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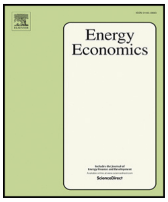

Introduction of the carbon tax in Italy: Is there room for a quadruple-dividend effect?

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ABSTRACT

This study seeks to examine the environmental and societal impacts of a carbon tax in Italy, where the policy has yet to be implemented but has been the subject of much debate. We use numerical simulations based on the EUROGREEN macro-system dynamic model (D'Alessandro et al., 2020) to evaluate the potential benefits and drawbacks of this policy from 2010 to 2050.

We employ a sequential scenario approach, starting with a baseline that incorporates Italy's Integrated National Energy and Climate Plan (PNIEC), followed by the introduction of a gradually increasing carbon tax. Additionally, we test two hypotheses regarding the possible adaptive behaviors of consumers and producers in response to the policy. Our analysis evaluates the long-term impacts of the carbon tax on GDP, unemployment, public debt, carbon emissions, and income inequality, in pursuit of a "quadruple-dividend" effect.

Our findings suggest that the carbon tax: (*i*) has a limited impact on reducing carbon emissions, with a difference of only 2% compared to the PNIEC by 2050, (*ii*) has the potential to mitigate regressive effects through the redistribution of its revenue to low-income households, resulting in an improvement of approximately 2 Gini-points compared to the PNIEC, and (*iii*) can achieve a quadruple-dividend effect only if consumers and industries adapt their behavior to the policy.

Our research argues that Italy could reap the benefits of a carbon tax, with the revenue being redistributed to low-income households, leading to a more equitable and sustainable energy transition. This can only be achieved by combining top-down policies with bottom-up initiatives and public interventions, making environmental taxation more acceptable to the general public.

1. Introduction

The idea to implement a carbon tax (CT) to curb carbon emissions dates back to the seminal work of Pigou (1920) who first introduced the polluter-pay principle to account for the negative externality generated by greenhouse gas emissions. The idea is rather simple: imposing a tax for each ton of CO_2 emitted should push brown industries to invest in cleaner production processes, to keep competitiveness on, and then reduce the overall air pollution by internalizing (via price) the negative externality thereby generated. Recently the debate on environmental taxation is gaining momentum as a fundamental tool in the transition towards a low-carbon economy (Wesseh and Lin, 2019) able to ensure high employment levels (Carraro and Siniscalco, 2013). Indeed, differently from the emission trading system, the carbon tax generates public revenues that can be redistributed to mitigate the possible negative socio-economic side effects in terms of economic performance and income distribution.

Although its promises call for a wide application of the carbon tax, in a context of highly required environmental reforms to tackle climate change, the possibility to put this policy tool into practice is far from being easy and only a few countries introduced it so far. Based on the last report of the World Bank (see Ramstein et al., 2019), in 2018 only less than 50 countries – responsible for ~20% of global emissions – implemented a carbon tax or scheduled it for implementation, generating tax revenue of about US$ 44 billion. However, the range of the tax greatly varies from a minimum of only 1 US$ per ton of CO_2 (Mexico, Ukraine, and Poland) to a maximum of 127 US$/t$CO_2$ (Sweden). In Italy, a proper carbon tax has never been introduced although an environmental tax reform was implemented at the beginning of 1999. It was based on a re-modulation of excise duties on the transport sector and the introduction of a consumption tax on coal and natural bitumen (see Tiezzi, 2005, for a description).

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[1] See https://www.eea.europa.eu/help/glossary/eea-glossary/double-dividend.

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A key concept to assess the impact of environmental taxation is the so-called double-dividend hypothesis (see Freire-González, 2018, for a review) defined as the possibility that environmental taxes can both "reduce pollution (the first dividend) and reduce the overall economic costs associated with the tax system by using the revenue generated to displace other more distortive taxes that slow economic growth at the same time (the second dividend)" (European Environmental Agency[1]). In recent years, the need to include also the social effects lead to the definition of the triple-dividend effect by considering improvements in terms of long-term employment and GDP growth, carbon emissions, and public indebtedness (Pereira et al., 2016). In this vein, we further extend this list by including the distributional effect by looking at income inequality. Hence, we aim at analyzing the promises and threats of a carbon tax in Italy to check under what conditions a *quadruple-dividend* effect can be reached.

1.1. Literature review

From a methodological viewpoint, the literature splits into two branches. On the one hand, mainstream economists aim to calculate analytically the 'optimal' carbon tax by using computable general equilibrium (CGE) models. Notably, Nordhaus (1993), developed a Dynamic Integrated Climate-Economy model (DICE) to calculate the optimal global carbon tax associated with lump-sum rebates. DICE-type and CGE models have further extended our understanding on how to incorporate climate damage functions (Diaz and Moore, 2017) also considering multiple interacting climate tipping points with irreversible economic damages (Cai et al., 2016). It appears that a conclusive answer to the optimal level of the carbon tax has not yet been achieved since that the optimal carbon tax reported by the literature varies between a few tens and a few hundreds of dollars per ton of carbon (Tol, 2020). However, when inequality concerns are considered, following a 'climate and development' scheme as proposed by the Agenda 2030, then higher tax rates are considered more suitable to raise funding for redistribution and poverty alleviation (Clarke et al., 2009; Sörgel et al., 2021). In terms of economic performance, Chamhuri et al. (2009) showed that successively higher carbon tax rates can be paired with lower emissions without affecting GDP growth in Malaysia, while (Khastar et al., 2020), applying a GTAP-E general equilibrium model, showed that carbon tax policies lead to adverse effects on GDP but industries in Finland end up with higher competitiveness. In terms of distributional effects, (Oladosu and Rose, 2007) suggested that a CT of 25 US\$/tCO$_2$ in the US is mildly progressive in income distribution, (Allan et al., 2014) indicated that a CT of 50 £/tCO$_2$ secured a double dividend in Scotland, although (Kirchner et al., 2019) showed that lump-sum payments are not the best way of balancing the trade-off between equity and efficiency in Austria. Zhang et al. (2017b) considered two integrated policy mixes, wherein carbon tax revenue is recycled to reduce capital tax or support clean energy subsidy in order to ensure a double dividend from the CT in China.

On the other hand, scholars have applied the Input–Output (IO) approach to evaluate both the reduction of emissions and the degree of progressivity (if any) of environmental taxation. Tiezzi (2005) found no regressive effects from the simulation of green taxation in Italy because it has been implemented only in the transport sector. Moreover, system dynamics modeling has been applied in India, where (Gupta et al., 2019) showed that carbon tax can substantially contribute to cutting emissions from road passenger transport. On the contrary, Wier et al. (2005) – combining the IO with the household expenditure (i.e., national consumer survey statistics) – allowing for substitutional effects within the economic sectors, found that the carbon tax has regressive effects in Denmark. Other recent studies provided evidence of adverse distributional effects as a consequence of the CT (e.g., Mathur and Morris, 2014; Renner, 2018). However, Fremstad and Paul (2019) showed that if carbon tax revenues fund a carbon dividend then this policy might have progressive effects in the US. Recycling schemes to make carbon tax progressive vary and include, among others, lump-sum transfers, linear income tax reductions, and equal per capita refund (Klenert and Mattauch, 2016).

