HYD,t}^{\frac{\theta_{RES}-1}{\theta_{RES}}} \end{array} \right]^{\frac{\theta_{RES}}{\theta_{RES}-1}}, \tag{5}$$

where $\theta_{RES}$ is the elasticity of substitution between the electricity generated from solar ($EL_{SOL,t}$), wind ($EL_{WIN,t}$), biomass ($EL_{BIO,t}$) and hydroelectric energy ($EL_{HYD,t}$) and $\rho_{EL_{SOL}}$, $\rho_{EL_{WIN}}$ and $\rho_{EL_{BIO}}$ represent the share of the electricity generated from solar, wind and biomass in the production of electricity from RES, respectively.

Furthermore, it is assumed that electricity from renewable sources is generated according to the following production function:

$$\hat{RES}_t = A_{\hat{RES},t} K_{\hat{RES},t}^{\alpha_{\hat{RES}}} F_{\hat{RES}}^{1-\alpha_{\hat{RES}}}, \tag{6}$$

where $\hat{RES}_t = \{EL_{SOL,t}, EL_{WIN,t}, EL_{BIO,t}, EL_{HYD,t}\}$, $A_{\hat{RES},t}$ is a measure of productivity, $K_{\hat{RES},t}$ is the corresponding capital employed in the production of RES and $F_{\hat{RES}} = \{SOL, WIN, BIO, HYD\}$ denotes the endowment of natural resources related to solar, wind, biomass and hydroelectric sources.

The production of electricity generated from fossil fuels contributes to carbon emissions according to

$$Z_{EL,t} = (1-U_{EL,t})\varphi_{EL} EL_{FOS,t}^{\mu_{EL}}, \tag{7}$$

where $Z_{EL,t}$ denotes the level of emissions, $U_{EL,t}$ represents the abatement effort, $\mu_{EL} > 0$ is the elasticity between emissions and electricity generated from fossil fuels and $\varphi_{EL} > 0$ is a technological parameter.[7] A policy oriented to mitigate emissions from the electricity sector may be mapped onto the model through an exogenous reduction of $Z_{EL,t}$.

## 3.2 Intermediate-good producers

The intermediate goods sector is made up of a continuum of monopolistically competitive producers. This sector can be identified as the manufacturing sector. The production function for the typical firm is of the following form:

$$Y_t = A_t d(M_t) \left[ \rho_{VA}^{\frac{1}{\theta_Y}} VA_t^{\frac{\theta_Y-1}{\theta_Y}} + (1-\rho_{VA})^{\frac{1}{\theta_Y}} EL_t^{\frac{\theta_Y-1}{\theta_Y}} \right]^{\frac{\theta_Y}{\theta_Y-1}}, \tag{8}$$

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[7] In modelling emissions and abatement we follow Nordhaus (2008), Heutel (2012) and Annicchiarico and Di Dio (2015), (2016).

where $A_t$ represents total factor productivity, $VA_t$ is the value added, $EL_t$ represents electric energy, $\rho_{VA}$ is the share of value added used in the production of the intermediate good, while $\theta_Y$ is the elasticity of substitution between value added and electricity.[8] Furthermore, $d(M_t)$ represents a damage function, mapping the stock of carbon dioxide in the atmosphere to the economic damage on productivity. The functional form follows Golosov et al. (2014) in the simple adaptation of Annicchiarico and Di Dio (2016):

$$d(M_t) = e^{-\phi(M_t - \overline{M})}, \tag{9}$$

where $M_t$ is the world stock of emissions, $\overline{M}$ is the pre-industrial stock level of emissions and $\phi$ is a positive parameter measuring the intensity of this negative externality.[9]

The value added $VA_t$ is produced combining capital $K_t$ and labour $L_t$ according to the following CES technology:

$$VA_t = \left[ \rho_{K_{VA}}^{\frac{1}{\theta_{VA}}} \left(u_t^K K_t\right)^{\frac{\theta_{VA}-1}{\theta_{VA}}} + \left(1-\rho_{K_{VA}}\right)^{\frac{1}{\theta_{VA}}} L_t^{\frac{\theta_{VA}-1}{\theta_{VA}}} \right]^{\frac{\theta_{VA}}{\theta_{VA}-1}}, \tag{10}$$

where $\theta_{VA}$ is the elasticity of substitution between capital and labour, $u_t^K$ is the rate of utilization at which capital is utilized and $\rho_{K_{VA}}$ represents the share of capital used to generate the value added. Moreover, $L_t$ represents a CES aggregate of two labour inputs, namely labour supplied by two different types of unionized workers, related to Ricardian ($L_R$) and non-Ricardian ($L_{NR}$) households:

$$L_t = \left[ \rho_{L_R}^{\frac{1}{\sigma_L}} \left(ef_{L_R} L_{R,t}\right)^{\frac{\sigma_L-1}{\sigma_L}} + \left(1-\rho_{L_R}\right)^{\frac{1}{\sigma_L}} \left(ef_{L_{NR}} L_{NR,t}\right)^{\frac{\sigma_L-1}{\sigma_L}} \right]^{\frac{\sigma_L}{\sigma_L-1}}, \tag{11}$$

where $\sigma_L$ is the elasticity of substitution between labour inputs supplied by Ricardian and non-Ricardian households respectively, $ef_{L_R}$ and $ef_{L_{NR}}$ are efficiency parameters measuring the efficiency of the two different labour inputs, while $\rho_{L_R}$ and $1-\rho_{L_R}$ represent the shares of utilization. $L_{R,t}$ and $L_{NR,t}$ represent, in turn, CES bundles of different types of labour services with elasticities of substitution equal to $\sigma_{L_R} > 1$ and $\sigma_{L_{NR}} > 1$, respectively.

Emissions at firm level, $Z_{Y,t}$, are assumed to be a by-product of output. However, this relationship is affected by the abatement effort $U_t$. In particular, we assume:

$$Z_{Y,t} = (1-U_t)\varphi_Y Y_t^{\mu_Y}, \tag{12}$$

where $\mu_Y > 0$ is the elasticity between output and emissions, while $\varphi_Y > 0$ is a technological parameter relating emissions to output. Abatement is, in turn, a costly activity for firms. A policy to mitigate intermediate-sector emissions is mapped onto the model through the reduction of $Z_{Y,t}$.

We further assume that firms face adjustment costs when resetting their price and when changing their labour inputs and the level of electricity employed for production. Given the monopolistic competition structure of the sector, firms are able to charge a markup over their marginal cost.

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[8] Notice that $EL_t$ represents, in turn, a CES bundle of electricity inputs provided by monopolistic competitive producers. See Annicchiarico et al. (2016a) for further details.

[9] Damages from climate change include, among other factors, loss of life, deterioration in the quality of life, and depreciation of the capital stock. These damages should also include any resources used to prevent disasters and, more generally, to lessen the impact of climate change on humans and human activity. See Golosov et al. (2014) for further details.

## 3.3 Exporting and importing firms

We assume the existence a continuum of monopolistically competitive exporting firms transforming domestic intermediate goods into exportable goods using a linear technology. These firms demand goods from domestic intermediate good producers and sell them in foreign markets by charging a price markup over their marginal cost. Also exporting firms are assumed to face adjustment cost when resetting their prices. The overall demand for exports, $EXP_t$, depends on global demand and on the relative price between domestically produced goods and foreign goods.

By the same token, there is a continuum of monopolistically competitive importers. Importing firms act in different domains, namely they import coal $COA_t$, crude oil $OIL_t$, gas $GAS_t$ and $EL_{NUC,t}$ to be sold to the electricity sector and foreign intermediate goods, $IMPF_t$, to be sold to the domestic final good sector. Finally, importing firms are also assumed to import refined oil, $ROIL_t$, and biofuel, $BIOF_t$, to be sold to households. Non-competitive importing firms charge a price markup over the import prices.

## 3.4 Final-good producers

Firms producing final non-tradable goods are assumed to be symmetric and to act under perfect competition. The representative firm producing the final non-tradable good $E_t$ combines a bundle of domestically produced intermediate goods $Y_{H,t}$ (where $Y_{H,t}$ represents the domestic absorption of domestic production, i.e. $Y_{H,t} = Y_t - EXP_t$) with a bundle of imported intermediate goods $IMPF_t$ according to a constant elasticity of substitution (CES) technology:

$$E_t = \left[ (1-\alpha_{IMPF})^{\frac{1}{\sigma_{IMPF}}} Y_{H,t}^{\frac{\sigma_{IMPF}-1}{\sigma_{IMPF}}} + \alpha_{IMPF}{}^{\frac{1}{\sigma_{IMPF}}} IMPF_t{}^{\frac{\sigma_{IMPF}-1}{\sigma_{IMPF}}} \right]^{\frac{\sigma_{IMPF}}{\sigma_{IMPF}-1}}, \tag{13}$$

where $\sigma_{IMPF}$ is the elasticity of substitution between domestically produced and internationally produced intermediate goods, and $\alpha_{IMPF}$ represents the share of foreign intermediate goods used in the production of the final goods.

## 3.5 Households

Population is constant and normalized to one and is divided into two types of households differing over their ability to access financial markets: the non Ricardian households, who simply consume their disposable income (i.e. the hand to mouth consumers) and the Ricardian households, who are able to smooth consumption over time. The population share of Ricardian and non-Ricardian households is $s_R$ and $1 - s_R$, respectively. In what follows, the indexes $R$ and $NR$ refer, respectively, to Ricardian and non-Ricardian household-specific variables and parameters. Both kinds of households are assumed to consume the final good purchased from final good producers and fuel from importing firms, while they supply a bundle of differentiated labour inputs to be employed by the intermediate good producers, as already explained above. However, labour decisions are made by a central authority within the household: a union will represent each variety of labour services supplied as employee.

### 3.5.1 Ricardian households

Ricardian households are characterized by the following lifetime utility function:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left( u(C_t^R - h_{C^R}\overline{C}_{t-1}^R) - \omega_{L_R} \int_0^1 \frac{L_{R,t}^H(h_{L_R})^{1+v_{L_R}}}{1+v_{L_R}} dh_{L_R} \right), \tag{14}$$

where $C_t^R$ denotes consumption; $L_{R,t}^H(h_{L_R})$ denotes labour in the activity $h_{L_R}$; $\beta$ is the discount factor; $h_{C^R}$ is the habit persistence parameter; $v_{L_R}$ is the inverse of the Frisch elasticity of labour supply and $\omega_{L_R}$ is a scale parameter governing the disutility arising from labour.

