

Introducing carbon tax in Italy: Is there room for a quadruple-dividend effect?

*Tiziano Distefano** and *Simone D'Alessandro*[†]

January 2023

Abstract

This study aims to contribute to the literature on the environmental effectiveness and societal impacts of a carbon tax. As a case study, we select Italy where this policy is absent although often debated in the parliamentary arena. We run numerical simulations, based on an extension of the *EUROGREEN* macro-system dynamic model (D'Alessandro et al., 2020) to evaluate the possible threat and advantages of this policy tool from 2010 to 2050.

We follow a sequential scenario strategy: first, we build a baseline that includes the Italian Energetic Plan (PNIEC), then we introduce carbon tax which amount increases over time. On top of that, we test two hypotheses regarding possible adaptive behaviours by both consumers and producers. We investigate whether a “quadruple-dividend” effect can be achieved, by evaluating the long-term impacts on GDP and unemployment, public indebtedness, carbon emissions, and income inequality.

Scenario outcomes suggest that the carbon tax *i*) has mild effects in curbing carbon emission if compared with the PNIEC as the difference between the two scenarios is just about 2%, with respect to the 1990 level, in 2050, *ii*) generates revenues capable to contrast regressive effects, if redistributed to low-income households, with a reduction of about 2 Gini-points if compared with the PNIEC, and *iii*) attains a quadruple-dividend effect only if consumer and industries adapt to the policy. We argue that Italy could benefit from the introduction of a carbon tax. We also discuss the necessity to combine top-down policies with other public interventions to boost bottom-up adaptive strategies. This joint process could make environmental taxation more acceptable and facilitate a fairer sustainable energy transition.

*Corresponding Author. Department of Economics and Management, University of Florence. E-mail: tiziano.distefano@unipi.it.

[†]University of Pisa

Keywords— ecological macroeconomics; input-output; inequality; behavioural change; policy scenario analysis

JEL: E61, F47, Q57

1 Introduction

The idea to implement a carbon tax (CT) to curb carbon emissions dates back to the seminal work of Pigou (1920) who firstly 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 reducing 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 Jr 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 performances 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 in practice is far from being easy and only 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 a 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).

A key concept to assess the impact of the 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 distortionary taxes that slow economic growth at the same time (the second dividend)” (European Environmental Agency¹). 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 carbon tax in Italy to check under what conditions a *quadruple-dividend* effect can be reached.

¹See <https://www.eea.europa.eu/hel p/glossary/eea-glossary/double-dividend>.

35 1.1 Literature Review

36 From a methodological viewpoint, the literature splits in two branches. On the one hand, main-
37 stream economists aim to calculate analytically the 'optimal' carbon tax by using computable
38 general equilibrium (CGE) models. Notably, Nordhaus (1993), developed a Dynamic Integrated
39 Climate-Economy model (DICE) to calculate the optimal global carbon tax associated with
40 lump-sum rebates. DICE-type and CGE models have further extended our understanding on
41 how to incorporate climate damage functions (Diaz and Moore, 2017) also considering multi-
42 ple interacting climate tipping points with irreversible economic damages (Cai et al., 2016). It
43 appears that a conclusive answer to the optimal level of carbon tax has not yet been achieved
44 since that the optimal carbon tax reported by the literature varies between a few tens and a
45 few hundreds of dollars per ton of carbon (Tol, 2020). However, when inequality concerns are
46 considered, following a 'climate and development' scheme as proposed by the Agenda 2030, then
47 higher tax rates are considered more suitable to raise funding for redistribution and poverty al-
48 leviation (Clarke et al., 2009; Sorgel et al., 2021). In terms of economic performance, Chamhuri
49 et al. (2009) showed that successively higher carbon tax rates can be paired with lower emissions
50 without affecting GDP growth in Malaysia, while Khastar et al. (2020), applying a GTAP-E
51 general equilibrium model, showed that carbon tax policies lead to adverse effects on GDP but
52 industries in Finland end up with higher competitiveness. In terms of distributional effects,
53 Oladosu and Rose (2007) suggested that a CT of 25 US\$/tCO₂ in the US is mildly progressive
54 in income distribution, Allan et al. (2014) indicated that a CT of 50 \$/tCO₂ secured a double
55 dividend in Scotland, although Kirchner et al. (2019) showed that lump-sum payments are not
56 the best way of balancing the trade-off between equity and efficiency in Austria. Zhang et al.
57 (2017) considered two integrated policy mixes, wherein carbon tax revenue is recycled to reduce
58 capital tax or support clean energy subsidy in order to ensure a double dividend from the CT
59 in China.

60 On the other hand, scholars have applied the Input-Output (IO) approach to evaluate both
61 the reduction of emissions and the degree of progressivity (if any) of environmental taxation.
62 Tiezzi (2005) found no regressive effects from the simulation of a green taxation in Italy because
63 it has been implemented only on the transport sector. Moreover, system dynamics modelling
64 has been applied in India, where Gupta et al. (2019) showed that carbon tax can substantially
65 contribute in cutting emissions from road passenger transport. On the contrary, Wier et al. (2005)
66 { combining the IO with the household expenditure (i.e., national consumer survey statistics)
67 { allowing for substitutional effects within the economic sectors, found that the carbon tax has
68 regressive effects in Denmark. Other recent studies provided evidence of adverse distributional
69 effects as a consequence of the CT (e.g., Mathur and Morris, 2014; Renner, 2018). However,
70 Fremstad and Paul (2019) showed that if carbon tax revenues fund a carbon dividend then this
71 policy might have progressive effects in the US. Recycling schemes to make carbon tax progressive

72 vary and include, among others, lump-sum transfers, linear income tax reductions and equal per
73 capita refund (Klenert and Mattauch, 2016).