Finally, with respect to international trade, the idea of a unilateral carbon budget adjustment (CBA) was introduced to face politicians and industry representatives alike who fear that imports from countries without carbon regulations can gain cost-of-production advantages over domestic goods (Condon and Ignaciuk, 2013). The assessment of the effectiveness of export adjustments is not yet conclusive. A meta-analysis by Branger and Quirion (2014) found that CBA played an important role in reducing leakage while other studies found that most of the leakage reduction from CBA is due to only import adjustments (Böhringer et al., 2012). The literature review of Cosbey et al. (2020) showed that many of the most important welfare effects of CBA inherently depend on assumptions about specific design choices, which could influence conclusions about the costs and benefits of CBA.

As seen, a conclusive response about the effects of the carbon tax has not yet been reached as the emergence of contrasting results reveals. In part, this might be due to the contextual conditions that characterize each country; however, we identify as a major weakness, in the previous studies, the lack of recognition of the complex relations and dynamical feedback effects among the social, economic, and environmental spheres. This calls for a wider approach able to take into account non-linear dynamics, uncertainty, agents' heterogeneity, and the institutional context (see Hafner et al., 2020, for a review). We aim at filling this gap by extending the EUROGREEN model, developed by D'Alessandro et al. (2020), to question under what conditions a quadruple-dividend effect can be achieved. We, therefore, evaluate the long-term impacts of a carbon tax on GDP and labor, public indebtedness, carbon emissions, and income inequality. In this regard, we build alternative scenarios to evaluate the impacts of a carbon tax in Italy and we extend previous studies by defining a wide framework that includes the main socio-economic and environmental variables and their reciprocal linkages.

Our study acknowledges that carbon tax design plays a key role in affecting the distributional impacts and that trade-offs between efficiency and equity always exist when designing carbon tax (Wang et al., 2016). However, the extent of these trade-offs and the possibility to achieve a quadruple-dividend effect largely depend on the pace of innovation for energy efficiency improvements and on the possibility of consumers to adapt by changing their consumption bundle.

2. Model

This study extends the EUROGREEN model (see D'Alessandro et al., 2020; Cieplinski et al., 2021, for a full description) that is grounded on Ecological Macroeconomics (Fontana and Sawyer, 2016) within a post-Keynesian framework (see Lavoie, 2014, for a detailed description). The present model is based on system dynamics and the core is represented by the application of the Input–Output (IO) approach that allows for the combination of the monetary and energy units, as well as the labor force. This approach is gaining momentum as a viable tool for modeling complex systems under energy constraints (Nieto et al., 2020b).

Fig. 1 shows the structure of the model in a nutshell by representing the main variables and linkages from which it is possible to simulate the dynamic and feedback loop effects. Note that, differently from the available and valuable literature that recently applied similar approaches to build scenarios on energy transition (e.g. Walsh et al., 2017; Capellán-Pérez et al., 2020), in our study the main socio-economic variables follow endogenous paths. Hence, we do not impose, for instance, any expected GDP growth or planned labor productivity improvements but they are outcomes rather than assumptions. The advantage is that we do not force the system to follow pre-determined paths that, by contrast, emerge from the inner dynamics of the model. However, given the high degree of complexity and a large number of variables and parameters used, we had to consider some exogenous features, such as:

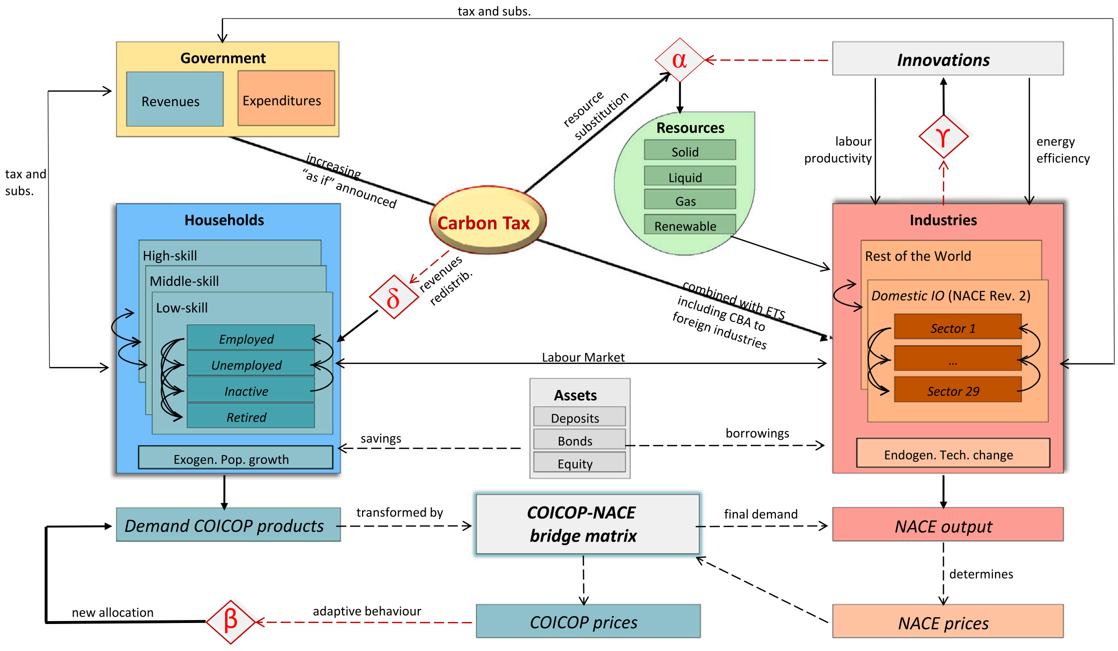

Fig. 1. Macroview. It presents the main variables and connections of the current extended version of the *EUROGREEN* model (D'Alessandro et al., 2020). We distinguish between the COICOP (see Table A2.2) households' consumption categories and the NACE Rev. 2 (see Table A2.3) industrial classification for which we built a bridging matrix. Red rhombuses indicate the exogenous parameters (policy or behavioral hypothesis) applied to build each scenario: α is applied to replicate the PNIEC plan in the baseline scenario, in particular, it changes the energy source combination to increase the use of renewable energy sources; β determines the elasticity of demand and changes the consumption bundle accordingly; γ affects the pace of innovations for energy-efficiency improvements, and δ redistributes carbon tax revenues according to specific income thresholds. For all the acronyms, see the Glossary in Appendix A.1.2.

imports are calculated by using constant import share coefficients (on the basis of historical real data); *exports* depend on a constant elasticity to domestic price variation and on exogenous industry-specific growth rate; the labor force dynamics is affected by an exogenous *skill-specific trend*, derived from the data, to take into account the developments in education; the workers are always employed under a *full-time* contract; and the *governments' expenditure* for final demand changes over time according to an exogenous data-driven trend.[2] In what follows, we only focus on the main methodological novelties here introduced with respect to the EUROGREEN model.