We assume a logarithmic utility function for consumption:

$$u(C_t^R - h_{C^R}\overline{C}_{t-1}^R) = \log(C_t^R - h_{C^R}\overline{C}_{t-1}^R). \tag{15}$$

and the flow budget constraint is

$$\begin{aligned} P_{C,t}C_t^R + B_t^R + S_t B_t^{F,R} + P_{I,t}I_t^R + P_{I_{RES},t}I_{RES,t}^R = {} & \left(1 - \tau_t^{L_R} - \tau_{h,t}^{W_{L_R}}\right) \int_0^1 W_{L_R,t}(h_{L_R}) L_{R,t}^H(h_{L_R}) dh_{L_R} + \\ & + R_{t-1}B_{t-1}^R + R_{t-1}^* S_t B_{t-1}^{F,R} + \\ & + \tau_t^K \delta_K P_{I,t} u_t^K K_t^R + \\ & + (1 - \tau_t^K) r_t^K P_{I,t} u_t^K K_t^R + \\ & + \tau_t^{K_{RES}} \delta_{K_{RES}} P_{I_{RES},t} K_{RES,t}^R + \\ & + (1 - \tau_t^{K_{RES}}) r_t^{K_{RES}} P_{I_{RES},t} K_{RES,t}^R + \\ & + tcrk_t P_{I,t} I_t^R + tcrk_{RES,t} P_{I_{RES},t} I_{RES,t}^R + \\ & - TAX_t^R + Tr_t^R + V_t^R - ADJ_t^R, \end{aligned} \quad . \tag{16}$$

where $P_{C,t}$ is the consumption price index; $I_t^R$ and $I_{RES,t}^R$ denote investment in intermediate goods and in the RES sector respectively; $P_{I,t}$ and $P_{I_{RES},t}$ are the prices of the two types of investment goods; $tcrk$, $tcrk_{RES}$, $\tau_t^K$ and $\tau_t^{K_{RES}}$ denote, respectively, the subsidies and tax rates on investment and capital in both intermediate goods and the RES sector; $\delta_K$ and $\delta_{K_{RES}}$ are the depreciation rates of capital; $B_t^R$ and $B_t^{F,R}$ are the amount of domestic (government) and foreign bonds (denominated in foreign currency) purchased by the Ricardian households; $R_t$ is the nominal risk free interest rate; $R_t^*$ is the risk adjusted interest rate on foreign assets; $S_t$ denotes the nominal exchange rate defined the home currency per unit foreign currency; $W_{L_R,t}(h_{L_R})$ is the wage relative to the activity $h_{L_R}$; $\tau_t^{L_R}$ and $\tau_{h,t}^{W_{L_R}}$ are the social security and labour tax rates levied on households; $TAX_t^R$ and $Tr_t^R$ are lump-sum taxes and transfers; $V_t^R$ denotes profits earned from the ownership of intermediate good producing firms, electricity producing firms, importing and exporting firms. Finally. the term $ADJ_t^R$ represents a catchall variable capturing the overall adjustment costs sustained by households when re-setting wages, changing investments in RES and physical capital and adjusting the level of capital utilization.

The capital laws of motion are

$$K_{t+1}^R = (1 - \delta_K) K_t^R + I_t^R, \tag{17}$$

$$K_{RES,t+1}^{R} = (1-\delta_{K_{RES}})K_{RES,t}^{R} + I_{RES,t}^{R}. \tag{18}$$

We assume that $C_t^R$ is a consumption bundle aggregating final good consumption $C_{Y,t}^R$ and fuel consumption $C_{F,t}^R$ used to satisfy transportation needs:

$$C_t^R = \left[ {\alpha_{C_Y}}^{\frac{1}{\theta_C}} {C_{Y,t}^R}^{\frac{\theta_C - 1}{\theta_C}} + (1-\alpha_{C_Y})^{\frac{1}{\theta_C}} {C_{F,t}^R}^{\frac{\theta_C - 1}{\theta_C}} \right]^{\frac{\theta_C}{\theta_C - 1}}, \tag{19}$$

where $\theta_C$ is the elasticity of substitution between goods and fuel consumption and $\alpha_{C_Y}$ is the share of goods consumption.

In turn, fuel consumption is a bundle that aggregates refined oil, $ROIL_t^R$ and biofuel, $BIOF_t^R$:

$$C_{F,t}^R = \left[ {\alpha_{ROIL}}^{\frac{1}{\theta_{C_F}}} {ROIL_t^R}^{\frac{\theta_{C_F} - 1}{\theta_{C_F}}} + (1-\alpha_{ROIL})^{\frac{1}{\theta_{C_F}}} {BIOF_t^R}^{\frac{\theta_{C_F} - 1}{\theta_{C_F}}} \right]^{\frac{\theta_{C_F}}{\theta_{C_F} - 1}}, \tag{20}$$

where $\theta_{C_F}$ denotes the elasticity of substitution between consumption of refined oil and biofuel and $\alpha_{ROIL}$ is the share of refined oil.

Solving the cost minimization problem yields the demand for $C_{Y,t}^R$ and $C_{F,t}^R$, given by

$$C_{Y,t}^R = \alpha_{C_Y} \left[ \frac{P_{C_Y,t}(1+\tau_t^C)}{P_{C,t}} \right]^{-\theta_C} C_t^R, \tag{21}$$

$$C_{F,t}^R = (1-\alpha_{C_Y}) \left( \frac{P_{C_F,t}}{P_{C,t}} \right)^{-\theta_C} C_t^R, \tag{22}$$

where $P_{C_Y,t}$ and $P_{C_F,t}$ are the price indexes of goods and fuel consumption respectively, while $\tau_t^C$ is the tax rate on consumption. The overall consumption price index is defined as

$$P_{C,t} = \left\{ \alpha_{C_Y} [P_{C_Y,t}(1+\tau_t^C)]^{1-\theta_C} + (1-\alpha_{C_Y}) {P_{C_F,t}}^{1-\theta_C} \right\}^{\frac{1}{1-\theta_C}}. \tag{23}$$

The demands for $ROIL_t^R$ and $BIOF_t^R$ are simply given by

$$ROIL_t^R = \alpha_{ROIL} \left[ \frac{P_{ROIL,t}(1+\tau_t^{ROIL})}{P_{C_F,t}} \right]^{-\theta_{C_F}} C_{F,t}^R, \tag{24}$$

$$BIOF_t^R = (1-\alpha_{ROIL}) \left[ \frac{P_{BIOF,t}(1+\tau_t^{BIOF})}{P_{C_F,t}} \right]^{-\theta_{C_F}} C_{F,t}^R, \tag{25}$$

where $\tau_t^{ROIL}$ and $\tau_t^{BIOF}$ are the tax rates on refined oil and biofuel, respectively, and the fuel consumption price index is defined as

$$P_{C_F,t} = \left\{ \alpha_{ROIL} [P_{ROIL,t}(1+\tau_t^{ROIL})]^{1-\theta_{C_F}} + (1-\alpha_{ROIL}) [P_{BIOF,t}(1+\tau_t^{BIOF})]^{1-\theta_{C_F}} \right\}^{\frac{1}{1-\theta_{C_F}}}, \tag{26}$$

where $P_{ROIL,t}$ and $P_{BIOF,t}$ are the price indexes of $ROIL_t^R$ and $BIOF_t^R$, respectively.

A fiscal intervention on the supply side of the labour market aiming at stimulating employment and preserving fiscal revenues is implemented by a tax shift from labour (by reducing $\tau_t^{L_R}$) to refined oil consumption taxes (by increasing $\tau_t^{ROIL}$ ). Similarly, a fiscal intervention aiming at enhancing the use of renewable resources reduces $\tau^{K_{RES}}$ and simultaneously increases $\tau_t^{ROIL}$. The change in the tax rates will depend on the relative size of the tax bases, so as to ensure that the fiscal reform is ex-ante budget neutral.

### 3.5.2 Non-Ricardian households

The representative non-Ricardian consumer chooses the optimal allocation between consumption and leisure and consumes her net income. The utility function is

$$U_t^{NR} = u(C_t^{NR} - h_{C^{NR}}\overline{C}_{t-1}^{NR}) - \omega_{L_{NR}} \int_0^1 \frac{L_{NR,t}^H(h_{L_{NR}})^{1+\upsilon_{L_{NR}}}}{1+\upsilon_{L_{NR}}} dh_{L_{NR}}, \tag{27}$$

while the flow budget constraint is

$$\begin{aligned} P_{C,t}C_t^{NR} = {} & \left(1 - \tau_t^{L_{NR}} - \tau_{h,t}^{W_{L_{NR}}}\right) \int_0^1 W_{L_{NR},t}(h_{L_{NR}}) L_{NR,t}^H(h_{L_{NR}}) dh_{L_{NR}} - TAX_t^{NR} \\ & + Tr^{NR} - ADJ_t^{NR} \end{aligned} \tag{28}$$

where all variables are as in the previous section and the superscript $NR$ stands for "non Ricardian" and $ADJ_t^{NR}$ represents the adjustment costs sustained by households when re-setting wages. Also in this case we assume a logarithmic utility function for consumption

In a symmetric way with respect to the case of Ricardian households, we assume that $C_t^{NR}$ is a consumption bundle aggregating good-consumption $C_{Y,t}^{NR}$ and fuel consumption $C_{F,t}^{NR}$:

$$C_t^{NR} = \left[\alpha_{C_Y}^{\frac{1}{\theta_C}} C_{Y,t}^{NR\,\frac{\theta_C-1}{\theta_C}} + (1-\alpha_{C_Y})^{\frac{1}{\theta_C}} C_{F,t}^{NR\,\frac{\theta_C-1}{\theta_C}}\right]^{\frac{\theta_C}{\theta_C-1}}, \tag{29}$$

where

$$C_{F,t}^{NR} = \left[\alpha_{ROIL}^{\frac{1}{\theta_{C_F}}} ROIL_t^{NR\,\frac{\theta_{C_F}-1}{\theta_{C_F}}} + (1-\alpha_{ROIL})^{\frac{1}{\theta_{C_F}}} BIOF_t^{NR\,\frac{\theta_{C_F}-1}{\theta_{C_F}}}\right]^{\frac{\theta_{C_F}}{\theta_{C_F}-1}}. \tag{30}$$

Solving the corresponding cost minimization problems one can easily obtain the first order conditions for non-Ricardian households.

## 3.6 Aggregation

Given the above assumptions, about the role played by non-Ricardian households, the aggregate level of the main macroeconomics variables immediately follows, that is $K_t$=$s_R K_t^R$, $K_{RES,t} = s_R K_{RES,t}^R$, $I_t = s_R I_t^R$, $I_{RES,t} = s_R I_{RES,t}^R$, $B_t = s_R B_t^R$ and $B_t^F = s_R B_t^{FR}$, where we have dropped the $R$ subscript to indicate that these economic variables are now expressed in aggregate terms.

The total level of capital employed in the the production of clean energy is then

$$K_{RES,t} = K_{WIN,t}^{RES} + K_{HYD,t}^{RES} + K_{BIO,t}^{RES} + K_{SOL,t}^{RES}. \tag{31}$$

The overall supply of labor employed in the intermediate good sector is then found to be:

$$L_{R,t} = s_R L_{R,t}^H, \tag{32}$$

$$L_{NR,t} = (1 - s_R) L_{NR,t}^H. \tag{33}$$

Aggregate consumption is obtained as the weighted average consumption of Ricardian and non-Ricardian households:

$$C_t = s_R C_t^R + (1 - s_R) C_t^{NR}, \tag{34}$$

while the aggregate final-good consumption is

$$C_{Y,t} = s_R C_{Y,t}^R + (1 - s_R) C_{Y,t}^{NR}, \tag{35}$$

and the aggregate fuel consumption is

$$C_{F,t} = s_R C_{F,t}^R + (1 - s_R) C_{F,t}^{NR}. \tag{36}$$

Furthermore, aggregate consumption of refined oil and biofuel are

$$ROIL_t = s_R ROIL_t^R + (1 - s_R) ROIL_t^{NR}, \tag{37}$$
$$BIOF_t = s_R BIOF_t^R + (1 - s_R) BIOF_t^{NR}, \tag{38}$$

where it is further assumed that the consumption of $ROIL_t$ generates emissions according to the following relationship:

$$Z_{ROIL,t} = \varphi_{ROIL} ROIL_t^{\mu_{ROIL}}, \tag{39}$$

where $\mu_{ROIL} > 0$ is the elasticity between emissions and refined oil consumption and $\varphi_{ROIL} > 0$ is a technological parameter.