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

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

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

102 2 Model

103 This study extends the EUROGREEN model (see D'Alessandro et al., 2020; Cieplinski et al.,
104 2021, for a full description) that is grounded on Ecological Macroeconomics (Fontana and Sawyer,
105 2016) within a post-Keynesian framework (see Lavoie, 2014, for a detailed description). The
106 present model is based on system dynamics and the core is represented by the application of
107 the Input-Output (IO) approach that allows to combine monetary and energy units, as well as

108 labour force. This approach is gaining momentum as a viable tool for modeling complex systems
109 under energy constraints (Nieto et al., 2020).

110 Figure 1 shows the structure of the model in a nutshell by representing the main variables and
111 linkages from which it is possible to simulate the dynamic and feedback loop effects. Note that,
112 differently from the available and valuable literature that recently applied similar approaches to
113 build scenarios on energy transition (e.g. Walsh et al., 2017; Capellan-Pérez et al., 2020), in our
114 study the main socio-economic variables follow endogenous paths. Hence, we do not impose, for
115 instance, any expected GDP growth or planned labour productivity improvements but they are
116 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,

Figure 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 bridge matrix. Red rhombuses indicates the exogenous parameters (policy or behavioural 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.

117
118 given the high degree of complexity and the large number of variables and parameters used,
119 we had to consider some exogenous features, such as imports are calculated by using constant
120 import share coefficients (on the basis of historical real data); exports depend on a constant

121 elasticity to domestic price variation and on exogenous industry-specific growth rate; the labour
 122 force dynamics is affected by an exogenous skill-specific trend, derived from the data, to take
 123 into account the developments in education; the workers are always employed under full-time
 124 contract; and the governments' expenditure for final demand changes over time according to an
 125 exogenous data-driven trend². In what follows, we only focus on main methodological novelties
 126 here introduced with respect to the EUROGREEN model.

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

$$E_i(t) = \alpha_i x_i(t) \quad (1)$$

Energy production requires three main fossil sources { i.e. solid, liquid, gas } each of which
 has a different impact in terms of CO₂ 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 from E_i , from a source-sector specific share β_i^s (such that
 $\sum_s \beta_i^s = 1$), and then we apply a source-sector specific coefficient of conversion (α_i^s) to obtain
 the source-sector specific carbon emissions E_i^s . Namely

$$E_i^s(t) = E_i(t) \beta_i^s \quad (2)$$

$$\alpha_i^s(t) = E_i^s(t) \alpha_i^s \quad (3)$$

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

136 ii) COICOP-NACE bridge matrix : in order to assess the impact of carbon tax at a
 137 lower scale (i.e., individual consumption) we combine data collected on the basis of different
 138 classifications (Cai and Rueda-Cantuche, 2019). This issue of data merging is of highly relevance
 139 in macroeconomic policy analysis models (Capros et al., 2013). In our case, this means that data
 140 coming from the Household Budget Survey (HSB) { which collect information about the purpose
 141 for which expenditures are made (i.e., COICOP classification) } must be organized according
 142 to the Statistical Classification of Products by Activity (CPA). Hence, a first conversion from

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

143 COICOP to CPA is required (Kronenberg, 2011). The COICOP-NACE bridge matrix (B^c)
 144 is based on data elaborated from Eurostat (Cai and Vandyck, 2020; Cazcarro et al., 2022) and
 145 subsequently is balanced with respect to the IO structure using the RAS algorithm (see Distefano
 146 et al., 2020, for an explanation). See the Appendix A.1.1 for a step-by-step description and Tables
 147 A2.2 and A2.3, for the full list of COICOP and NACE's categories, respectively.

148 iii) Demand elasticity. The COICOP-NACE bridge matrix B^c assigns to each COICOP
 149 category the respective share of each NACE sector (Sommer and Kratena, 2017). By the same
 150 token, we can recover the in ation by COICOP products (c^c), once we have data for the in ation
 151 by NACE sectors (that are directly affected by the technological progress and policy interven-
 152 tions) by using the transpose of the bridge matrix, namely: $c^c(t) = (B^c)^T (t)$, where (t)
 153 is the vector of in ation, with respect to the previous year, by NACE sectors. We consider 12
 154 groups (g) obtained by combining three skills { dependent on the level of education of individuals
 155 (low, middle, and high) } and four working status (employed, unemployed inactive, and retired).
 156 Moreover, we assume that each individual in each group acts as a representative agent and then
 157 the average propensity to consume is the same within each group. We assume variations of
 158 industrial prices level lead to responses in al demand by COICOP products via the coe ficient
 159 ϵ^c . More precisely, we assume that each individual belonging to a speci c group(g) reacts only
 160 if the average in ation of a COICOP product c di ers from the average in ation of her whole
 161 consumption bundle, namely