(i) **Energy system**: we collect data from Eurostat on the physical energy flow account (PEFA) that presents supply and use tables on the physical flows of energy (in TJ) and that distinguishes between natural renewable resources (supplied by the environment) and energy products supplied by the firms. Then, to obtain the total energy demand (E_i) by sector i we apply a coefficient of conversion (ζ_i, calibrated on real data) that returns the TJ required for each unit of economic output (x_i), namely

$$E_i(t) = x_i(t) \cdot \zeta_i. \tag{1}$$

Energy production requires three main fossil sources – i.e. solid, liquid, and gas – each of which has a different impact in terms of CO_2 emissions. To avoid double counting issues, we consider, following PEFA's criteria, that electricity is not polluting because it is partially derived from fossil fuels whose emissions have already been accounted for. Then, we calculate (from real data) the amount of each energy source s from E_i, from a source-sector specific share θ_i^s (such that $\sum_s \theta_i^s = 1$), and then we apply a source-sector specific coefficient of conversion (ϕ_i^s) to obtain the source-sector specific carbon emissions Ω_i^s. Namely

$$E_i^s(t) = E_i(t) \cdot \theta_i^s(t), \tag{2}$$

$$\Omega_i^s(t) = E_i^s(t) \cdot \phi_i^s. \tag{3}$$

Note that θ_i^s varies over time because the shares of energy sources depend on investments for energy-efficiency improvements, on the activation of energy policies, and on the carbon tax, as described in the next section.

(ii) **COICOP-NACE bridge matrix**: in order to assess the impact of a carbon tax at a lower scale (i.e., individual consumption) we combine data collected on the basis of different classifications (Cai and Rueda-Cantuche, 2019). This issue of data merging is of high relevance in macroeconomic policy analysis models (Capros et al., 2013). In our case, this means that data coming from the Household Budget Survey (HSB) – which collects information about the purpose for which expenditures are made (i.e., COICOP classification) – must be organized according to the Statistical Classification of Products by Activity (CPA). Hence, a first conversion from COICOP to CPA is required (Kronenberg, 2011). The COICOP-NACE bridge matrix ($\boldsymbol{B}^c$) is based on data elaborated from Eurostat (Cai and Vandyck, 2020; Cazcarro et al., 2022) and subsequently is balanced with respect to the IO structure using the RAS algorithm (see Distefano et al., 2020, for an explanation). See Appendix A.1.1 for a step-by-step description and Tables A2.2 and A2.3, for the full list of COICOP and NACE's categories, respectively.

(iii) **Demand elasticity.** The COICOP-NACE bridge matrix $\boldsymbol{B}^c$ assigns to each COICOP category the respective share of each NACE sector (Sommer and Kratena, 2017). By the same token, we can recover the inflation by COICOP products (π^c), once we have data for the inflation by NACE sectors (that are directly affected by the technological progress and policy interventions) by using the transpose of the bridge matrix, namely: $\boldsymbol{\pi}^c(t) = (\boldsymbol{B}^c)^T\, \boldsymbol{\pi}(t)$, where $\pi(t)$ is the vector of inflation, with respect to the previous year, by NACE sectors. We consider 12 groups (g) obtained by combining three skills – dependent on the level of education of individuals (low, middle, and high) – and four working statuses (employed, unemployed inactive, and retired). Moreover, we assume that each individual in each group acts as a representative agent and then the average propensity to consume is the same within

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[2] The interested reader can find the complete description of the original model developed by D'Alessandro et al. (2020) in the SupplementaryInformation.

each group. We assume variations of industrial prices level lead to responses in final demand by COICOP products via the coefficient β^c. More precisely, we assume that each individual belonging to a specific group (g) reacts only if the average inflation of a COICOP product c differs from the average inflation of her whole consumption bundle, namely

$$\Delta\pi_g^c = \pi^c - \pi_g = \pi^c - \sum_c \pi^c \cdot \beta_g^c, \tag{4}$$

where $\sum_c \beta_g^c = 1$. We consider the elasticity (ϵ^c) as the sensitivity to a price increase in c compared to price changes faced by overall consumption commodities, then the vector of consumption shares varies over time as:

$$\beta_g^c(t) = [1 - \epsilon^c(t) \cdot \Delta\pi_g^c(t)] \cdot \beta_g^c(t-1), \tag{5}$$

with $0 \leq \epsilon^c \leq 1$ because we assume that the demand gradually reacts to the inflation.[3] This is justified by the fact that, although energy demand is rigid, it might become more elastic in the long term when consumers can gradually adapt to the increase in prices related to the carbon tax. The assumption over the dynamic of $\epsilon^c(t)$ will determine a specific scenario, as described below. For instance, if $\epsilon^c(t) = 0$ then the consumer is totally unresponsive to price changes and the consumption shares keep the same as the initial one, while if $\epsilon^c(t) = 1$ then she reacts proportionally to the difference in the inflation rates ($\Delta\pi_g^c$).

(iv) **"Leontief-type" innovations.** The firms try to modify their intermediate demand, tracked by the input–output table, depending on price changes. In our framework, this adjustment is mediated by changes in technical coefficients $a_{j,k}$ that return the share of input bought from sector j to produce a unit of output in sector k. Then, $\Delta a_{j,k}$ is considered as a proxy of technological change; if it increases (decreases) it means that k needs more (less) input from j per each unit of production. As explained in D'Alessandro et al. (2020), we consider an innovation process that is in part rooted in a stochastic process and in part is driven by firms' investments. In particular, we assume four possible cases: no innovations (T_1), a new technology that is either relatively more labor- (T_2) or energy- (T_3) intensive, and an innovation that allows saving both labor and energy (T_4). Note that the probability of T_2 and T_3 depends on the firm's choice regarding the direction and volumes of investments. So, if firms invest more in energy-efficiency improvements, then the probability of T_3 increases. However, the stochastic nature of the innovative process does not ensure that T_3-type innovations always emerge in case of more investments. Once the firms decide what type of technologies to adopt – on the basis of a cost-minimizing decision rule – then the shares of inputs ($a_{j,k}$) used to realize their product are modified according to the historical changes. The size of the jump is picked from a Gaussian distribution with mean and standard deviations obtained from past input–output tables (1996–2009) coming from the national accounts: namely, $\Delta a_{j,k} \overset{d}{\sim} N(\overline{a}_{j,k}, \sigma_{a_{j,k}})$.[4]