Total emissions are defined as

$$Z_t^{TOT} = Z_{Y,t} + Z_{EL,t} + Z_{ROIL,t}. \tag{40}$$

The stock of emissions $M_t$ evolves as follows

$$M_t = (1 - \delta_M) M_{t-1} + Z_{Y,t} + Z_{EL,t} + Z_{ROIL,t} + Z_t^{RoW}, \tag{41}$$

where $\delta_M$ is the fraction of pollution which naturally decays in each time period and $Z_t^{RoW}$ denotes emissions from the rest of the world.

We assume that all the investment goods used to build capital in the RES sector are imported, so that total imports can be defined as

$$\begin{aligned} IMPT_t = {} & \frac{S_t P_{IMPF,t}^*}{P_t} IMPF_t + \frac{S_t P_{OIL,t}^*}{P_t} OIL_t + \frac{S_t P_{COA,t}^*}{P_t} COA_t + \frac{S_t P_{GAS,t}^*}{P_t} GAS_t + \\ & + \frac{S_t P_{EL_{NUC},t}^*}{P_t} EL_{NUC,t} + \frac{S_t P_{ROIL,t}^*}{P_t} ROIL_t + \frac{S_t P_{BIOF,t}^*}{P_t} BIOF_t + \frac{S_t P_{I_{RES},t}^*}{P_t} I_{RES,t}, \end{aligned} \tag{42}$$

where asterisks denote foreign prices and $P_t$ is the domestic production price index.

In equilibrium the following price conditions must hold:

$$P_{E,t} = P_{C_Y,t} = P_{I,t} \equiv \left[ (1 - \alpha_{IMP}) (P_t)^{1-\sigma_{IMP}} + \alpha_{IMP} (P_{IMPF,t})^{1-\sigma_{IMP}} \right]^{\frac{1}{1-\sigma_{IMP}}}, \tag{43}$$

while $P_{I_{RES},t} = S_t P_{I_{RES},t}^*$.

## 3.7 The government and the monetary authority

The flow budget constraint of the government evolves as

$$\begin{aligned} B_t &= R_{t-1}B_{t-1} + P_{E,t}G_t + Tr_t - TAX_t - LTAX_t - CTAX_t + \\ &\quad -KTAX_t - EXCTOT_t - P_{Z,t}(Z_{Y,t} + Z_{EL,t}), \end{aligned} \tag{44}$$

where $Tr_t$, $LTAX_t$, $CTAX_t$, $KTAX_t$ and $EXCTOT_t$ represent aggregate transfers, labour taxes, consumption taxes, taxes and subsidies on capital and excises, respectively:

$$Tr_t = s_R Tr_t^R + (1 - s_R) Tr_t^{NR}, \tag{45}$$

$$TAX_t = s_R TAX_t^R + (1 - s_R) TAX_t^{NR}, \tag{46}$$

$$LTAX_t = L_{R,t}W_{L_R,t}\left(\tau_t^{L_R} + \tau_{h,t}^{W_{L_R}} + \tau_{f,t}^{W_{L_R}}\right) + L_{NR,t}W_{L_{NR},t}\left(\tau_t^{L_{NR}} + \tau_{h,t}^{W_{L_{NR}}} + \tau_{f,t}^{W_{L_{NR}}}\right), \tag{47}$$

$$CTAX_t = \tau_t^C P_{C_Y,t}C_t,$$

$$\begin{aligned} KTAX_t = {} & \tau_t^K\left(r_t^K - \delta_K\right)P_{I,t}u_t^K K_t - tcrk_t P_{I,t}I_t + \tau_t^{K_{RES}}\left(r_t^K - \delta_{K_{RES}}\right)P_{I_{RES},t}K_{RES,t} + \\ & - tcrk_{RES,t}P_{I_{RES},t}I_{RES,t}, \end{aligned} \tag{48}$$

$$EXCTOT_t = \tau_t^{ROIL}\frac{P_{ROIL,t}}{P_t}ROIL_t + \tau_t^{BIOF}\frac{P_{BIOF,t}}{P_t}BIOF_t, \tag{49}$$

where $\tau_{f,t}^{W_{L_R}}$ and $\tau_{f,t}^{W_{L_{NR}}}$ denote the social security contribution rates bearing on firms. When $Z_{Y,t}$ and $Z_{EL,t}$ are set exogenously by the cap policy, then the price of emission permits $P_{Z,t}$ is endogenously determined. As a result, $P_{Z,t}(Z_{Y,t} + Z_{EL,t})$ represents revenues from the sale of emission permits. Alternatively, when $P_{Z,t}$ represents a carbon-tax rate on emissions and is set exogenously, then $Z_{Y,t}$ and $Z_{EL,t}$ are endogenously determined and thus $P_{Z,t}(Z_{Y,t}+Z_{EL,t})$ are the overall revenues from such tax. The lump-sum component of taxation $TAX_t$ is set endogenously as a function of public debt so as to ensure that the government budget is always balanced.

Finally, the monetary authority sets the short-term nominal interest rate in accordance with a Taylor-type rule:

$$\frac{R_t}{\overline{R}} = \left(\frac{R_{t-1}}{\overline{R}}\right)^{\iota_r}\left[\left(\frac{\Pi_t}{\overline{\Pi}}\right)^{\iota_\pi}\left(\frac{Y_t}{\overline{Y}}\right)^{\iota_y}\left(\frac{S_t}{\overline{S}}\right)^{\iota_S}\right]^{1-\iota_r}, \tag{50}$$

where $\iota_r$, $\iota_\pi$, $\iota_y$, and $\iota_S$, are policy parameters and the barred variables refer to the steady-state counterparts of the relevant variables at the numerator of each term.

## 3.8 Foreign assets and resource constraint

The economy's net foreign asset position denominated in domestic currency evolves as:

$$S_t B_t^F = R_{t-1}^* S_t B_{t-1}^F + S_t P_{X,t}^* EXP_t - P_t IMPT_t, \tag{51}$$

where $IMPT_t$ represents total imports according to (42), while $P_{X,t}^*$ is the price set on exports in foreign currency.

Finally, the economy resource constraint reads as

$$Y_t = \frac{P_{C_Y,t}}{P_t}(C_{Y,t} + I_t + G_t) + \frac{S_t P_{X,t}^*}{P_t}EXP_t - IMPT_t + ADJ_t + AC_t, \tag{52}$$

where $ADJ_t$ represents the overall adjustment costs of the economy and $AC_t$ denotes total abatement costs sustained by electricity producers and by intermediate good firms.

# 4 Parametrization and model solution

The model is calibrated for Italy using quarterly data. Table 1 describes the main economic ratios. The consumption-GDP and the investment-GDP ratios are set, respectively, to 61.3% and 17.5%, so that the implied steady state levels of public expenditure and imports are equal to 20% and 36%, respectively. The annual public debt-GDP ratio is set equal to 130% of GDP and the trade balance is zero in steady state. The discount factor $\beta$ is set equal to 0.99, implying a steady state value of the real interest rate of 1%. The depreciation rates of capital ($\delta_K$ and $\delta_{K_{RES}}$) are set equal to 0.025, so that the steady state rental rate of capital is 4%.

Turning to the household side, the inverse of the Frisch elasticities ($\nu_{L_R}$ and $\nu_{L_{NR}}$) are set equal to 1. According to the estimates by Annicchiarico et al. (2015), the share of Ricardian and non-Ricardian households ($s_R$, $1 - s_R$) are set to 0.7 and 0.3 respectively, and the habit persistence parameters ($h_{C^R}$, $h_{C^{NR}}$) are set to 0.9 for Ricardian households and 0.2 for non-Ricardian households. The fraction of time spent working is set equal to 0.3 for both.

Table 2 shows the gross production of electricity generated by fossil fuel sources and RES together with their respective shares in total electricity production in 2013 (see AEEGSI 2014). We draw on these data to set the share of each electricity generation source and calibrate the weights of the nested CES electricity production functions accordingly. Specifically, each weight represents the share of a source relative to the electricity bundle it belongs to.

In Italy the most relevant source of electricity generation is natural gas which accounts for 38% of total electricity production. Among the other fossil-fuel sources, coal accounts for 16% and oil for 7.5%. On the RES side, electricity generated from solar, wind and biomass represents respectively 7.8%, 5.2% and 4.9% of total electricity produced, whereas the largest contribution comes from hydroelectric energy which amounts to 18.5%.[10] As a whole, the share of fossil-fuel sources and RES are 62% and 38%, respectively.

Table 3 lists the parameter values of the CES functions related to electricity generation and intermediate good production. It is worth underlining that the model described above encompasses all conventional sources used to generate electricity, including nuclear energy despite the fact that the latter is not used in the Italian electricity sector. In this analysis the electricity generated from nuclear energy is thus set to zero.

We set the elasticity of substitution between electricity generated from conventional sources and RES, $\theta$, equal to 0.6. The elasticity of substitution between electricity generated from coal and oil and natural gas, $\theta_{FOS}$, is set at 0.9 and that between coal and oil, $\theta_{COAOIL}$, at 0.3. The previous values are set according to Bartocci and Pisani (2013). Strictly speaking, this parametrization entails a degree of complementarity among inputs used in the electricity generation. On the contrary, the electricity generated from RES, $\theta_{RES}$, is characterized by a certain degree of substitutability among its components, so that we set the elasticity equal to 2, in line with Bartocci and Pisani (2013) and Bosetti et al. (2009).

For what concerns the production function of intermediate goods, we set the elasticity of substitution between value added and electricity, $\theta_Y$, equal to 0.8. Following Bartocci and Pisani (2013) we set the elasticity of substitution between capital and labour, $\theta_{VA}$, at 0.9 and the factor shares of value added and capital ($\rho_{VA}$ and $\rho_{K_{VA}}$) at 0.96 and 0.53 respectively. The elasticity between

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[10] Notice that geothermic energy appears in Table 2, but is not included in the model so that the sum of the electricity shares in the model is slightly lower than 100.

Ricardian and non-Ricardian labour inputs $\sigma_L$ is set equal to 1.4. The elasticities of substitution among varieties of domestically-produced intermediate goods and electricity ($\theta_{Y_H}$ and $\theta_{EL}$) are set equal to 2.65 as well as the rest of the elasticities included in the model in order to define the degree of substitution among varieties.

The model includes several rigidities in the form of adjustment costs. According to the estimates by Annicchiarico et al. (2015) and Ratto et al. (2009) the parameters measuring the degree of price and wage rigidity ($\gamma_{P_Y}$, $\gamma_{W_{L_R}}$ and $\gamma_{W_{L_{NR}}}$) are set equal to 20, 15 and 15, respectively. The parameters related to the adjustment cost on investment in capital and labour of the intermediate goods sector, ($\gamma_I$, $\gamma_{L_R}$ and $\gamma_{L_{NR}}$), are set equal to 75.9, 71 and 71, respectively. The remaining parameters related to the degree of price and quantity rigidity are all set equal to 6.

There are three emission functions in the model according to the source of pollution, namely output, electricity generated from fossil fuels and gasoline consumption for transportation. Each function has two parameters determining its shape: the emission intensity parameter, $\varphi_X$, and the elasticity $\mu_X$, where $X = \{Y, EL_{FOS}, ROIL\}$. We estimate the elasticities computing the respective percentage variations between 2005-2013 in order to take into account the relevant period in which environmental regulations were implemented.