$$\frac{c_g}{g} = \epsilon^c \quad g = \epsilon^c \sum_c c^c \quad (4)$$

162 where $\sum_c \frac{c_g}{g} = 1$. We consider the elasticity (ϵ^c) as the sensitivity to a price increase inc com-
 163 pared to price changes faced over all consumption commodities, then the vector of consumption
 164 shares varies over time as:

$$c_g(t) = [1 - \epsilon^c(t) \quad \epsilon^c(t)] \quad c_g(t-1); \quad (5)$$

165 with $0 \leq \epsilon^c \leq 1$ because we assume that the demand gradually reacts to the in ation³. This
 166 is justi ed by the fact that, although energy demand is rigid, it might become more elastic in
 167 the long-term when consumers can gradually adapt to the increase of prices related to carbon
 168 tax. The assumption over the dynamic of $\epsilon^c(t)$ will determine a speci c scenario, as described
 169 below. For instance, if $\epsilon^c(t) = 0$ then the consumer is totally unresponsive to price changes
 170 and the consumption shares keep the same as the initial one, while if $\epsilon^c(t) = 1$ then she reacts
 171 proportionally to the di erence in the in ation rates ($\frac{c_g}{g}$).

³Independently from the elasticity, it is possible to demonstrate that $\sum_c \frac{c_g}{g} = 1$ for any period, by combining Eq. (5) with Eq. (4).

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

190 The introduction of carbon tax boosts firms to direct investments towards energy-saving
 191 innovations. We introduce a parameter (θ) as a proxy of the degree of adaptation. Similarly to
 192 the consumption module, we have that $0 \leq \theta \leq 1$ because we assume that as the carbon tax increases
 193 the intermediate cost of the energy-intensive inputs increases and then firms try to reduce energy
 194 use and/or to substitute brown with green energy through a change in the composition of inputs
 195 (i.e., the technical coefficients). Note that, if $\theta = 0$ then the Leontief matrix can vary according
 196 to the historical trends, while when $\theta > 0$ then the size of change when T_3 -type innovations
 197 are introduced is higher. We model this behaviour by assuming that, at the industry level, the
 198 average of the variation in the technical coefficients of the Leontief matrix is proportional to the
 199 historical standard deviation, namely

$$a_{j;k}(t) = a_{j;k}(t-1) + \theta \frac{\sigma_{a_{j;k}}}{a_{j;k}(t-1)} \epsilon_{a_{j;k}}(t); \quad (6)$$

200 where $\epsilon_{a_{j;k}}$ varies over time as described in the next section. Note that, in case of T_3 -type innovations
 201 the sign of $\epsilon_{a_{j;k}}$ is negative when the sector j sells energy-intensive and/or brown products. This
 202 process might be the consequence of external effects or coordination practices among firms that
 203 may reinforce technology improvements.

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

204 **3 Scenario Setting**

205 Given the complexity of the socio-economic system, we follow a "sequential scenario" strategy
 206 (Nieto et al., 2020) in the definition of the narratives in order to isolate the impacts of each
 207 different hypothesis and evaluate their cumulative effects. In other words, we assume that each
 208 new scenario includes all the hypotheses of the previous ones more a new single condition. This
 209 procedure ensures to better isolate the effect of a new single assumption, thus avoiding spurious
 210 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 PNIEC , such as a partial exogenous yearly reduction of 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. Simultaneously, this measure affects the energy-mix composition such that the share of each non-energy industries' investments in renewable energy generation. In this regard, we assume that, in each period, the source-sector specific share ϕ_i^s changes according to the exogenous coefficient ξ_i^s that imposes the phasing-out of solid and liquid fuels by 2025 and 2050, respectively. Namely

$$\begin{aligned} & \text{X} && \phi_i^s(t) = \xi_i^s(t-1) \phi_i^s(t); \\ \text{s:t:} & && \phi_i^s(t) = 1 : \\ & \text{s} && \end{aligned}$$

- 211 2. **Carbon Tax (CT₀)**: it starts from €30 per ton of CO₂ in 2020 and it increases yearly
 212 by about €5/tCO₂, until 2050 when it reaches the maximum of €188/tCO₂ in 2050, as
 213 described in D'Alessandro et al. (2020). Note that, we decide to design the carbon tax
 214 so that it reaches high levels because, on the base of the empirical evidence (Runst and
 215 Thonipara, 2020), it should result as an effective tool. We consider the impact of inter-
 216 national trade, to address concerns about carbon leakage risks (EU-Commission, 2021),
 217 by imposing an equivalent CT on imported goods according to their incorporated carbon
 218 emissions (i.e., Carbon Border Adjustment, CBA). Note that, even under this assump-
 219 tion, both CT and CBA increase the production cost and the price of final output, thus
 220 contributing to reduce the competitiveness of exports.