The introduction of carbon tax boosts firms to direct investments towards energy-saving innovations. We introduce a parameter (γ) as a proxy of the degree of adaptation. Similarly to the consumption module, we have that $0 \leq \gamma \leq 1$ because we assume that as the CT increases the intermediate cost of the energy-intensive inputs increases, and then firms try to reduce energy use and/or to substitute brown with green energy through a change in the composition of inputs (i.e., the technical coefficients). Note that, if $\gamma = 0$ then the Leontief matrix can vary according to the historical trends, while when $\gamma > 0$ then the size of change when $T3$-type innovations are introduced is higher. We model this behavior by assuming that, at the industry level, the average of the variation in the technical coefficients of the Leontief matrix is proportional to the historical standard deviation, namely

$$a_{j,k}(t) = a_{j,k}(t-1) + \Delta a_{j,k} \cdot (1 + \gamma(t) \cdot \sigma_{a_{j,k}}), \tag{6}$$

where γ varies over time as described in the next section. Note that, in the case of $T3$-type innovations the sign of $\Delta a_{j,k}$ is negative when the sector j sells energy-intensive and/or brown products. This process might be the consequence of external effects or coordination practices among firms that may reinforce technology improvements.

3. Scenario setting

Given the complexity of the socio-economic system, we follow a "sequential scenario" strategy (Nieto et al., 2020a) in the definition of the narratives in order to isolate the impacts of each different hypothesis and evaluate their cumulative effects. In other words, we assume that each new scenario includes all the hypotheses of the previous ones more than a new single condition. This procedure ensures to better isolate the effect of a new single assumption, thus avoiding spurious interpretations. In particular, we define four scenarios:

1. **Baseline**: it represents the business-as-usual case, so it is based on the current economic structure. However, we include the main policies indicated in the Italian Integrated National Energy and Climate Plan (*PNIEC*), such as a partial exogenous yearly reduction of the sectoral energy demand of 0.8% (see MiSE-MATTM-MIT, 2020, pag. 66) and an *electrification* process that aims at increasing the electric power generation with renewable resources as indicated in the PEFA Manual[5]. Simultaneously, this measure affects the energy-mix composition such that the share of each non-energy industry's investments in renewable energy generation. In this regard, we assume that, in each period, the source-sector specific share θ_i^s changes according to the exogenous coefficient α_i^s that imposes the phasing-out of solid and liquid fuels by 2025 and 2050, respectively. Namely

$$\theta_i^s(t) = \theta_i^s(t-1) \cdot \alpha_i^s(t),$$
$$s.t. \sum_s \theta_i^s(t) = 1.$$

2. **Carbon Tax** (CT_0): it starts from €30 per ton of CO_2 in 2020 (close to the real carbon price in the ETS market) because it would have been unrealistic to start with a value as, for example, in Sweden. Indeed, the Yellow Vest protests and the recent public debate on the increase in energy prices show that citizens may be reluctant in the face of draconian interventions. However, it gradually increases every year by about €5/tCO_2, until 2050 when it reaches the maximum of €188/tCO_2 in 2050, as described in D'Alessandro et al. (2020). Note that, we decide to design the carbon tax so that it reaches levels higher than the current maximum (i.e., 127 US/$ in Sweden) because, on the basis of the empirical evidence (Runst and Thonipara, 2020), stronger CT should result in an effective tool.[6] We consider the impact of international trade, to address concerns about carbon leakage risks (EU-Commission, 2021), by imposing an equivalent CT on imported goods according to their incorporated carbon emissions (i.e., Carbon Border Adjustment, CBA). Note that, even under this assumption, both CT and CBA increase the production

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[3] Independently from the elasticity, it is possible to demonstrate that $\sum_c \beta_g^c(t) = 1$ for any period, by combining Eq. (5) with Eq. (4).

[4] See the SupplementaryInformation in D'Alessandro et al. (2020) for a detailed description of the modelization of the technological progress and the calibration of historical changes.

[5] Note that "renewable energy forms are actually captured in two products: 'Electrical energy' (i.e. electricity, P26) and 'Derived heat' (P27)" (Eurostat, 2014, p. 44)

[6] Note that, we also tested stronger carbon taxes but the results looked similar if the revenues are redistributed to poorer people who will increase consumption and emissions.

cost and the price of the final output, thus contributing to reducing the competitiveness of exports. Moreover, we take data from the European Environmental Agency regarding allowances and emissions of the firms that participate in the European Emission Trading System (EU-ETS). In this regard, to avoid double counting, we subtract the amount of CO_2 emissions already regulated by the EU-ETS when calculating the CT. Hence, the total cost faced by polluting sectors is given by what they paid in the EU-ETS on net emissions – for simplicity and to avoid arbitrage we assume that the EU-ETS price aligns with the carbon tax – and the CT paid on emissions not regulated by the EU-ETS. Finally, we introduce a simple rule to redistribute the CT revenues in favor of low-income groups by considering the second gross income floor threshold τ_2 (of 15,000.00€) as defined in the Italian taxation system. Hence, each household belonging to a given group receives an average income of y_g plus a subsidy δ_g – otherwise, if $y_g > \tau_2$ then $\delta_g = 0$ – financed through the CT in order that the poorer will benefit more. Namely

$$\delta_g(t) = CT(t) \cdot \frac{\tau_2 - y_g(t-1)}{\sum_g (\tau_2 - y_g(t-1))}. \tag{7}$$

3. **Demand adaptation** (CT_β): it adds to CT_0 the possibility of consumers adapting to price variations due to the introduction of the carbon tax, as described by Eq. (5). In particular, we assume that consumers gradually adapt to the CT and then that ϵ^c gradually goes from 0 (no reaction to price changes) to 1 (maximum adaptation) by following this simple rule:

   $$\epsilon^c(t) = \frac{CT(t)}{max(CT)}. \tag{8}$$

   Note that when $t < 2020$, then $\epsilon^c(t) = 0$ because the CT was not implemented.
4. **Energy-efficiency improvements** ($CT_{\beta+\gamma}$): it adds on top of CT_β higher levels of investments for energy-efficiency improvements, as described above, to develop new technologies able to substitute the polluting ones that become less convenient when the CT is introduced. The size of the change in the technical coefficients, for any sector pair, is proportional to γ. Its weight heightens inasmuch CT increases because we assume that firms, as the polluting inputs become costlier, try to reduce their use in the production process, namely

   $$\gamma(t) = \frac{CT(t)}{max(CT)}, \tag{9}$$

   and when $t < 2020$, then $\gamma(t) = 0$ because the CT were not implemented. Note that in both cases, consumer and firms adapt gradually to the carbon tax because the underlying assumption is that they behave "as if" the government announce the targeted CT over time, and then this information is incorporated in agents' expectations.

Note that the last two scenarios aim at evaluating the effectiveness of the CT under the hypothesis that agents adapt to the policy. Then, the adaptive behavior should be interpreted as a hypothetical case that underlines the importance to align top-down policies with bottom-up responses, avoiding negative social frictions to the acceptance of environmental taxation.