We compute the elasticity between output and emissions using ISTAT data for industrial production and emissions from the industrial sector. For the level of emissions generated by electricity from fossil fuel production we use Terna data on thermoelectric electricity, whereas ISTAT data are used for the relative level of emissions. For the elasticity between gasoline consumption and emissions, we use ISTAT data for emissions derived from transportation, while data on household consumption of gasoline are reported by the Italian Ministry of Economic Development. We obtain the following values for the relative elasticities: $\mu_Y = 1.2$, $\mu_{EL_{FOS}} = 1.5$ and $\mu_{ROIL} = 0.6$.

Finally, the scale parameters of the abatement cost function for intermediate good firms and electricity producers ($\phi_1$ and $\phi_1^{EL}$) are set both to 0.025, while the parameters governing the convexity of the functions ($\phi_2$ and $\phi_2^{EL}$) are set both to 1.278. For these parameters we have drawn on previous studies estimating the parameters for the European Union (see Cline 2011).

Using this parametrization, the non-linear version of GEEM is solved in a TROLL platform which relies a Newton-type algorithm to solve non-linear deterministic models. To conduct our simulation exercise, we examine the deterministic response of the economy to unexpected permanent changes in the exogenous policy variables taking place at the beginning of the simulation time horizon. It should be noted that the analysis of the effects of permanent shocks requires solving a two-point boundary-problem, specifying the initial conditions for the predetermined variables and the terminal conditions for the forward looking variables. The more rigorous approach to solve this problem would make it necessary to derive the new steady state of the model and use the theoretical equilibrium values as terminal conditions. However, when dealing with a large scale model this solution strategy can be very taxing. Alternatively, one may opt to reformulate the problem so that the terminal conditions are invariant to policy changes, as proposed by Roeger and in't Veld (1999). In this paper we have opted for this latter strategy.

# 5 GHG mitigation schemes and energy policies

We consider several policy scenarios for the Italian economy by using an array of shocks designed to evaluate the impact of mitigation and energy policies. It is worth noting that we will not deal with specific policy provisions that have been implemented or that the Italian government is about to implement. Indeed, our scenarios are intended to be only illustrative of the potential effects of a set of policy experiments. Accordingly, the simulation hypotheses concerning the credibility, the design and the size of the shocks are to some extent arbitrary. Further, simulations are carried out under the assumption that reforms are fully credible and the underlying policy measures are gradually introduced over 15 or 5 years. The gradual introduction of policy change allows us to analyze the effects of a slower implementation, motivated either by possible institutional delays or by the need to form consensus for policy changes. As common practice in applied economic modelling, all policy changes are assumed to be permanent. Households and firms have perfect foresight, therefore any possible source of uncertainty about the underlying path of policy changes is ruled out. As a result, forward looking agents adjust their behaviour accordingly, fully anticipating the long-run effects of the reforms.

Table 4 summarizes the scenarios. In particular, we consider two mitigation scenarios and three examples of energy policies. Specifically, the first scenario (Scenario 1A) considers an emission reduction of 10 per cent involving both the manufacturing and electricity sectors implemented in a gradual way over a period of 15 years. This shock is introduced by reducing the $Z_{Y,t}$ and $Z_{EL,t}$ in equations (12) and (7), respectively, while the emissions generated from the consumption of refined oil, $ROIL_t$, is not subject to any cap and it is thus free to adjust. In particular, the policy is implemented by imposing a gradual reduction of the overall emissions of both sectors at an annual pace of 0.67 per cent with respect to the baseline. The emission permit price $P_{Z,t}$, thus, is endogenously determined by the model. Furthermore, an alternative mitigation scenario is implemented by imposing a carbon tax on emissions (i.e. Scenario 1B). In this case $P_{Z,t}$ turns out to be the policy instrument and it is meant to be the carbon-tax rate. This shock is implemented by moving up the carbon tax rate $P_{Z,t}$ in order to reduce emissions by 10 per cent both in the manufacturing and electricity sectors ($Z_{Y,t}$ and $Z_{EL,t}$ that are now free to move). Also in this case the shock is implemented in a gradual way so as to generate a cumulated reduction of emissions in both sectors over a period of 15 years. In particular, this policy is mapped onto the model imposing gradual increases of equal size in the carbon tax, so as to achieve the final emission goal. It should be noted that while the final target is the same in both scenarios (whether a cap or a tax is used), the pace at which the policy objective is reached changes substantially. In other words, in our experiments the cap and the tax policies are different by construction, therefore having distinct implications in a deterministic setting.[11]

In both mitigation scenarios we consider two cases of recycling. In the first case, the fiscal revenues generated by the auctioning of permits or by the higher carbon tax revenues are fully used to reduce lump-sum taxes, while in the second case these revenues (1 per cent of output) are earmarked for reducing labour taxes.[12]

Scenarios 2-4 envisage three different experiments of energy policies aimed at discouraging consumption of refined oil. In order to analyse the interaction between different policies, under these three scenarios the model is solved both under the assumption that emissions are free to change and under the assumption of a fixed cap on overall emissions. In the first case, when emissions move freely, $P_{Z,t}$, the carbon-tax rate, is kept constant, while imposing a cap on the overall emissions entails that $P_{Z,t}$, the permit price, is endogenously determined within the model and moves according

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[11] In this respect, Dissou and Karnizova (2016) clearly show how the economic performances of the two mitigation policies, designed to be identical in a deterministic environment, may differ in a stochastic environment when the origin of the shocks is to be found also in the energy sector.

[12] Specifically. we reduce $\tau_t^{L_R}$ and $\tau_t^{L_{NR}}$ in equations (16) and (28).

to the policy action at stake.

In Scenario 2 we implement a budget-neutral tax shift from labour to refined oil consumption taxes (fuel excise taxes with rate $\tau_t^{ROIL}$). This policy shift is thus designed to reduce taxation on labour income by 1 per cent of output in the baseline simulation. In particular, we vary $\tau_t^{L_R}$ and $\tau_t^{L_{NR}}$ in equations (16) and (28). At the same time, an increase in the refined oil consumption tax rate, $\tau_t^{ROIL}$, is introduced in such a way to generate a corresponding ex-ante increase in fiscal revenues by 1 per cent of output in the baseline simulation. For this scenario we consider a gradual implementation of 5 years.

Scenario 3 envisages a budget-neutral shift from social security contribution bearing on firms to refined oil consumption taxes. This policy implies a reduction of the social security contribution rates, $\tau_{f,t}^{W_{L_R}}$ and $\tau_{f,t}^{W_{L_{NR}}}$, while the refined oil consumption tax rate $\tau_t^{ROIL}$ is increased, so as to leave the initial balanced budget position unchanged. The size is set at 1 per cent of output.

Finally, in Scenario 4 we consider a budget-neutral tax shift from taxes on renewable sources ($\tau_t^{K_{RES}}$) to fuel excise taxes ($\tau_t^{ROIL}$) equivalent to 0.1 per cent of baseline output. All the scenarios in this area are implemented in a gradual way over a period of 5 years.

In what follows we report the results of our simulations by showing the effects on the main macroeconomic variables. The impact of policy changes are evaluated for the first 2 years following the implementation as well as over the medium-long run. All the variables are expressed in percentage deviations from their initial steady state values, with the exceptions of the abatement costs and of the permit price (or carbon tax) expressed as percentage points (p.p.) deviations.

## 5.1 GHG emission reduction schemes

We start our analysis by considering the effects of measures aimed at directly reducing emissions. All these scenarios, in fact, envisage a gradual reduction of emissions by 10 per cent in 15 years.

Consider Scenario 1A, where a cap on emissions is gradually introduced. The left-hand side of Table 5 displays the economy's response to a decrease of emissions for the manufacturing and the electricity sectors when the major fiscal revenues are used to cut lump-sum taxes. In this scenario output, consumption, investment and labour decrease persistently over the short as well as the medium-long term. The negative effects on the economic activity tend to accrue in 15 years, while at later stages these negative effects substantially lessen.

In the context of reducing emission cap producers can comply with it through four channels. First, firms can increase the abatement effort so as to make emissions less dependent on the polluting source, namely output (for manufacturing firms) and the electricity generated from fossil fuels (for the electricity sector). Second, firms can buy emission permits whose price comes from the auctioning of these permits. The price of emission permits is thus expected to increase as a result of higher demand for them. Third, since emission abatement and emission permits are costly, the steady reduction in emissions pushes manufacturing firms to cut back on production to sustain lower abatement costs, limiting their emissions according to the diminishing cap. As a result of the lower level of output and higher abatement costs, less resources are available for consumption and investment, so that such mitigation policy entails a crowding-out effect on the main components of aggregate demand. Four, in the electricity sector firms may find it optimal to move towards a more intensive use of renewable sources. Nevertheless, the reduced economic activity, along with higher abatement costs, will induce electricity producers to cut down all their production, including RES and dirty sources of energy. Indeed, investments in RES also inch down, though less than proportionally than those in fossil sources,[13] in part for the fact that the overall electricity production is reduced and in part for the fact that electricity producers will find it more convenient to abate rather than change production towards RES technologies. In this respect, it is worth noting that electricity from RES is less costly than that from fossils, since it does not incorporate any cost related to the abatement or emission permits. This is why, as a result of the less intensive use of electricity from fossils (-0.79 per cent with respect to the baseline after 5 years) relative to the electricity from renewable sources (-0.42 per cent with respect to the baseline after 5 years), the electricity price is shown to move down.

As expected, we observe a sustained increase in the emission permit price that peaks at 9.39 percentage points when the reform is fully implemented (15 years) and then it is shown to inch down to 3.05 percentage points in the subsequent years. As a matter of fact, during the first 15 years of the gradual mitigation policy firms must bear additional abatement costs to comply with it. This is why abatement costs out of output are shown to increase up to 0.13 percentage points after 15 years. At later stages, when the policy action is completed and the reform target is met, the economy is less emission dependent and thus firms do not need to sustain additional abatement costs. As a result, abatement costs do not change substantially (0.14 after 20 years), permit demand reduces and thus permit price stabilizes at a lower level.

All in all, climate mitigation policies are costly, especially in the short-medium run. The heavy real and nominal adjustment costs, that make the transition more taxing, and the limited possibility to substitute away from the fossil source of energy exacerbate the negative effects on consumption and investments. It should be noted that during the transition consumption decreases for both categories of households, however in relative terms non-Ricardian households experience larger reduction of consumption. Intuitively, these households are more exposed to the changed economic conditions and suffer from the diminished level of economic activity induced by the mitigation scheme. In the long run, when the shift towards major abatement is fully underway, output decreases by -0.94 per cent, while aggregate consumption and investments still remain below their baseline values by around 0.5 and 0.4 per cent respectively. It is worth noting that this scenario considers that the all fiscal revenues generated by the auctioning of carbon price go for the reduction of lump-sum taxation. This explains why consumption of non-Ricardian households is shown to increase in the long run. Lower lump-sum taxes help to ease the pressure on the budgets of the more vulnerable fraction of the private sector.

The right-hand side of Table 5 shows the impact of the emission mitigation policy along with a mechanism of recycling the revenues generated by auction. In particular, it is now assumed that labour income taxes move down of 1 percent of the baseline output. In this case the tax reduction has a number of positive effects on economic activity by reducing distortions on employment decisions, and therefore, on the level of economic activity. By diminishing the allocative inefficiency of direct taxation, this measure provides incentives to increase labour supply, thus gross wages and unit labour costs decrease, while the negative effect on output is significantly mitigated relatively to the previous scenario, where the extra revenues are used to cut the lump-sump component of taxation. Investments tend to positively react as a result of the perspective amelioration of the economic conditions. However, the higher cost borne by firms, due to the major abatement effort imposed by the mitigation policy, is significantly diminished by the beneficial effects stemming from a more efficient labour market.[14] As expected, also in this case the price of emission permits increases as

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[13] This limited substitutability between conventional sources and RES is captured by the parameter $\theta$ in (1).