221 Moreover, we take data from the European Environmental Agency regarding allowances
 222 and emissions of the firms that participate to the European Emission Trading System (EU-
 223 ETS). In this regard, to avoid double counting, we subtract the amount of CO₂ emissions

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

224 already regulated by the EU-ETS when calculating the CT. Hence, the total cost faced
 225 by polluting sectors is given by what they paid in the EU-ETS on net emissions $\{$ for
 226 simplicity and to avoid arbitrage we assume that the EU-ETS price aligns with the carbon
 227 tax $\{$ and the CT paid on emissions not regulated by the EU-ETS. Finally, we introduce a
 228 simple rule to redistribute the CT revenues in favour of low-income groups by considering
 229 the second gross income floor threshold y_2 (of 15,000.00€) as defined in the Italian taxation
 230 system. Hence, each household belonging to a given group receives an average income of
 231 y_g plus a subsidy s_g otherwise, if $y_g > y_2$ then $s_g = 0$ financed through the CT in order
 232 that the poorer will benefit more. Namely

$$s_g(t) = CT(t) \frac{p - y_2 - y_g(t-1)}{y_g(t-1)}; \quad (7)$$

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

$$\alpha(t) = \frac{CT(t)}{\max(CT)}; \quad (8)$$

238 Note that when $t < 2020$, then $\alpha(t) = 0$ because the CT was not implemented.

239 4. Energy-efficiency improvements (β): it adds on top of CT higher levels of
 240 investments for energy-efficiency improvements, as described above, to develop new tech-
 241 nologies able to substitute the polluting ones that becomes less convenient when the CT
 242 is introduced. The size of the change in the technical coefficients, for any sector pair, is
 243 proportional to β . Its weight heightens inasmuch CT increases, because we assume that
 244 firms, as the polluting inputs become costlier, try to reduce their use in the production
 245 process, namely

$$\beta(t) = \frac{CT(t)}{\max(CT)}; \quad (9)$$

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

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

254 We run the above-described scenarios from 2010 to 2050, in Italy. The empirical calibration
255 of the parameters and initial values for the Italian economy, underpinned on official data, provide
256 a consistent and coherent basis to understand the feasibility of carbon tax measure. To fix the
257 unknown parameters of the model we have considered official data from 2010 to 2018 (when
258 available) and implemented the optimization function provided by the software Vensim SDD⁶
259 to calibrate the parameters in order to align with the real data collected for the main variables.
260 Figures below report the real data (when available) together with the numerical simulations.

261 4 Results

262 For the sake of clarity, we present the scenario outcomes in three separate subsections given the
263 large number of indicators considered. In particular, we show separately the consequences of a
264 CT in terms of energy end environmental (4.1), socio-economic (4.2), and distributional (4.3)
265 effects. In each case, the Baseline scenario (black line) is compared to the scenarios described in
266 Section 3. Note that, carbon tax is simulated from the year 2020 (vertical dotted line in each
267 Figure) onward, without considering the economic shutdown due to the current pandemic crisis
268 whose modelisation would require an investigation that goes beyond the scope of the present
269 study, but that we are considering for next researches. We plot the averages and the 95%
270 confidence interval out of 1000 simulations in order to avoid arbitrary outcomes and to clean out
271 stochastic effects associated to numerical simulations.⁷

272 4.1 Energy and environment

273 Figure 2 plots the patterns related to the main energy and environmental indicators considered
274 in this study. We start with the CO₂ emissions because it is the key environmental indicator to
275 assess the effectiveness of carbon tax. The ENIEC plan commits Italy to a reduction of -40%
276 and -60% points in 2030 and 2050, respectively, compared with the level of emissions in 1990.
277 Panel 2a shows that the CT slightly affects the path of CO₂ emissions if compared with the
278 Baseline (black) in which carbon pollution reduces of about 52% points in 2050, equivalently to
279 1% yearly reduction from 2020. The CT₀ scenario (green line) determines only a moderate
280 difference, of about 2% points on average, mostly because the tax revenues are redistributed to
281 low-income groups thus determining a negative side-effect, from the environmental point of view,
282 due to the increase in national consumption that translates in higher energy uses. Hence, in case
283 of no adaptive behaviours, it appears that the higher consumption levels, led by CT subsidies,

⁶We run a multi-objective parameter optimization mode (which allows to automatize runs performed in simulation mode) as provided by the software Vensim SDD. Technical details can be found here: <https://vensim.com/optimization/#model-calibration>

⁷Note that the results are robust to the number of simulations and they look similar even if we increase the trials.

284 o sets most of the benefits related to increases of renewable sources in the energy power system.
285 However, when both consumers (red line) and firms (blue line) adapt to higher energy prices
286 then the improvements are remarkable. Indeed, under the CT_+ scenario the emissions are cut
287 by 61.85% (-3.75%) by the 2050, in line with what targeted by the PNIEC.

288 To explain these differences, we briefly comment here the changes in the energy system under
289 each scenario, while in subsection 4.2 we discuss the economic outcomes. Panel 2b shows that
290 part of the differences are determined by the higher percentage of clean electric power generation.
291 The CT seems to have little effects, but if it is paired with a higher elasticity of substitution of
292 private demand (green line) then the share of renewable in the electric power generation reaches
293 about 80% in 2050, so doubling the value of 2020. The addition of high investments for energy
294 efficiency improvements determine a further increase of 10% of renewable sources allowing to
295 generate cleaner electricity. Note that an upward trend is observed even under the Baseline (black
296 line) because we include the planned interventions of the PNIEC in the business-as-usual case,
297 so affecting each scenario. Similar considerations come from the analysis of the energy intensity
298 index (panel 2c) that is a proxy of the energy efficiency of the economy. Under the Baseline
299 (black) and CT_0 (green) it slightly improves over the whole period, while remarkable differences
300 are observed only under the other two cases. Again, the combination of adaptive households
301 demand and innovations for energy-efficiency improvements allows for the saving energy (per
302 unit of production), with an overall reduction of more than 30 points from 2020 to 2050. Finally,
303 when looking at the variation in the distribution of private consumption bundle (panel 2d), we
304 observe that the impact on the demand of energy products is less heavy if firms are consistently
305 involved in Leontief-type innovations. In other words, a higher reaction of private investments
306 to the CT determines lower energy price variations allowing the consumers to keep higher levels
307 of energy use (although cleaner (see also Figure A3.2 in Appendix A.3)).