We run the above-described scenarios from 2010 to 2050, in Italy. The empirical calibration of the parameters and initial values for the Italian economy underpinned on official data, provide a consistent and coherent basis to understand the feasibility of carbon tax measures. To fix the unknown parameters of the model we have considered official data from 2010 to 2018 (when available) and implemented the optimization function provided by the software Vensim SDD[7] to calibrate the parameters in order to align with the real data collected for the main variables. The figures below report the real data (when available) together with the numerical simulations.

4. Results

For the sake of clarity, we present the scenario outcomes in three separate subsections given the large number of indicators considered. In particular, we show separately the consequences of a CT in terms of energy end environmental 4.1, socio-economic 4.2, and distributional 4.3 effects. In each case, the Baseline scenario (black line) is compared to the scenarios described in Section 3. Note that, the carbon tax is simulated from the year 2020 (vertical dotted line in each Figure) onward, without considering the economic shutdown due to the current pandemic crisis whose modelization would require an investigation that goes beyond the scope of the present study, but that we are considering for next researches. We plot the averages and the 95% confidence interval out of 1000 simulations in order to avoid arbitrary outcomes and to clean out stochastic effects associated with numerical simulations.[8]

4.1. Energy and environment

Fig. 2 plots the patterns related to the main energy and environmental indicators considered in this study. We start with the CO_2 emissions because it is the key environmental indicator to assess the effectiveness of carbon tax. The *PNIEC* plan commits Italy to a reduction of −40% and -60% points in 2030 and 2050, respectively, compared with the level of emissions in 1990. Panel 2(a) shows that the CT slightly affects the path of CO_2 emissions if compared with the Baseline (black) in which carbon pollution reduces of about 52% points in 2050, equivalently to ∼ 1% yearly reduction from 2020. The CT_0 scenario (green line) determines only a moderate difference, of about 2% points on average, mostly because the tax revenues are redistributed to low-income groups thus determining a negative side-effect, from the environmental point of view, due to the increase in final consumption that translates in higher energy uses. Hence, in case of no adaptive behaviors, it appears that the higher consumption levels, led by CT subsidies, offset most of the benefits related to increases of renewable sources in the energy power system. However, when both consumers (red line) and firms (blue line) adapt to higher energy prices then the improvements are remarkable. Indeed, under the $CT_{\beta+\gamma}$ scenario the emissions are cut by 61.85% (± 3.75%) by 2050, in line with what is targeted by the *PNIEC*.

To explain these differences, we briefly comment here on the changes in the energy system under each scenario, while in Section 4.2 we discuss the economic outcomes. Panel 2(b) shows that part of the difference is determined by the higher percentage of clean electric power generation. The CT seems to have little effect, but if it is paired with a higher elasticity of substitution of private demand (green line) then the share of renewable in the electric power generation reaches about 80% in 2050, so doubling the value of 2020. The addition of high investments for energy efficiency improvements determines a further increase of ∼10% of renewable sources allowing the production of cleaner electricity. Note that an upward trend is observed even under the Baseline (black line) because we include the planned interventions of the *PNIEC* in the business-as-usual case, so affecting each scenario. Similar considerations come from the analysis of the energy intensity index (panel 2(c)) which is a proxy of the energy efficiency of the economy. Under the Baseline (black) and CT_0 (green), it slightly improves over the whole period, while remarkable differences are observed only under the other two cases. Again, the combination

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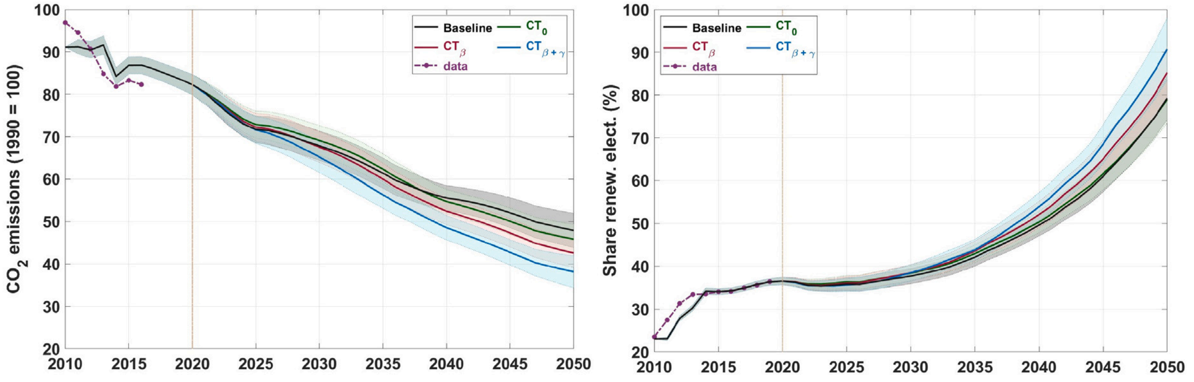
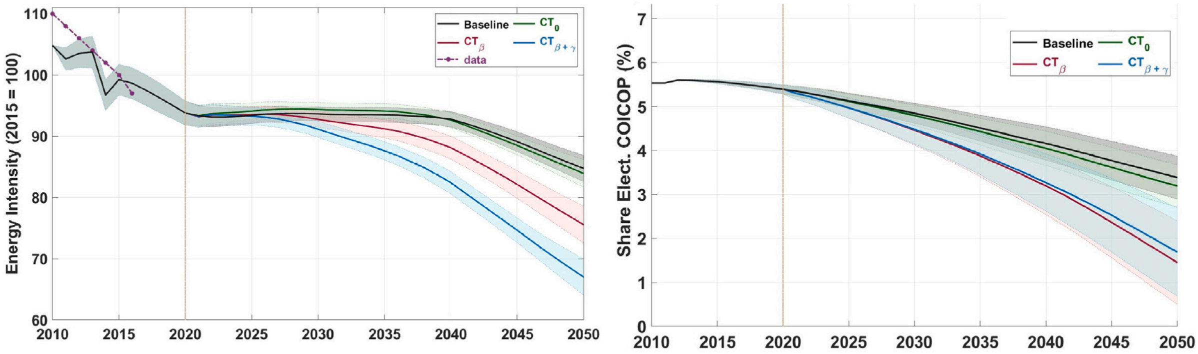
[7] We run a multi-objective parameter optimization mode (which allows automatizing runs performed in simulation mode) as provided by the software Vensim SDD. Technical details can be found here: https://vensim.com/optimization/#model-calibration.

[8] Note that the results are robust to the number of simulations and they look similar even if we increase the trials.