[14] Not surprisingly, the same results come up in Conte et al. (2010), whose model features adjustment costs of the

much as in the previous scenario reflecting the underlying mitigation policy. Overall, we observe that in the long run with this policy mix the trade-off between environmental quality and economic activity is fully overcome. Indeed, after 20 years we observe a positive impact on output, investment and consumption. In particular, most of these gains accrue to the liquidity-constraint households (i.e. non-Ricardian household) who experience a strong increase in consumption. This result points to an important re-distributional aspect also of this combined policy intervention.[15]

Table 6 reports the results of a mitigation policy through a carbon tax levied on intermediate and electricity sector emissions (Scenario 1B). The carbon tax is thus steadily increased in order to reach a 10-per-cent reduction of emissions over 15 years. As in the previous scenario, the left-hand side of the Table displays the economy's impact when the fiscal revenues from such tax are used to cut lump-sum taxes, while in the right-hand side of the Table the fiscal revenues are used to reduce labour taxes.

The introduction of a carbon tax induces a persistent and negative effect on output, consumption and labour, respectively, by -0.74, -0.35 and -0.56 per cent. Nonetheless, in transition the magnitude of these effects is milder than that observed in Scenario 1A. The different transitory dynamics is due to the way in which the policy scenario has been designed, to the the fact that the channel through which the mitigation policy propagates is different from that of the Scenario 1A and to the existence of heavy real and nominal adjustment costs. As explained in the previous Section, in fact, while the final goal in Scenarios 1A and 1B is the same, the pace at which this goal is achieved is different and depends crucially on the instrument used.[16] The imposition of a gradual increasing carbon tax allows producers to smooth the costs of transition towards a low carbon economy and to reduce the adjustment costs. Indeed, working as a corporate taxation, the carbon tax reduces profits, so inducing firms to downsize production costs. However, since producers are not obliged to immediately cut emissions by a size exogenously set, as under a cap policy, they are able to re-set their production plan and factor input mix consistently with the new mitigation scheme in a gradual way. This also explains why during the first years of the mitigation process we observe a smaller reduction of emissions under a carbon tax, than under a cap.

The reduced level of economic activity, in turn, yields, through general equilibrium effects, lower wages that translate into lower consumption. Nonetheless, non-negligible distributional effects across households are also observed, since non-Ricardian households experience a significant drop in their consumption (-1.29 after 5 years and -1.07 after 10 years), while the reduction is fairly moderate for Ricardian households (-0.15 after 5 years and -0.22 after 10 years). This is due to the fact that the Ricardian households, having a higher habit persistence, partly sustain their levels of consumption by increasing income from physical assets. This is why investments display a positive response to the policy shock. To sum up, also the carbon tax involuntarily shifts the mitigation cost disproportionately to the side of non-Ricardian households who, in general, are more vulnerable and exposed to economic changes than Ricardian households. This redistributive effect is particularly severe in

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same type as in our model. Moreover, the parametrization of the adjustment cost variables in is similar in the two models.

[15] Our results are consistent with the findings of Bukowski and Kowal (2010) and Conte et al. (2010) who consider different mitigation schemes in the context of DGE models. The impact of climate action on output is generally negative along the adjustment path, unless the mitigation package embodies a fiscal measure able to reduce distortions in the labour market and/or foster R&D activity, not necessarily only in the "green" sector.

[16] Of course one can set an exogenous path for the carbon tax able to replicate the same results observed under the cap during transition. Results are available from the authors upon request.

the short run, where adjustment costs prevent the immediate materialization of the positive effects from the tax revenues (through lump-sum transfers). However, in the long run the effects on consumption of non-Ricardian households are positive, but less pronounced than those observed under a cap policy.

In the right side of the Table 6, we display the effects of the carbon tax policy when the revenues are used to cut labour taxes. Also in this case recycling revenues is found to be beneficial for the economy that now experiences positive effects on output, consumption and labour already from the second year onwards. The lower tax wedge increases labour supply and induces firms to substitute electricity with labour. Non-Ricardian households experience an initial drop in consumption, followed by a substantial increase which materializes already after 5 years. In particular, after 20 years non-Ricardian households will benefit from the lower labour tax recording a 6.72 per cent increase in their consumption. As a consequence, also emissions from refined oil, not subject to the policy reform, will increase accordingly.

Two important policy messages can be drawn from this set of experiments. The first is that the choice of the instrument chosen (cap versus carbon tax) as a way to fight climate change can influence the size of associated economic costs as long as they induce different patterns of emissions along the adjustment path. In this respect, given a common final goal in terms of emissions reduction, a policy consisting in a gradual and homogenous reduction of the cap and a policy consisting in a gradual and homogenous increase in the carbon tax can lead to very different outcomes during the adjustment process. The latter in fact implies a sort of backloading of emission reduction, with small initial cuts at the beginning and large cuts in the future, so diminishing the adjustment costs by means of a major intertemporal smoothing. The second policy message is that the choice of the recycling rule (lump-sum transfers versus reduction of labour income tax) influences the size of the associated long-run beneficial effects on the economy.

## 5.2 Energy policies

In this set of scenarios we consider interventions in the area of energy policy aimed at discouraging the use of fossil fuels. In particular, these scenarios envisage tax shifts towards refined oil consumption (i.e. ROIL) and designed to be ex ante budget neutral. All the experiments in this area are conducted under the alternative hypotheses either that the economy is not subject to an emission cap ($Z_{Y,t}$ and $Z_{EL,t}$ that are now free to move and so $P_{Z,t}$ is the constant carbon tax) or that the overall emission cap, $Z_t^{TOT}$, is kept constant ($P_{Z,t}$, thus, is endogenous). We will see that both these assumptions allow us to isolate the effects of policy interventions and shocks under two different environmental policy regimes, emission cap or carbon tax on emissions, and thus we are able to observe the consequent re-allocation effects in the emission distribution across sectors under different environmental policies.

We start with Scenario 2, where we assume a gradual shift in the tax burden from labour income to fuel excise taxes. As in the second mitigation experiment, this policy has the intent of reducing the allocative inefficiency in the labour market as a way to offset, and possibly overcome, the potential negative effects on the level of economic activity arising from higher taxation on consumption of fossil fuels. Table 7 reports the results for this scenario. In the case of carbon tax (see the left panel of the Table), we observe that shifting the burden of taxation from labour to consumption reduces inefficiencies and distortions in the labour market, giving rise to an increase in output by 0.72 per cent after 5 years and by 1.04 after 15 years, and in labour by 0.8 per cent after 5 years and by 1.27 per cent after 15 years. As expected, the increase in labour triggers a corresponding increase in investment until the optimal capital-labour ratio is re-established. The beneficial effect of the tax shift is also recorded on aggregate consumption, while, as expected, a small dip in refined oil consumption is observed after 10 years from the onset of the simulation. In the first 5 years we observe, instead, a slight increase in the consumption of refined oil since, initially, the (positive) income effect derived from lower taxes on labour income overcomes the (negative) substitution effect induced by the higher taxation on refined oil. In contrast, biofuel consumption rises persistently, so as to partially compensate the reduction in oil consumption. It is worth noting that non-Ricardian households will significantly benefit from the reduction of labour taxation, since their consumption is highly sensitive to variations in net labour income. As a result, the benefits accruing to Ricardian households are lower than those to non-Ricardian households. As emissions are free to adjust (while $P_{Z,t}$ is kept constant), we observe that $Z_t^{TOT}$ rises as a consequence of the upward trend of output. Notably, manufacturing and electricity firms tend to push emissions up due to the higher production of goods and electricity, while emissions from refined oil consumption tend to slightly decrease in the medium-long term as a consequence of the downward trend in refined oil consumption. The expansionary effect of this fiscal intervention is able to generate a corresponding shift of RES investments and also an increasing use of electricity from renewable sources, although the electricity from fossil fuels is shown to go slightly higher than that from renewable sources as a result of no constraint on emissions.

The positive effect on output, labour and consumption of the tax shift might be hampered by the emission cap on total emissions. This is shown in the right-hand side of Table 7. Indeed, the presence of an emission cap fairly mitigates the positive effects of the fiscal reform for output, consumption and labour, but also for investment in renewable sources. The major implication from the cap is basically that the economy faces an increase in the intermediate costs in order to comply with the emission cap. Indeed the emission price $P_{Z,t}$ is shown to increase over the relevant simulation time horizon. However, given that a single cap is set for all the economic sectors, namely manufacturing and electricity, the corresponding distribution of emissions across sectors depends on the relative weight of the abatement costs. In particular, the electricity sector, with lower abatement costs, is shown to fully bear the costs induced by the presence of the cap, while the intermediate good sector will experience an increase, though small, of emissions. Nonetheless, the electricity sector will produce electricity more intensively from renewable sources in order to alleviate the cost of abating.

In Scenario 3 we study the potential effects of a tax shift from social security contribution borne by firms to fuel excise taxes. See Table 8. Also in this case we consider two different hypotheses regarding the emission policy, namely carbon tax and emission cap. In this scenario the labour tax wedge is reduced on the side of employers, making labour cost lower. As expected, we observe a positive effect on the main macroeconomic variables, with the exception of investments, since cheaper labour induces producers to substitute capital for labour in the production. This negative effect on investment is more intense when emissions are free to change (see the left panel of the Table), since the allocative effects of this tax swap are less strong when emissions are fixed at a given cap. In the long run wages adjust gradually, absorbing the reduction of the labour cost and eroding the competitive advantage of firms stemming from labour cost reduction. Overall, since wages adjust upwards, the effects of this tax policy on the level of economic activity, and so on emissions, when these are free to adjust, are minor than those experienced in Scenario 2. The consumption of biofuel increases immediately, while that of refined oil initially increases and then decreases, since the tax shift is implemented gradually and the positive income effect (due to the higher wages) initially offsets the substitution effects. This also explains why emissions from consumption of refined oil increase under both emission policies in the first years of the simulation. The implication of having a cap on emissions, rather than a carbon tax, translates into a weaker, though positive, response of the main macroeconomics variables.

We conclude our analysis by studying the effects of a gradual tax swap designed to encourage investments in renewable sources and discourage the consumption of refined oil on the part of households (Scenario 4). As in the previous scenarios we undertake our analysis considering the case of a carbon tax in contrast to the case of a binding cap. See Table 9 for results. Indeed, investments in renewable sources increase already in the short run by around 10 per cent from the baseline up to about 15 per cent after 20 years as a result of the higher expected profitability of the RES induced by lower taxes. As a consequence, the demand for electricity increases, while the production structure moves towards clean inputs benefiting from the fiscal incentives, with a corresponding decrease in the use of fossil fuel.[17] Hence, emissions in the electricity sector sharply decline, since production is now more reliant on clean sources. Furthermore, the price of electricity steadily declines, as the marginal cost of renewable resources is lower than that of fossil fuels.[18] However, the medium-run positive effects on output tend to be reinforced in the long run. Instead, the impact on total consumption and investment is negligible also in the long run. It should be noted that in this experiment we do not observe any re-distributional effect in favour of the non-Ricardian households. In this experiment, in fact, the higher taxation on the consumption of refined oil is not counterbalanced by a reduction of the tax wedge of labour as is done in the previous scenarios.