308 4.2 Economic and social performances

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

317 Panel 3c plots the pathways of total real exports in each scenario. The outcomes suggest
318 that the carbon tax plus the CBA negatively affects the international competitiveness of Italy
319 because it increases the input costs (both domestic and imported). However, if agents adapt,

320 the competitiveness can be recovered as shown by the higher level of real exports in the long run
321 under CT and CT₊ scenarios. This might be explained by looking at the output-to-GDP ratio
322 (Panel 3c) which is a proxy economic efficiency: indeed, given the same level of material output
323 if the ratio decreases it means that the economic system is able to get higher value added with
324 the same level of production, and vice versa. It appears that the CT₀ case would worsen the
325 competitiveness, while if consumers and firms adapt, then the ratio stays at a considerable lower
326 level with respect to the other cases.

327 To conclude this subsection, we evaluate the yearly public deficit-to-GDP ratio as a proxy
328 of the fiscal sustainability of carbon tax. Panel 3d shows an U-shaped trajectory under the
329 Baseline and CT₀ cases departing from about 2.5% in 2020, reaching a minimum in the 2030s of
330 about 0.5% and then it rises again until 2050 going back to the initial percentage. In any case,
331 it stands within the yearly rate of about 3% in 2050 that represents the roof of the current EU
332 Excessive Deficit Procedure. Even better is the fiscal performance when economic agents are
333 adaptive: in both cases, mostly under the CT₊ scenario (blue line), it appears that the public
334 deficit-to-GDP ratio stabilises below 1%, in the long-run, thanks to a higher economic growth.

335 4.3 Labour and inequality

336 The imposition of carbon tax brings concern on the distributional effects { other than the en-
337 vironmental and economic ones seen above { that belongs to the debate about the degree of
338 progressivity of the CT. So, to complete our analysis, we calculate the Gini index as a measure
339 of income inequality.⁸

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

350 Panel 4c reports the number of employed workers to complement the above results. It appears
351 that in the Baseline scenario the employment increases less, from about 21 millions people in
352 the 2020s to around 25.5 millions at the end of the period. Panel 4d shows the projections with
353 respect to the unemployment rate that follows cyclical patterns in all scenarios in the range

⁸In 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.

354 between 7% and 10%. The main difference is given by the amplitudes of the cycles that are
355 ampler when carbon tax is implemented. However, the presence of faster innovations for energy-
356 efficiency improvements allows a reduction of unemployment at the end of the simulation period
357 (8% in 2050). This difference is also explained by panel 4b that reports a slower increase of
358 the labour productivity under CT + case with respect to the other scenarios. This is confirmed
359 by previous empirical studies that showed the positive job creation effects of environmentally-
360 friendly technological change (Gagliardi et al., 2016) and so, in our case, they result in a win-win
361 solution able to curb emissions while keeping higher levels of GDP and employment.

362 5 Discussion

363 5.1 Limitations

364 This study tried to provide a wide framework to evaluate the direct and the side-effects of carbon
365 tax, in Italy, under both a socio-economic and energy-environmental viewpoints. To this scope,
366 we developed a comprehensive model in which several dynamic relations and feedback loop effects
367 have been included. However, a higher complexity of the model goes hand in hand with higher
368 computational costs and data requirements. This represents the first possible limitations of
369 the current study. Although the data were taken from highly reliable institutions such as the
370 Eurostat, ISTAT and the International Energy Agency, we had to merge all this information
371 coherently with the model requirements. The main example is the construction of the bridge
372 matrix that connects private household consumption to the Input-Output sectors that required
373 the translation of three different product categorisation (i.e., COICOP, CPA, and NACE Rev.
374 2). All in all, despite the unavailable uncertainties present in the data, the final database resulted
375 quite accurate, reliable, and consistent with official values.

376 A second issue may arise from the decision to run a country-specific study that forced us
377 to over-simplify the impact of the international trade; for instance, we did not distinguish by
378 the country of origin for imported goods. In the case of Italy this might be relevant since it is
379 highly dependent on imports of energy from few key countries, like France and Russia. Hence, a
380 deeper description of the international trade would have allowed for the definition of fine-tuned
381 burden carbon tax rates. We decided, following most of the available literature, to focus on a
382 specific country also to highlight the role of country-specific contingencies in policy evaluations.
383 Third, given the different level of aggregation between the PNIEC plan and the current model,
384 we cannot distinguish between the multiple renewable energy technologies (RET) considered in
385 the Italian plan to obtain efficiency gains, hence we apply an exogenous coefficient "as if" they
386 were implemented at the firm level. Moreover, we did not include any barriers to the use and
387 application of RET concerning variability management measures or lack of primary materials
388 (and related geopolitical aspects) to build the infrastructures (solar power plant, geothermal heat

389 pumps, etc) required to produce renewable energy (see Scholten et al., 2020, for a discussion).
390 Finally, we did not consider the overarching negative impacts of the current pandemic and Russo-
391 Ukraine war because the modelisation of the short- and long-term consequences would require
392 a separate study that goes beyond the purpose of the current analysis. All things considered,
393 the lack of available data and the excessive increase in the complexity of the model (and in the
394 number of equations) would have made this kind of analysis difficult to implement.