(a) Carbon emissions **(b)** Clean electricity



(c) TPES-to-GDP ratio **(d)** Households' energy consumption*

Fig. 2. Scenario analysis: environmental-energy indicators. Comparison of real data (violet) with the numerical outcomes – from 2010 to 2050 – under the Baseline (black) and the other three scenarios: CT_0 (green), CT_β (red), and $CT_{\beta+\gamma}$ (blue). The following indicators are considered: (a) CO$_2$ emissions normalized with respect to 1990, (b) percentage of renewable energy sources in the electric power generation, (c) energy intensity ratio as TPES/GDP normalized with respect to 2015, and (d) share of household's energy consumption. The vertical dotted line indicates the year 2020 when the policies are introduced. The solid lines and shaded areas around them indicate the averages and 95% confidence intervals, respectively, out of 1000 independent simulations. * Note that in the case of panel (d) we do not report historical values because of lack of data. Eurostat only provides the households' energy expenditures, from the COICOP classification, for 2010 and 2015 whose share was rather stable at around 5.7% and close to our numerical results in those years ($\sim 5.5\%$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of adaptive household demand and innovations for energy-efficiency improvements allows for the saving of energy (per unit of production), with an overall reduction of more than 30 points from 2020 to 2050. Finally, when looking at the variation in the distribution of the private consumption bundle (panel 2(d)), we observe that the impact on the demand for energy products is less heavy if firms are consistently involved in Leontief-type innovations. In other words, a higher reaction of private investments to the CT determines lower energy price variations allowing the consumers to keep higher levels of energy use – although cleaner (see also Figure A3.2 in Appendix A.3).

4.2. Economic and fiscal performances

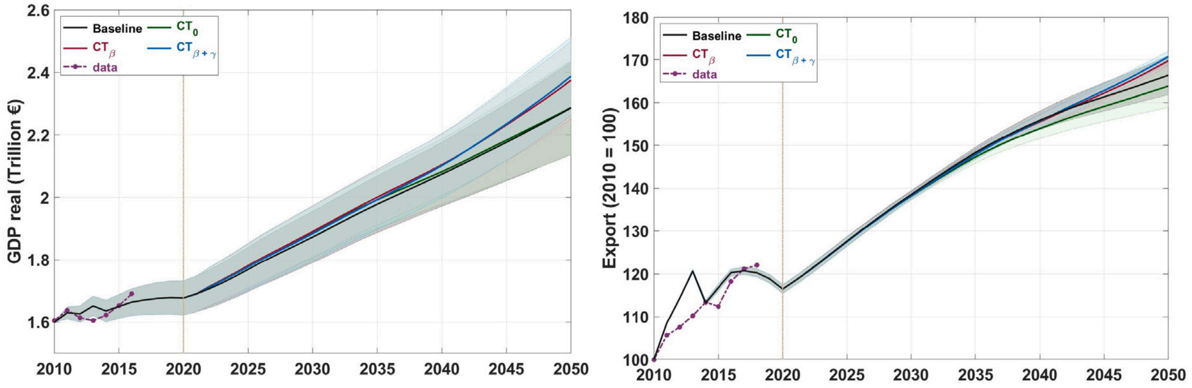
From the economic side, the main indicator usually considered is the real GDP and most institutions and governments are interested in the aftermaths of an imposition of a tax on national production and consumption. Panel 3(a) shows an increasing trend of the real GDP under each scenario, but with higher rates in the case of adaptive behaviors. Under the CT_0 scenario the adverse economic effects due to carbon tax are compensated by the redistribution of the tax revenues to the poorer which boosts consumption (and emissions). On the contrary, the scenarios CT_β (red) and $CT_{\beta+\gamma}$ (blue) follow steeper ascending trajectories although higher GDP does not translate in higher emissions, thus ensuring a relatively decoupling effect.

Panel 3(b) plots the pathways of total real exports in each scenario. Although exports increase under each scenario, the outcomes suggest that the carbon tax plus the CBA negatively affects the international competitiveness of Italy because it increases the input costs (both domestic and imported). However, if agents adapt, the competitiveness can be recovered as shown by the higher level of real exports in the long run under CT_β and $CT_{\beta+\gamma}$ scenarios. This might be explained by looking at the output-to-GDP ratio (Panel 3(c)) which is a proxy for economic efficiency: indeed, given the same level of output if the ratio decreases it means that the economic system is able to get higher valued added with the same level of production, and vice versa. It appears that the CT_0 case would worsen the competitiveness, while if consumers and firms adapt, then the ratio stays at a considerably lower level with respect to the other cases.

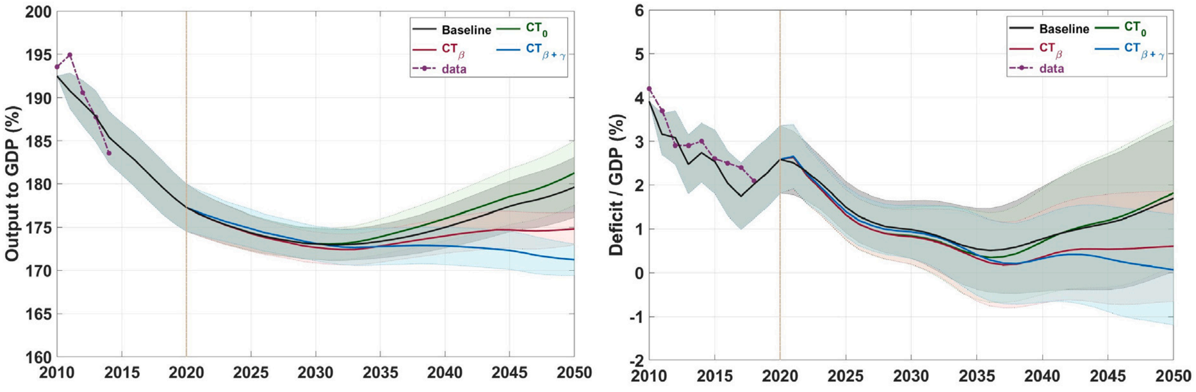
To conclude this subsection, we evaluate the yearly public deficit-to-GDP ratio as a proxy of the fiscal sustainability of carbon tax. Panel 3(d) shows a U-shaped trajectory under the Baseline and CT_0 cases departing from about 2.5% in 2020, reaching a minimum in the 2030s of about 0.5% and then it rises again until 2050 going back to the initial percentage. In any case, it stands within the yearly rate of about 3% in 2050 which represents the roof of the current EU Excessive Deficit Procedure. Even better is the fiscal performance when economic agents are adaptive: in both cases, mostly under the $CT_{\beta+\gamma}$ scenario (blue line), it appears that the public deficit-to-GDP ratio stabilizes below 1%, in the long-run, thanks to higher economic growth.

4.3. Labor and inequality

The imposition of carbon tax brings concern about the distributional effects – other than the environmental and economic ones seen above – that belong to the debate about the degree of progressivity of the CT.