When we compare the simulation results under the two emission policies we notice the following. First, contrary to the previous tax policy experiments, the effects on GDP are now very similar. This is due to the fact that a reduction of taxation on RES investment increases imports, since RES investment goods are imported from abroad. Second, emissions decline slightly under a carbon tax, while in the case of a cap we observe a reallocation of permits in favour of the intermediate goods sector. Despite the fact that this policy mix tends to reduce emissions, the cap is found to be always binding since, being abatement a costly activity, intermediate goods producers opt to abate less and pollute more.

# 6 Conclusions

In this paper we have investigated the response of the economy to emission mitigation schemes and to tax policies reducing the use of polluting energy sources in favour of cleaner sources. The analysis has been conducted with GEEM, a new dynamic general equilibrium model for the Italian economy, primarily designed for the study of climate and energy policies. Environmental policies, in particular climate actions, are likely to produce pervasive effects on the economy, significantly interacting with other policies. The environmental constraint, represented by climate policies, along with the additional costs of abatement and the possibility of shifting from one energy source to another, is

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[17] This simulation experiment is similar to that proposed by Bartocci and Pisani (2014), who consider a gradual increase in the tax on fuel for private transportation combined with a reduction of the tax on electricity and an increase in the subsidies for electricity generated by RES. Our results are consistent with their findings, although the transmission channels of the policy are fairly different in the two models and their dynamic transition towards the new steady state is faster than that observed in our simulations. The the lack of any nominal rigidities on wage and price adjustment tend, coupled with the multi-country structure of their model, render the adjustment path to the policy shift more rapid.

[18] This is consistent with the empirical evidence on the impact of RES utilisation on the wholesale electricity market. See, e.g., Clo et al., (2015) and Gelabert et al. (2011).

shown to shape the response of the economy to policy changes in different areas of intervention. Our results show the strong impact of mitigation policies on the level and the composition of economic activity, the importance of recycling revenues from environmental policy, as a means to reconcile different policy objectives, and the significant reallocation of emission permits across sectors stemming from various fiscal policy combinations aimed at discouraging the consumption of fossil fuel, while recycling the extra revenues in favour of energy from RES or labour.

Overall, our results have many policy implications. First, it emerges a potentially strong case on both economic and distributional grounds for using the revenues from auctioned emission permits or from the carbon tax in order to reduce taxes on labour income. With this policy mix policymakers can efficiently strike the right balance between environmental goals and economic costs which can be pervasive, especially during the adjustment process. Second, a credible mitigation plan envisaging small initial cuts of emissions and large cuts at later stages seems to reduce the adjustment costs towards a low carbon economy by allowing agents to smooth the burden of adjustment more efficiently. Third, the interlinkages between environmental policy interventions and the broader tax system are very complex. As a matter of fact, a strong redistribution of resources and costs across sectors stems from the combination of energy policies and tax interventions, when the extra revenues from raising taxation in one domain are used to either reduce inefficiency in other markets or to encourage economic activity. In this respect, combined economic policies should be carefully designed in the light of these potential re-allocative implications. Finally, climate actions could potentially condition the response of an economy embarking on a comprehensive process of structural reforms aiming at fostering growth potential. Our results suggest that ambitious environmental targets and long-run economic needs can be reconciled only through the implementation of a comprehensive and coherent green growth strategy.

The paper neglects several important issues. The model represents the Italian economy in isolation, taking as given the behaviour of the rest of the world. As a consequence, the policy scenarios analyzed in this paper do not consider the implications of a multi-country implementation of mitigation schemes. Instead, owing to the beggar-thy-neighbour nature of some of the policies considered in this paper, it would be interesting to investigate this issue in the context of a multi-country model, accounting for the potential spillover effects across countries and the adoption of coordinated climate actions. Moreover, the present version of GEEM abstracts from endogenous technological change which can be an important factor driving the impact of climate policies and the adoption of cleaner technologies along with the use of renewable energy sources. We leave these points for future research.

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# Data source for parametrization

ISTAT - Istituto Nazionale di Statistica, http://dati.istat.it

MISE - Ministero dello Sviluppo Economico - Dipartimento per l'Energia - DGSAIE.
http://www.sviluppoeconomico.gov.it/index.php/it/cittadino-e-consumatori/prezzi/mercati-dei-carburanti%

Terna - http://terna.it/it-it/sistemaelettrico/statisticheeprvisioni.aspxData

# Tables

Table 1: Economic Ratios

| | |
|---|---|
| Consumption (% GDP) | 61.3 |
| Investment (% GDP) | 17.5 |
| Import (% GDP) | 36 |
| Public expenditure (% GDP) | 20 |

Table 2: Electricity gross production by source (GWh)

| Source | Production | % of total production |
|---|---|---|
| Natural Gas | 109,990 | 38.21 |
| Coal | 45,812 | 15.92 |
| Oil | 21,738 | 7.55 |
| Hydro | 53,240 | 18.5 |
| Solar | 22,400 | 7.78 |
| Wind | 15,000 | 5.21 |
| Biomass | 14,000 | 4.86 |
| Geothermic | 5,650 | 1.96 |

Source: AEEGSI 2014 annual report

Table 3: CES parameters calibration

| Parameter | Calibration | Description |
|---|---|---|
| *Electricity generation* | | |
| $\theta$ | 0.6 | Elasticity of substitution between conventional sources and RES |
| $\theta_{FOS}$ | 0.9 | Elasticity of substitution between coal-and-oil and gas |
| $\theta_{COAOIL}$ | 0.3 | Elasticity of substitution between coal and oil |
| $\theta_{RES}$ | 2 | Elasticity of substitution among RES |
| $\theta_{Y_H}$ | 2.65 | Elasticity of substitution among varieties of domestically-produced intermediate goods |
| $\rho_{EL_{CON}}$ | 0.63 | Factor share of conventional sources |
| $\rho_{COA}$ | 0.68 | Factor share of coal |
| $\rho_{COAOIL}$ | 0.38 | Factor share of coal-and-oil |
| $\rho_{EL_{SOL}}$ | 0.21 | Factor share of solar |
| $\rho_{EL_{WIN}}$ | 0.14 | Factor share of wind |
| $\rho_{EL_{BIO}}$ | 0.13 | Factor share of biomass |
| *Intermediate goods production* | | |
| $\theta_Y$ | 0.8 | Elasticity of substitution between value added and electricity |
| $\theta_{VA}$ | 0.9 | Elasticity of substitution between capital and labour |
| $\theta_{EL}$ | 2.65 | Elasticity of substitution among varieties of electricity |
| $\sigma_L$ | 1.4 | Elasticity of substitution between Ricardian and Non-Ricardian labour |
| $\rho_{VA}$ | 0.96 | Factor share of value added |
| $\rho_{K_{VA}}$ | 0.53 | Factor share of capital |

Table 4: Simulated Scenarios

| Classification | Scenario | Description | Size | Timing |
|---:|---:|---:|---:|---:|
| GHG mitigation | 1A, 1B | Emission reduction | -10% | 15 years |
|  | 2 | Tax shift from labour to refined oil consumption taxes | - 1% of GDP | 5 years |
| Energy policies | 3 | Tax shift from social security contribution to refined oil consumption taxes | - 1% of GDP | 5 years |
|  | 4 | Tax shift from RES to refined oil consumption taxes | - 0.1% of GDP | 5 years |

Table 5: Scenario 1A - GHG Emission Mitigation -10% in 15 Years - Cap Policy

| | with lump-sum tax reduction | | | | | | with labour income tax reduction | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Years | 1 | 2 | 5 | 10 | 15 | 20 | 1 | 2 | 5 | 10 | 15 | 20 |
| GDP $Y_t$ | -0.13 | -0.30 | -0.68 | -1.08 | -1.83 | -0.94 | -0.09 | -0.20 | -0.35 | -0.30 | -0.71 | 0.22 |
| Consumption $C_t$ | -0.14 | -0.30 | -0.55 | -0.65 | -0.64 | -0.54 | -0.03 | -0.05 | -0.09 | -0.16 | -0.06 | 0.43 |
| *Consumption - Ricardian* $C_t^R$ | -0.13 | -0.27 | -0.49 | -0.61 | -0.69 | -0.71 | -0.02 | -0.05 | -0.09 | -0.10 | -0.12 | -0.14 |
| *Consumption - Non Ricardian* $C_t^{NR}$ | -0.42 | -0.99 | -1.84 | -1.61 | 0.70 | 3.51 | -0.11 | -0.05 | -0.07 | -1.54 | 1.35 | 14.09 |
| *Consumption - Final Good* $C_{Y,t}$ | -0.14 | -0.30 | -0.55 | -0.65 | -0.64 | -0.54 | -0.03 | -0.05 | -0.09 | -0.16 | -0.07 | 0.43 |
| *Consumption - Fuel* $C_{F,t}$ | -0.14 | -0.30 | -0.55 | -0.65 | -0.64 | -0.55 | -0.02 | -0.04 | -0.08 | -0.16 | -0.06 | 0.42 |
| *Consumption - Roil* $ROIL_t$ | -0.14 | -0.30 | -0.55 | -0.65 | -0.63 | -0.55 | -0.02 | -0.04 | -0.08 | -0.16 | -0.06 | 0.42 |
| *Consumption - Biofuel* $BIOF_t$ | -0.14 | -0.30 | -0.55 | -0.65 | -0.64 | -0.55 | -0.02 | -0.04 | -0.09 | -0.16 | -0.07 | 0.42 |
| Investments $I_t$ | -0.15 | -0.18 | -0.24 | -0.33 | -0.41 | -0.38 | 0.80 | 0.77 | 0.68 | 0.59 | 0.52 | 0.51 |
| RES Investments $I_{RES,t}$ | -0.99 | -1.07 | -1.21 | -1.39 | -1.30 | -0.79 | -0.82 | -0.86 | -0.90 | -0.90 | -0.67 | -0.16 |
| Labour $L_t$ | -0.04 | -0.12 | -0.32 | -0.67 | -1.11 | -0.87 | 0.00 | 0.00 | 0.10 | 0.42 | 0.36 | 0.51 |
| Real wages $W_t$ | -0.27 | -0.63 | -1.31 | -1.87 | -1.83 | -0.92 | -0.23 | -0.53 | -1.41 | -2.88 | -2.93 | -0.71 |
| CPI $P_{C_{Y,t}}$ | 0.04 | 0.07 | 0.09 | 0.03 | -0.16 | -0.05 | 0.02 | 0.01 | 0.00 | 0.07 | -0.04 | -0.09 |
| GDP Deflator $P_t$ | 0.01 | 0.00 | 0.00 | 0.00 | -0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -0.01 | 0.00 |
| Emissions - Total $Z_t^{TOT}$ | -0.37 | -0.97 | -2.73 | -5.63 | -8.53 | -8.74 | -0.36 | -0.95 | -2.69 | -5.59 | -8.49 | -8.67 |
| *Emissions - Intermediate* $Z_{Y,t}$ | -0.41 | -1.06 | -2.97 | -6.17 | -9.59 | -9.66 | -0.40 | -1.04 | -2.91 | -6.05 | -9.46 | -9.60 |
| *Emissions - Electricity* $Z_{EL,t}$ | -0.43 | -1.13 | -3.32 | -6.97 | -10.11 | -10.77 | -0.45 | -1.19 | -3.47 | -7.24 | -10.38 | -10.89 |
| *Emissions - Roil* $Z_{ROIL,t}$ | -0.08 | -0.18 | -0.33 | -0.39 | -0.38 | -0.33 | -0.01 | -0.03 | -0.05 | -0.09 | -0.04 | 0.25 |
| Electricity - Total $EL_t$ | -0.09 | -0.24 | -0.66 | -1.20 | -1.58 | -1.39 | -0.09 | -0.22 | -0.58 | -0.98 | -1.20 | -0.90 |
| *Electricity - Fossil* $EL_{FOS,t}$ | -0.11 | -0.29 | -0.79 | -1.43 | -1.87 | -1.62 | -0.11 | -0.27 | -0.71 | -1.22 | -1.48 | -1.11 |
| *Electricity - RES* $EL_{RES,t}$ | -0.06 | -0.15 | -0.42 | -0.77 | -1.04 | -0.97 | -0.05 | -0.13 | -0.33 | -0.55 | -0.68 | -0.50 |
| Electricity Price $P_{EL,t}$ | -0.08 | -0.20 | -0.41 | -0.45 | -0.53 | 0.24 | -0.13 | -0.26 | -0.43 | -0.45 | -0.44 | 0.40 |
| Abatement Costs - % GDP, p.p. | 0.00 | 0.01 | 0.03 | 0.08 | 0.13 | 0.14 | 0.00 | 0.01 | 0.04 | 0.09 | 0.15 | 0.17 |
| Emission Permit Price $P_{Z,t}$, p.p. | 0.71 | 1.56 | 3.29 | 4.71 | 9.39 | 3.05 | 0.39 | 1.92 | 3.73 | 5.33 | 9.18 | 2.98 |