395 5.2 Summary and policy conclusion

396 This study proposed a dynamic macro-simulation model to evaluate the socio-economic and
397 environmental-energy aftermaths of carbon tax, in Italy. To provide a wide perspective we ran
398 four alternative scenarios { from 2010 to 2050 { characterised by different degrees of systemic
399 responses, in terms of consumers adaptive behaviour and firms propensity to invest in energy
400 efficient technologies. The main methodological contributions with respect to the available lit-
401 erature were threefold: firstly, we show the outcomes by considering several socio-economic and
402 environmental-energy indicators to provide a holistic framework to ground a wiser policy eval-
403 uation. Secondly, we included simple adaptive behaviours by the economic agents (consumers
404 and firms) in response to carbon tax. This decision entails the possibility to overcome a rigid
405 framework and to evaluate how endogenous structural changes modify the impacts of the CT.
406 To this purpose, instead of dealing with an analytical approach, we opted for numerical simu-
407 lations that are able to simulate the possible outcomes when dealing with complex systems in
408 which a large number of variables and parameters vary simultaneously. Thirdly, these sequential
409 scenario strategy yields both short- and long-run results and makes it possible to compare what
410 would happen if a new condition (e.g., variable, policy, parameter, and so on) is introduced. So,
411 our flexible framework { grounded on the EUROGREEN model (D'Alessandro et al., 2020)
412 { is generalisable and it contemplates the possibility to add other policies (social and/or envi-
413 ronmental) thus allowing the definition of fine-tuned policy-packages calibrated on the base of
414 contingent conditions.

415 Our main results suggested that carbon tax can be used to reduce income inequality if
416 redistributed to low-income groups. In this case, the increase in national demand makes the CT
417 less effective in curbing carbon emissions if compared with the PNIEC plan, resulting in a
418 reduction of -54.2% (±3.45%) and -52.1% (±4.04%), respectively, in 2050 with respect to the
419 1990 levels. However, if consumers and firms follow adaptive behaviours a 'quadruple-dividend'
420 effect is observed: remarkable emission reductions of -61.85% (±3.75%) are associated to better
421 economic performance { in 30 years the real GDP level and the number of employees increased
422 of +42.39% (±2.67%) and +21.30% (±2.97%), respectively { lower income inequality (-2 Gini
423 points), and sustainable public indebtedness { with a deficit to GDP ratio of about 0.6% in

424 2050.⁹

425 In this vein, we want to conclude by discussing a possible way to increase the the political
426 acceptance of carbon tax policy (Wissema and Dellink, 2007). If one looks at real-case examples,
427 it emerges that in many occasions carbon tax provoked protests as those exemplified by the
428 "Yellow Vest" movement in France. However, a deeper look shows us that one of the main reasons
429 behind this negative reaction has to be found in the distributional concerns as exemplified by the
430 statement of a movement organizer who declared: "We're not anti-environmental [...]. This is a
431 movement against abusive taxation period." What can be done to alleviate the social unrest? It
432 appears that the criteria followed by a government to allocate the carbon tax revenues is crucial
433 for the public's acceptance (Steenkamp, 2021). Our results indicate that the carbon tax revenues
434 can effectively be recycled, with a very simple scheme, in favour of low-income households to
435 sustain the satisfaction of basic needs, including the energetic ones (e.g., heating, cooking, trans-
436 port). This shows that environmental taxes do not necessarily entail regressive effects. In line
437 with most recent results from the literature (e.g., Vieira et al., 2021), we argue that additional
438 policies are necessary to achieve the 2050 net-zero target because of socioeconomic frictions,
439 which have been often overlooked. Hence, a progressive carbon tax scheme should be integrated
440 with other interventions to boost adaptive behaviours (e.g., reallocating the consumption bundle
441 and/or finding out-of-market solutions to compensate for the increase of energy prices). These
442 interventions might include, but are not limited to: i) education to promote sustainable practices
443 (Suarez-Perales et al., 2021), ii) green eco-label standards to inform pro-environmental consumer
444 behaviour (Tauque et al., 2016), iii) energy use caps to limit the total amount of energy (Kiss,
445 2018), and iv) a "Kurzarbeit" strategy to ensure a shorter workweek with no shortfall in salaries
446 and then more free time paired with an income safety net (see Ashford et al., 2020). All in
447 all, we argue that Italy could benefit from a 'quadruple-dividend effect' from the introduction
448 of a progressive carbon tax only if this top-down policy tool is paired with efforts in favour of
449 bottom-up adaptive strategies to make it more acceptable and able to attain a fairer sustainable
450 energy transition.

451 References

- 452 Allan, G., P. Lecca, P. McGregor, and K. Swales (2014). The economic and environmental
453 impact of a carbon tax for Scotland: A computable general equilibrium analysis. *Ecological*
454 *Economics* 100 40{50.
- 455 Ashford, N. A., R. P. Hall, J. Arango-Quiroga, K. A. Metaxas, and A. L. Showalter (2020).