(a) Economic growth **(b)** Total exports



(c) Output to GDP ratio **(d)** Public deficit-to-GDP rate

Fig. 3. Scenario analysis: economic and fiscal indicators. Comparison of real data (violet) with the numerical outcomes – from 2010 to 2050 – under the Baseline (black) and the other three scenarios: CT_0 (green), CT_β (red), and $CT_{\beta+\gamma}$ (blue). The following indicators are considered: (a) yearly real GDP, (b) total real exports, (c) real output-to-GDP ratio, and (d) yearly public deficit-to-GDP ratio. The vertical dotted line indicates the year 2020 when the policies are introduced. The solid lines and shaded areas around them indicate the averages and 95% confidence intervals, respectively, out of 500 independent simulations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

So, to complete our analysis, we calculate the Gini index as a measure of income inequality.[9]

Under the Baseline, the Gini index follows an ascending trajectory (Panel 4(a)), passing from about 35% in 2010 to more than 37% in 2050, meaning that the Italian PNIEC plan seems to generate slightly regressive distributive effects. However, the picture changes when the carbon tax is introduced and the corresponding carbon tax revenues are redistributed to lower-income groups (following the rule applied by Eq. (7)). Indeed, the dynamics of income inequality depart from the Baseline and decrease by about 2 Gini points if compared with the PNIEC. The assumption related to behavioral changes (i.e., β and γ) does not alter the pattern in a significant way. The key message is that there is room to use the CT revenues to directly tackle inequality without affecting the environmental performance; rather, even better results are obtained if an even redistribution is coupled with pro-environmental behavioral changes.

Panel 4(c) reports the number of employed workers to complement the above results. It appears that in the Baseline scenario, employment increases less, from about 21 million people in the 2020s to around 25.5 million at the end of the period. Panel 4(d) shows the projections with respect to the unemployment rate that follows cyclical patterns in all scenarios in the range between 7% and 10%. The main difference is given by the amplitudes of the cycles that are ampler when the carbon tax is implemented. However, the presence of faster innovations for energy-efficiency improvements allows a reduction of unemployment at the end of the simulation period (~8% in 2050). This difference is also explained by panel 4(b) that reports a slower increase of the labor productivity under $CT_{\beta+\gamma}$ case with respect to the other scenarios. This is confirmed by previous empirical studies that showed the positive job creation effects of environmentally-friendly technological change (Gagliardi et al., 2016) and so, in our case, they result in a win–win solution able to curb emissions while keeping higher levels of GDP and employment.

5. Discussion

5.1. Limitations

This study tried to provide a wide framework to evaluate the direct and the side-effects of a carbon tax, in Italy, from both socioeconomic and energy-environmental viewpoints. To this scope, we developed a comprehensive model in which several dynamic relations and feedback loop effects have been included. However, the higher complexity of the model goes hand in hand with higher computational costs and data requirements. This represents the first possible limitation of the current study. Although the data were taken from highly reliable institutions such as the Eurostat, ISTAT, and the International Energy Agency, we had to merge all this information coherently with the model requirements. The main example is the construction of the bridge

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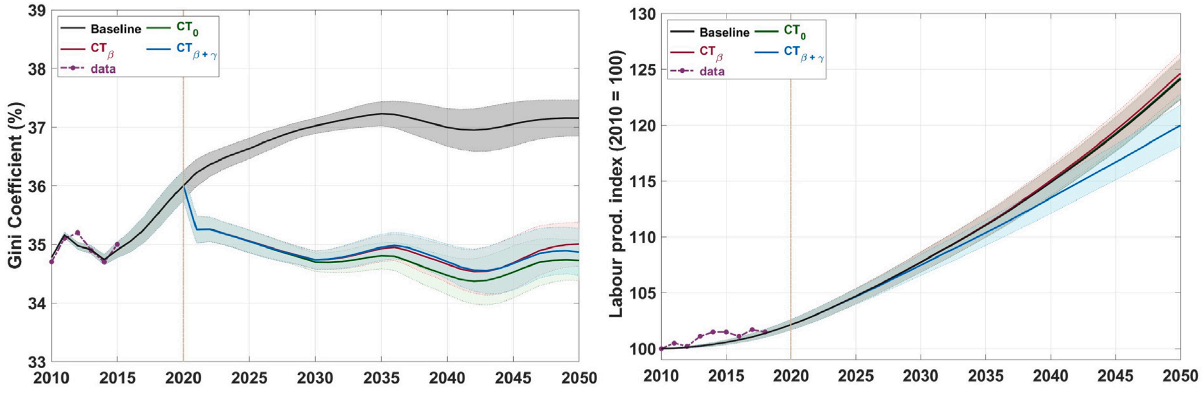
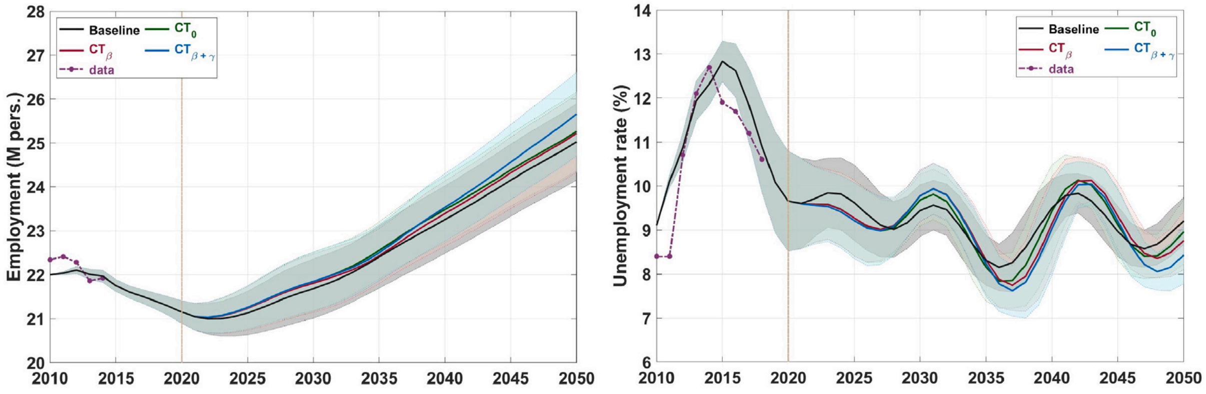
[9] In our case it is calculated on the basis of 13 heterogeneous population groups defined by the three skills and four occupational statuses of the households, plus the capitalists. See D'Alessandro et al. (2020) for a detailed description.



(a) Gini Index

(b) Labour productivity



(c) Occupation

(d) Unemployment rate

Fig. 4. Scenario analysis: Inequality and labor market. Comparison – from 2010 to 2050 – of the numerical outcomes under the Baseline (black) and the other three scenarios: CT_0 (green), CT_β (red), and $CT_{\beta+\gamma}$ (blue). The following indicators are considered: (a) the Gini index, (b) the labor productivity index, (c) the number of employees (in millions), and (d) the unemployment rate. The Gini index (top panel 4(a)) measures the degree of inequality in the income distribution, from a minimum value of 0% (no inequality) to 100% (maximum inequality). Panel 4(c) shows the number of employed workers (in millions). The vertical dotted line indicates the year 2020 when the policies are introduced. The solid lines and shaded areas around them indicate the averages and 95% confidence intervals, respectively, out of 500 independent simulations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

matrix that connects private household consumption to the Input–Output sectors which required the translation of three different product categorizations (i.e., COICOP, CPA, and NACE Rev. 2). All in all, despite the unavailable uncertainties present in the data, the final database resulted quite accurate, reliable, and consistent with official values.