All the variables are expressed as percentage deviations from steady state values, unless otherwise specified

Table 6: Scenario 1B - GHG Emission Mitigation -10% in 15 Years - Carbon Tax

| | with lump-sum tax reduction | | | | | | with labour income tax reduction | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Years | 1 | 2 | 5 | 10 | 15 | 20 | 1 | 2 | 5 | 10 | 15 | 20 |
| GDP $Y_t$ | -0.10 | -0.05 | -0.17 | -0.50 | -0.78 | -0.80 | -0.10 | 0.20 | 0.19 | 0.23 | 0.28 | 0.42 |
| Consumption $C_t$ | -0.08 | -0.13 | -0.19 | -0.25 | -0.29 | -0.31 | 0.01 | 0.1 | 0.26 | 0.37 | 0.46 | 0.47 |
| *Consumption - Ricardian* $C_t^R$ | -0.05 | -0.09 | -0.15 | -0.22 | -0.29 | -0.36 | 0.04 | 0.13 | 0.24 | 0.26 | 0.24 | 0.21 |
| *Consumption - Non Ricardian* $C_t^{NR}$ | -0.75 | -1.1 | -1.29 | -1.07 | -0.32 | 0.78 | -0.73 | -0.63 | 0.68 | 3.05 | 5.83 | 6.72 |
| *Consumption - Final Good* $C_{Y,t}$ | -0.08 | -0.14 | -0.2 | -0.26 | -0.29 | -0.31 | 0.00 | 0.08 | 0.25 | 0.36 | 0.46 | 0.47 |
| *Consumption - Fuel* $C_{F,t}$ | -0.07 | -0.11 | -0.18 | -0.24 | -0.29 | -0.32 | 0.03 | 0.13 | 0.28 | 0.39 | 0.47 | 0.48 |
| *Consumption - Roil* $ROIL_t$ | -0.07 | -0.11 | -0.18 | -0.24 | -0.29 | -0.32 | 0.03 | 0.13 | 0.28 | 0.39 | 0.47 | 0.48 |
| *Consumption - Biofuel* $BIOF_t$ | -0.07 | -0.10 | -0.18 | -0.24 | -0.29 | -0.32 | 0.03 | 0.13 | 0.28 | 0.39 | 0.47 | 0.48 |
| Investments $I_t$ | 2.85 | 2.81 | 2.64 | 2.36 | 2.11 | 1.89 | 4.56 | 4.51 | 4.27 | 3.92 | 3.61 | 3.34 |
| RES Investments $I_{RES,t}$ | -0.54 | -0.59 | -0.75 | -0.97 | -1.06 | -1.02 | -0.32 | -0.33 | -0.41 | -0.49 | -0.47 | -0.36 |
| Labour $L_t$ | -0.02 | -0.04 | -0.16 | -0.40 | -0.63 | -0.72 | 0.02 | 0.06 | 0.19 | 0.44 | 0.67 | 0.79 |
| Real wages $W_t$ | -0.14 | -0.26 | -0.45 | -0.84 | -1.05 | -1.01 | -0.12 | -0.19 | -0.44 | -1.08 | -1.58 | -1.51 |
| CPI $P_{C_{Y,t}}$ | 0.08 | 0.11 | 0.10 | 0.04 | -0.02 | -0.03 | 0.08 | 0.08 | 0.03 | 0.01 | -0.01 | 0.00 |
| GDP Deflator $P_t$ | -0.01 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | -0.03 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| Emissions - Total $Z_t^{TOT}$ | -0.31 | -0.60 | -2.06 | -5.00 | -8.51 | -12.09 | -0.31 | -0.49 | -1.85 | -4.71 | -8.3 | -12.21 |
| *Emissions - Intermediate* $Z_{Y,t}$ | -0.36 | -0.6 | -2.22 | -5.53 | -9.54 | -13.64 | -0.38 | -0.45 | -1.97 | -5.17 | -9.29 | -13.84 |
| *Emissions - Electricity* $Z_{EL,t}$ | -0.34 | -0.87 | -2.64 | -6.17 | -10.25 | -14.39 | -0.33 | -0.85 | -2.57 | -6.07 | -10.24 | -14.61 |
| *Emissions - Roil* $Z_{ROIL,t}$ | -0.04 | -0.06 | -0.11 | -0.15 | -0.18 | -0.19 | 0.02 | 0.08 | 0.17 | 0.23 | 0.28 | 0.29 |
| Electricity - Total $EL_t$ | -0.06 | -0.14 | -0.38 | -0.78 | -1.11 | -1.28 | -0.05 | -0.1 | -0.27 | -0.52 | -0.71 | -0.77 |
| *Electricity - Fossil* $EL_{FOS,t}$ | -0.07 | -0.17 | -0.46 | -0.94 | -1.32 | -1.52 | -0.06 | -0.13 | -0.34 | -0.66 | -0.9 | -0.99 |
| *Electricity - RES* $EL_{RES,t}$ | -0.03 | -0.08 | -0.24 | -0.5 | -0.71 | -0.84 | -0.02 | -0.05 | -0.14 | -0.26 | -0.35 | -0.37 |
| Electricity Price $P_{EL,t}$ | -0.20 | -0.31 | -0.32 | -0.29 | -0.19 | 0.08 | -0.28 | -0.42 | -0.36 | -0.27 | -0.16 | 0.08 |
| Abatement Costs - % GDP, p.p. | 0.00 | 0.01 | 0.03 | 0.08 | 0.15 | 0.22 | 0.00 | 0.01 | 0.03 | 0.09 | 0.16 | 0.25 |
| Carbon Tax $P_Z$, p.p. | 0.18 | 0.47 | 1.33 | 2.77 | 4.20 | 4.31 | 0.18 | 0.48 | 1.36 | 2.84 | 4.31 | 4.42 |

All the variables are expressed as percentage deviations from steady state values, unless otherwise specified

Table 7: Scenario 2 - Tax shift from labour to ROIL 1% GDP

| | carbon tax | | | | | | emission cap | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Years | 1 | 2 | 5 | 10 | 15 | 20 | 1 | 2 | 5 | 10 | 15 | 20 |
| GDP $Y_t$ | 0.13 | 0.28 | 0.72 | 1.02 | 1.04 | 0.98 | 0.05 | 0.13 | 0.43 | 0.75 | 0.84 | 0.81 |
| Consumption $C_t$ | 0.25 | 0.52 | 0.68 | 0.48 | 0.48 | 0.58 | 0.22 | 0.45 | 0.55 | 0.31 | 0.33 | 0.55 |
| *Consumption - Ricardian* $C_t^R$ | 0.22 | 0.43 | 0.44 | 0.28 | 0.29 | 0.30 | 0.20 | 0.38 | 0.34 | 0.16 | 0.17 | 0.16 |
| *Consumption - Non Ricardian* $C_t^{NR}$ | 1.02 | 2.59 | 6.47 | 5.29 | 4.93 | 7.35 | 0.88 | 2.26 | 5.63 | 3.76 | 4.13 | 9.75 |
| *Consumption - Final Good* $C_{Y,t}$ | 0.29 | 0.61 | 0.93 | 0.75 | 0.74 | 0.84 | 0.26 | 0.54 | 0.80 | 0.57 | 0.59 | 0.81 |
| *Consumption - Fuel* $C_{F,t}$ | 0.19 | 0.36 | 0.24 | 0.01 | 0.02 | 0.12 | 0.16 | 0.30 | 0.12 | -0.16 | -0.13 | 0.09 |
| *Consumption - Roil* $ROIL_t$ | 0.17 | 0.30 | 0.08 | -0.17 | -0.16 | -0.06 | 0.14 | 0.24 | -0.05 | -0.34 | -0.31 | -0.10 |
| *Consumption - Biofuel* $BIOF_t$ | 0.29 | 0.60 | 0.93 | 0.75 | 0.76 | 0.86 | 0.26 | 0.54 | 0.80 | 0.58 | 0.61 | 0.82 |
| Investments $I_t$ | 0.05 | 0.05 | 0.09 | 0.16 | 0.21 | 0.24 | 0.18 | 0.18 | 0.19 | 0.25 | 0.29 | 0.31 |
| RES Investments $I_{RES,t}$ | 0.47 | 0.51 | 0.56 | 0.60 | 0.64 | 0.66 | 0.13 | 0.16 | 0.25 | 0.38 | 0.48 | 0.52 |
| Labour $L_t$ | 0.10 | 0.28 | 0.80 | 1.25 | 1.27 | 1.17 | 0.08 | 0.22 | 0.67 | 1.11 | 1.11 | 0.95 |
| Real wages $W_t$ | 0.07 | 0.06 | -0.43 | -0.59 | -0.46 | -0.15 | -0.01 | -0.14 | -0.88 | -1.23 | -0.78 | 0.03 |
| CPI $P_{C_{Y,t}}$ | -0.08 | -0.15 | -0.11 | 0.07 | 0.08 | 0.01 | -0.07 | -0.14 | -0.11 | 0.09 | 0.10 | -0.02 |
| GDP Deflator $P_t$ | 0.00 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| Emissions - Total $Z_t^{TOT}$ | 0.12 | 0.26 | 0.62 | 0.88 | 0.91 | 0.89 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Emissions - Intermediate* $Z_{Y,t}$ | 0.15 | 0.33 | 0.84 | 1.19 | 1.19 | 1.11 | 0.01 | 0.03 | 0.15 | 0.26 | 0.23 | 0.14 |
| *Emissions - Electricity* $Z_{EL,t}$ | 0.06 | 0.15 | 0.39 | 0.65 | 0.78 | 0.85 | -0.05 | -0.13 | -0.33 | -0.47 | -0.42 | -0.29 |
| *Emissions - Roil* $Z_{ROIL,t}$ | 0.10 | 0.18 | 0.05 | -0.10 | -0.10 | -0.04 | 0.08 | 0.14 | -0.03 | -0.21 | -0.19 | -0.06 |
| Electricity - Total $EL_t$ | 0.03 | 0.09 | 0.24 | 0.41 | 0.51 | 0.57 | 0.00 | 0.00 | 0.03 | 0.12 | 0.24 | 0.34 |
| *Electricity - Fossil* $EL_{FOS,t}$ | 0.04 | 0.10 | 0.26 | 0.44 | 0.53 | 0.58 | 0.00 | 0.00 | 0.01 | 0.09 | 0.21 | 0.32 |
| *Electricity - RES* $EL_{RES,t}$ | 0.03 | 0.07 | 0.20 | 0.35 | 0.46 | 0.54 | 0.01 | 0.02 | 0.07 | 0.17 | 0.28 | 0.37 |
| Electricity Price $P_{EL,t}$ | 0.08 | 0.18 | 0.34 | 0.29 | 0.19 | 0.12 | 0.02 | 0.06 | 0.11 | 0.10 | 0.15 | 0.20 |
| Abatement Costs - % GDP, p.p. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 |
| Carbon Tax - Emission Permit Price $P_{Z,t}$, p.p. | 0 | 0 | 0 | 0 | 0 | 0 | 0.43 | 0.81 | 1.46 | 1.27 | 0.47 | 0.27 |