⁹Note 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 + 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%.

- 456 Addressing inequality: The first step beyond covid-19 and towards sustainability. *Sustainability* 12 (13), 5404.
457
- 458 Bohringer, C., E. J. Balistreri, and T. F. Rutherford (2012). The role of border carbon adjustment
459 in unilateral climate policy: Overview of an energy modeling forum study (emf 29). *Energy*
460 *Economics* 34 S97{S110.
- 461 Branger, F. and P. Quirion (2014). Would border carbon adjustments prevent carbon leakage
462 and heavy industry competitiveness losses? insights from a meta-analysis of recent economic
463 studies. *Ecological Economics* 99 29{39.
- 464 Cai, M. and J. M. Rueda-Cantuche (2019). Bridging macroeconomic data between statistical
465 classifications: the count-seed RAS approach. *Economic Systems Research* 3(8), 382{403.
- 466 Cai, M. and T. Vandyck (2020). Bridging between economy-wide activity and household-level
467 consumption data: Matrices for european countries. 30. 105395.
- 468 Cai, Y., T. M. Lenton, and T. S. Lontzek (2016). Risk of multiple interacting tipping points
469 should encourage rapid co 2 emission reduction. *Nature Climate Change* 6(5), 520{525.
- 470 Capellán-Pérez, I., I. de Blas, J. Nieto, C. de Castro, L. J. Miguel, O. Carpintero, M. Mediavilla,
471 L. F. Lobejn, N. Ferreras-Alonso, P. Rodrigo, et al. (2020). MEDEAS: a new modeling frame-
472 work integrating global biophysical and socioeconomic constraints. *Energy & Environmental*
473 *Science* 13(3), 986{1017.
- 474 Capros, P., D. Van Regemorter, L. Paroussos, P. Karkatsoulis, C. Fragkiadakis, S. Tsani, I. Char-
475 alampidis, T. Revesz, M. Perry, and J. Abrell (2013). GEM-E3 model documentation. JRC
476 Scientific and Policy Reports 26034.
- 477 Carraro, C. and D. Siniscalco (2013). *Environmental fiscal reform and unemployment*, Volume 7.
478 Springer Science & Business Media.
- 479 Cazcarro, I., A. Amores, I. Arto, and K. Kratena (2020). Bridge matrices for feeding macroe-
480 conomic models with consumption survey's profiles for the EU28 countries. In *Proceedings*
481 *of the 27th International Input-Output Conference (IIOA) Conference*, Glasgow, Scotland
482 Volume 30.
- 483 Cazcarro, I., A. F. Amores, I. Arto, and K. Kratena (2022). Linking multisectoral economic
484 models and consumption surveys for the european union. *Economic Systems Research* 3(4),
485 22{40.
- 486 Chamhuri, S., H. Abdul, et al. (2009). Computable general equilibrium techniques for carbon
487 tax modeling. *American Journal of Environmental Sciences* 5(3), 330{340.

- 488 Cieplinski, A., S. D'Alessandro, T. Distefano, and P. Guarnieri (2021). Coupling environmental
489 transition and social prosperity: a scenario-analysis of the italian case *Structural Change and*
490 *Economic Dynamics* 57, 265{278.
- 491 Clarke, L., J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni (2009). International climate
492 policy architectures: Overview of the emf 22 international scenarios. *Energy Economics* 31
493 S64{S81.
- 494 Condon, M. and A. Ignaciuk (2013). Border carbon adjustment and international trade: A
495 literature review.
- 496 Cosbey, A., S. Droege, C. Fischer, and C. Munnings (2020). Developing guidance for implement-
497 ing border carbon adjustments: Lessons, cautions, and research needs from the literature.
498 *Review of Environmental Economics and Policy*
- 499 D'Alessandro, S., A. Cieplinski, T. Distefano, and K. Dittmer (2020). Feasible alternatives to
500 green growth. *Nature Sustainability* 3(4), 329{335.
- 501 Diaz, D. and F. Moore (2017). Quantifying the economic risks of climate change *Nature Climate*
502 *Change* 7(11), 774{782.
- 503 Distefano, T., M. Tuninetti, F. Laio, and L. Ridol (2020). Tools for reconstructing the bilateral
504 trade network: a critical assessment. *Economic Systems Research* 32, 378{394.
- 505 EU-Commission (2021). Study on the possibility to set up a carbon border adjustment mechanism
506 on selected sectors. Technical report, European Commission.
- 507 Eurostat (2014). Physical Energy Flow Accounts (PEFA). Technical report, eUROSTAT.
- 508 Fontana, G. and M. Sawyer (2016). Towards post-Keynesian ecological macroeconomic *Eco-*
509 *logical Economics* 121 186{195.
- 510 Freire-Gonzalez, J. (2018). Environmental taxation and the double dividend hypothesis in CGE
511 modelling literature: A critical review. *Journal of Policy Modeling* 40(1), 194{223.
- 512 Fremstad, A. and M. Paul (2019). The impact of a carbon tax on inequality. *Ecological Eco-*
513 *nomics* 163 88{97.
- 514 Gagliardi, L., G. Marin, and C. Miriello (2016). The greener the better? Job creation e ects
515 of environmentally-friendly technological change. *Industrial and Corporate Change* 25(5),
516 779{807.