A second issue may arise from the decision to run a country-specific study that forced us to over-simplify the impact of international trade; for instance, we did not distinguish by country of origin for imported goods. In the case of Italy, this might be relevant since it is highly dependent on imports of energy from a few key countries, like France and Russia. Hence, a deeper description of international trade would have allowed for the definition of fine-tuned burden carbon tax rates. We decided, following most of the available literature, to focus on a specific country also to highlight the role of country-specific contingencies in policy evaluations. Third, given the different levels of aggregation between the PNIEC plan and the current model, we cannot distinguish between the multiple renewable energy technologies (RET) considered in the Italian plan to obtain efficiency gains, hence we apply an exogenous coefficient "as if" they were implemented at the firm level. Moreover, we did not include any barriers to the use and application of RET concerning variability management measures or lack of primary materials (and related geopolitical aspects) to build the infrastructures (solar power plant, geothermal heat pumps, etc.) required to produce renewable energy (see Scholten et al., 2020, for a discussion). Finally, we did not consider the overarching negative impacts of the current pandemic and the Russo-Ukraine war because the modelization of the short- and long-term consequences would require a separate study that goes beyond the purpose of the current analysis. All things considered, the lack of available data and the excessive increase in the complexity of the model (and in the number of equations) would have made this kind of analysis difficult to implement.

5.2. *Summary and policy conclusion*

This study proposes a dynamic macro-simulation model to assess the socioeconomic and environmental – energy impacts of a carbon tax in Italy. The study involves the evaluation of four alternative scenarios from 2010 to 2050, which are characterized by varying degrees of systemic responses in terms of consumer adaptive behavior and firm investment in energy-efficient technologies.

The main methodological contributions of this study with respect to existing literature are threefold. Firstly, it provides a holistic framework by considering a range of socio-economic and environmental-energy indicators for policy evaluation. Secondly, it incorporates simple *adaptive behaviors* of economic agents (consumers and firms) in response to the carbon tax, which overcomes the limitations of a rigid framework and enables the evaluation of how endogenous structural changes modify the impacts of the carbon tax. Thirdly, it employs a *sequential scenario* strategy to yield both short- and long-run results, thereby making it possible to compare the effects of introducing new conditions (e.g., variables, policies, parameters, etc.). This study opts for numerical simulations, rather than an analytical approach, to account for the complexity of systems with a large number of variables and parameters that vary simultaneously. The framework is grounded on the EUROGREEN model (D'Alessandro et al., 2020) and is flexible enough to accommodate additional policies (social and/or environmental), allowing for the definition of finely-tuned policy packages calibrated to specific conditions.

Our main results suggested that carbon tax can be used to reduce income inequality if redistributed to low-income groups. In this case, the increase in final demand makes the CT less effective in curbing carbon emissions if compared with the PNIEC plan, resulting in a reduction of −54.2% ($\pm 3.45\%$) and −52.1% ($\pm 4.04\%$), respectively, in 2050 with respect to the 1990 levels. However, if consumers and firms follow adaptive behaviors a 'quadruple-dividend' effect is observed: remarkable emission reductions of −61.85% ($\pm 3.75\%$) are associated with better economic performance – in 30 years the real GDP level and the number of employees increased of +42.39% ($\pm 2.67\%$) and +21.30% ($\pm 2.97\%$), respectively – lower income inequality (-∼ 2 Gini points), and sustainable public indebtedness — with a deficit to GDP ratio of about 0.6% in 2050.[10]

In light of these findings, it is crucial to consider the allocation of carbon tax revenues as a key factor in enhancing the political acceptance of carbon tax policies (Wissema and Dellink, 2007; Steenkamp, 2021). The evidence suggests that a well-designed revenue recycling scheme, aimed at supporting low-income households in satisfying their basic needs, including energy needs, can effectively mitigate the regressive effects of environmental taxes and alleviate social unrest (e.g., the "Yellow Vest" movement in France). This highlights the importance of carefully considering the distributional implications of carbon tax policies and ensuring that they are designed in a way that takes into account the needs and concerns of all members of society, as exemplified by the statement of a movement organizer who declared: "We're not anti-environmental [...]. This is a movement against abusive taxation period."

In line with most recent results from the literature (e.g., Vieira et al., 2021), we argue that additional policies are necessary to achieve the 2050 net-zero target because of socioeconomic frictions, which have been often overlooked. Hence, a progressive carbon tax scheme should be integrated with other interventions to boost adaptive behaviors (e.g., reallocating the consumption bundle and/or finding out-of-market solutions to compensate for the increase in energy prices). These interventions might include, but are not limited to: (i) education to promote sustainable practices (Suárez-Perales et al., 2021), (ii) green eco-label standards to inform pro-environmental consumer behavior (Taufique et al., 2016), (iii) energy use caps to limit the total amount of energy (Kiss, 2018), and (iv) a "Kurzarbeit" strategy to ensure a shorter workweek with no shortfall in salaries and then more free time paired with an income safety net (see Ashford et al., 2020). In conclusion, our findings suggest that the implementation of a progressive carbon tax in Italy has the potential to yield a quadruple-dividend effect, but only if it is coupled with bottom-up adaptive strategies that make it more socially acceptable and promote a fair energy transition. Our model highlights the importance of considering the distributional impact of carbon tax revenues and suggests that a simple scheme of recycling these revenues in favor of low-income households could alleviate social unrest and increase public acceptance. These findings may be relevant to other similar economies, but it is important to consider contextual socio-economic characteristics on a case-by-case basis in order to identify tailored interventions.

CRediT authorship contribution statement

Tiziano Distefano: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Simone D'Alessandro:** Conceptualization, Methodology, Formal analysis, Writing – review & editing.

Data availability

The model developed in Vensim DSS, together with the simulation output, Figures and Matlab codes, is available to replicate the results at Zenodo (doi: http://dx.doi.org/10.5281/zenodo.7621764 or link at https://zenodo.org/record/7621764#.Y-PKIXbSKUk).

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2023.106578.

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[10] Note that the deficit to GDP ratio respects the EU's Stability and Growth Pact (SGP) that forces the Member States to keep their deficits below 3% of its GDP, while the debt to GDP ratio reaches the and 74.7% (under the $CT_{\beta+\gamma}$ scenario) that is slightly above the threshold of 60% although but it sharply decreased with respect to the level of 2010 which was about 120%.

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