All the variables are expressed as percentage deviations from steady state values, unless otherwise specified

Table 8: Scenario 3 - Tax shift from firm social contribution to ROIL 1% GDP

| | carbon tax | | | | | | emission cap | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Years | 1 | 2 | 5 | 10 | 15 | 20 | 1 | 2 | 5 | 10 | 15 | 20 |
| GDP $Y_t$ | 0.09 | 0.16 | 0.41 | 0.50 | 0.44 | 0.37 | 0.02 | 0.07 | 0.24 | 0.37 | 0.36 | 0.30 |
| Consumption $C_t$ | 0.18 | 0.35 | 0.32 | 0.11 | 0.09 | 0.19 | 0.17 | 0.32 | 0.26 | 0.02 | 0.02 | 0.19 |
| *Consumption - Ricardian* $C_t^R$ | 0.17 | 0.32 | 0.24 | 0.03 | 0.01 | 0.00 | 0.16 | 0.30 | 0.19 | -0.03 | -0.05 | -0.06 |
| *Consumption - Non Ricardian* $C_t^{NR}$ | 0.46 | 1.09 | 2.26 | 2.18 | 2.00 | 4.73 | 0.37 | 0.88 | 1.77 | 1.33 | 1.64 | 6.18 |
| *Consumption - Final Good* $C_{Y,t}$ | 0.22 | 0.44 | 0.57 | 0.38 | 0.35 | 0.45 | 0.20 | 0.41 | 0.50 | 0.29 | 0.29 | 0.45 |
| *Consumption - Fuel* $C_{F,t}$ | 0.12 | 0.19 | -0.11 | -0.36 | -0.37 | -0.27 | 0.11 | 0.16 | -0.18 | -0.44 | -0.44 | -0.28 |
| *Consumption - Roil* $ROIL_t$ | 0.10 | 0.13 | -0.28 | -0.54 | -0.55 | -0.46 | 0.08 | 0.10 | -0.35 | -0.62 | -0.62 | -0.46 |
| *Consumption - Biofuel* $BIOF_t$ | 0.22 | 0.43 | 0.57 | 0.38 | 0.36 | 0.46 | 0.20 | 0.40 | 0.50 | 0.29 | 0.30 | 0.46 |
| Investments $I_t$ | -0.30 | -0.30 | -0.26 | -0.20 | -0.15 | -0.11 | -0.17 | -0.17 | -0.14 | -0.09 | -0.04 | -0.02 |
| RES Investments $I_{RES,t}$ | 0.29 | 0.31 | 0.32 | 0.32 | 0.33 | 0.33 | 0.10 | 0.11 | 0.16 | 0.23 | 0.27 | 0.28 |
| Labour $L_t$ | 0.06 | 0.16 | 0.45 | 0.60 | 0.52 | 0.38 | 0.04 | 0.11 | 0.37 | 0.53 | 0.43 | 0.26 |
| Real wages $W_t$ | 0.36 | 0.83 | 1.73 | 2.14 | 2.24 | 2.56 | 0.31 | 0.71 | 1.46 | 1.79 | 2.10 | 2.72 |
| CPI $P_{C_{Y,t}}$ | -0.07 | -0.12 | -0.05 | 0.06 | 0.06 | 0.00 | -0.07 | -0.12 | -0.06 | 0.08 | 0.07 | -0.02 |
| GDP Deflator $P_t$ | 0.01 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Emissions - Total $Z_t^{TOT}$ | 0.08 | 0.15 | 0.33 | 0.41 | 0.38 | 0.34 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Emissions - Intermediate* $Z_{Y,t}$ | 0.11 | 0.19 | 0.49 | 0.60 | 0.53 | 0.44 | 0.00 | 0.01 | 0.11 | 0.16 | 0.13 | 0.07 |
| *Emissions - Electricity* $Z_{EL,t}$ | 0.04 | 0.09 | 0.23 | 0.36 | 0.41 | 0.43 | -0.02 | -0.06 | -0.15 | -0.17 | -0.11 | -0.02 |
| *Emissions - Roil* $Z_{ROIL,t}$ | 0.06 | 0.08 | -0.17 | -0.32 | -0.33 | -0.27 | 0.05 | 0.06 | -0.21 | -0.37 | -0.37 | -0.28 |
| Electricity - Total $EL_t$ | 0.02 | 0.06 | 0.14 | 0.23 | 0.27 | 0.29 | 0.00 | 0.01 | 0.03 | 0.08 | 0.14 | 0.19 |
| *Electricity - Fossil* $EL_{FOS,t}$ | 0.03 | 0.06 | 0.15 | 0.24 | 0.28 | 0.29 | 0.00 | 0.00 | 0.01 | 0.07 | 0.13 | 0.18 |
| *Electricity - RES* $EL_{RES,t}$ | 0.02 | 0.05 | 0.12 | 0.20 | 0.25 | 0.28 | 0.01 | 0.02 | 0.05 | 0.11 | 0.17 | 0.21 |
| Electricity Price $P_{EL,t}$ | 0.08 | 0.17 | 0.27 | 0.21 | 0.14 | 0.10 | 0.04 | 0.09 | 0.12 | 0.11 | 0.12 | 0.15 |
| Abatement Costs - % GDP, p.p. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Carbon Tax - Emission Permit Price $P_{Z,t}$, p.p. | 0 | 0 | 0 | 0 | 0 | 0 | 0.53 | 0.52 | 0.91 | 0.65 | 0.08 | 0.02 |

All the variables are expressed as percentage deviations from steady state values, unless otherwise specified

Table 9: Scenario 4 - Tax shift from RES taxes to ROIL +0.1% GDP

| | carbon tax | | | | | | emission cap | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Years | 1 | 2 | 5 | 10 | 15 | 20 | 1 | 2 | 5 | 10 | 15 | 20 |
| GDP $Y_t$ | -0.01 | 0.01 | 0.03 | 0.05 | 0.07 | 0.09 | 0.02 | 0.04 | 0.10 | 0.10 | 0.09 | 0.09 |
| Consumption $C_t$ | 0.01 | 0.01 | -0.01 | -0.03 | -0.03 | -0.02 | 0.01 | 0.02 | 0.01 | 0.00 | -0.01 | -0.03 |
| *Consumption - Ricardian* $C_t^R$ | 0.01 | 0.01 | -0.01 | -0.03 | -0.03 | -0.02 | 0.01 | 0.02 | 0.01 | -0.01 | -0.01 | 0.00 |
| *Consumption - Non Ricardian* $C_t^{NR}$ | -0.03 | -0.04 | -0.06 | -0.05 | -0.04 | 0.00 | -0.01 | 0.03 | 0.13 | 0.25 | 0.00 | -0.58 |
| *Consumption - Final Good* $C_{Y,t}$ | 0.01 | 0.02 | 0.01 | -0.01 | -0.01 | 0.00 | 0.01 | 0.03 | 0.04 | 0.02 | 0.01 | 0.00 |
| *Consumption - Fuel* $C_{F,t}$ | 0.00 | -0.01 | -0.06 | -0.08 | -0.08 | -0.07 | 0.01 | 0.01 | -0.03 | -0.05 | -0.05 | -0.07 |
| *Consumption - Roil* $ROIL_t$ | 0.00 | -0.01 | -0.07 | -0.10 | -0.09 | -0.09 | 0.00 | 0.00 | -0.05 | -0.07 | -0.07 | -0.09 |
| *Consumption - Biofuel* $BIOF_t$ | 0.01 | 0.02 | 0.01 | -0.01 | 0.00 | 0.01 | 0.01 | 0.03 | 0.04 | 0.03 | 0.02 | 0.00 |
| Investments $I_t$ | 0.05 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 | 0.08 | 0.08 | 0.08 | 0.07 | 0.07 | 0.06 |
| RES Investments $I_{RES,t}$ | 10.35 | 11.51 | 13.50 | 14.19 | 14.54 | 14.77 | 10.44 | 11.60 | 13.58 | 14.20 | 14.52 | 14.75 |
| Labour $L_t$ | 0.00 | -0.01 | -0.01 | -0.01 | -0.01 | -0.02 | 0.00 | 0.01 | 0.02 | 0.01 | 0.00 | 0.01 |
| Real wages $W_t$ | 0.01 | 0.02 | 0.05 | 0.08 | 0.10 | 0.12 | 0.03 | 0.07 | 0.16 | 0.20 | 0.12 | 0.03 |
| CPI $P_{C_{Y,t}}$ | -0.02 | -0.02 | -0.01 | 0.00 | 0.00 | 0.00 | -0.02 | -0.02 | -0.01 | 0.00 | 0.00 | 0.01 |
| GDP Deflator $P_t$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Emissions - Total $Z_t^{TOT}$ | -0.03 | -0.05 | -0.11 | -0.10 | -0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| *Emissions - Intermediate* $Z_{Y,t}$ | -0.01 | 0.01 | 0.03 | 0.06 | 0.08 | 0.09 | 0.03 | 0.07 | 0.15 | 0.16 | 0.13 | 0.10 |
| *Emissions - Electricity* $Z_{EL,t}$ | -0.08 | -0.19 | -0.44 | -0.47 | -0.33 | -0.19 | -0.06 | -0.15 | -0.33 | -0.34 | -0.26 | -0.19 |
| *Emissions - Roil* $Z_{ROIL,t}$ | 0.00 | -0.01 | -0.04 | -0.06 | -0.06 | -0.05 | 0.00 | 0.00 | -0.03 | -0.04 | -0.04 | -0.05 |
| Electricity - Total $EL_t$ | 0.20 | 0.51 | 1.46 | 2.78 | 3.73 | 4.40 | 0.20 | 0.53 | 1.50 | 2.82 | 3.75 | 4.40 |
| *Electricity - Fossil* $EL_{FOS,t}$ | -0.04 | -0.09 | -0.17 | -0.04 | 0.22 | 0.48 | -0.03 | -0.07 | -0.12 | 0.01 | 0.24 | 0.48 |
| *Electricity - RES* $EL_{RES,t}$ | 0.62 | 1.63 | 4.56 | 8.29 | 10.72 | 12.29 | 0.63 | 1.65 | 4.60 | 8.33 | 10.74 | 12.29 |
| Electricity Price $P_{EL,t}$ | -0.38 | -0.95 | -2.45 | -3.97 | -4.89 | -5.53 | -0.37 | -0.93 | -2.40 | -3.94 | -4.89 | -5.55 |
| Abatement Costs % GDP, p.p. | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Carbon Tax - Emission Permit Price $P_{Z,t}$, p.p. | 0 | 0 | 0 | 0 | 0 | 0 | -0.24 | -0.17 | -0.34 | -0.21 | 0.01 | 0.09 |

All the variables are expressed as percentage deviations from steady state values, unless otherwise specified