- 517 Gupta, M., K. R. Bandyopadhyay, and S. K. Singh (2019). Measuring effectiveness of carbon
518 tax on Indian road passenger transport: A system dynamics approach *Energy Economics* 81
519 341-354.
- 520 Hafner, S., A. Anger-Kraavi, I. Monasterolo, and A. Jones (2020). Emergence of new economics
521 energy transition models: A review. *Ecological Economics* 177 106779.
- 522 Huang, H., D. Roland-Holst, C. Wang, and W. Cai (2020). China's income gap and inequality
523 under clean energy transformation: A CGE model assessment *Journal of Cleaner Produc-*
524 *tion* 251, 119626.
- 525 Khastar, M., A. Aslani, M. Nejati, K. Bekhrad, and M. Naaranoja (2020). Evaluation of the
526 carbon tax effects on the structure of Finnish industries: A computable general equilibrium
527 analysis. *Sustainable Energy Technologies and Assessments*, 37 100611.
- 528 Kirchner, M., M. Sommer, K. Kratena, D. Kletzan-Slamanig, and C. Kettner-Marx (2019). CO₂
529 taxes, equity and the double dividend { Macroeconomic model simulations for Austria. *Energy*
530 *Policy* 126, 295-314.
- 531 Kiss, V. (2018). Energy use caps under scrutiny: An ecological economics perspective *Society*
532 *and Economy* 40(1), 45-67.
- 533 Klenert, D. and L. Mattauch (2016). How to make a carbon tax reform progressive: The role of
534 subsistence consumption. *Economics Letters* 138 100-103.
- 535 Kronenberg, T. (2011). On the intertemporal stability of bridge matrix coefficients. In 19th
536 Input-Output Conference, June, pp. 13-17.
- 537 Lavoie, M. (2014). *Post-Keynesian economics: new foundations* Edward Elgar Publishing.
- 538 Mathur, A. and A. C. Morris (2014). Distributional effects of a carbon tax in broader US scal
539 reform. *Energy Policy* 66, 326-334.
- 540 MiSE-MATTM-MIT (2020). Integrated National Energy and Climate Plan. Truthout: [https://](https://ec.europa.eu/energy/sites/ener/files/documents/it_final_necp_main_en.pdf)
541 ec.europa.eu/energy/sites/ener/files/documents/it_final_necp_main_en.pdf. Ac-
542 cessed: 2020-03-25.
- 543 Nieto, J., O. Carpintero, L. F. Lobejn, and L. J. Miguel (2020). An ecological macroeconomics
544 model: The energy transition in the EU. *Energy Policy* 145, 111726.
- 545 Nieto, J., O. Carpintero, L. J. Miguel, and I. de Blas (2020). Macroeconomic modelling under
546 energy constraints: Global low carbon transition scenarios. *Energy Policy* 137, 111090.

- 547 Nordhaus, W. D. (1993). Optimal greenhouse-gas reductions and tax policy in the "DICE"
548 model. *The American Economic Review* 83(2), 313-317.
- 549 Okonkwo, J. U. (2021). Welfare effects of carbon taxation on south african households
550 *Energy Economics* 96 104903.
- 551 Oladosu, G. and A. Rose (2007). Income distribution impacts of climate change mitigation policy
552 in the Susquehanna River Basin Economy. *Energy Economics* 29(3), 520-544.
- 553 Pereira, A. M., R. M. Pereira, and P. G. Rodrigues (2016). A new carbon tax in Portugal: A
554 missed opportunity to achieve the triple dividend? *Energy Policy* 93, 110-118.
- 555 Pigou, A. C. (1920). *The economics of welfare* London, United Kingdom.
- 556 Ramstein, C., G. Dominioni, S. Etehad, L. Lam, M. Quant, J. Zhang, L. Mark, S. Nierop,
557 T. Berg, P. Leuschner, et al. (2019). State and trends of carbon pricing 2019 The World
558 Bank.
- 559 Renner, S. (2018). Poverty and distributional effects of a carbon tax in Mexico. *Energy Pol-
560 icy* 112, 98-110.
- 561 Runst, P. and A. Thonipara (2020). Dosis facit effectum why the size of the carbon tax matters:
562 Evidence from the Swedish residential sector. *Energy Economics* 91 104898.
- 563 Scholten, D., M. Bazilian, I. Overland, and K. Westphal (2020). The geopolitics of renewables:
564 New board, new game. *Energy Policy* 138, 111059.
- 565 Sommer, M. and K. Kratena (2017). The carbon footprint of European households and income
566 distribution. *Ecological Economics* 136 62-72.
- 567 Sorgel, B., E. Kriegler, I. Weindl, S. Rauner, A. Dirnhaichner, C. Ruhe, M. Hofmann, N. Bauer,
568 C. Bertram, B. L. Bodirsky, et al. (2021). A sustainable development pathway for climate
569 action within the UN 2030 agenda. *Nature Climate Change* 11(8), 656-664.
- 570 Steenkamp, L.-A. (2021). A classification framework for carbon tax revenue use. *Climate Pol-
571 icy* 21(7), 897-911.
- 572 Suarez-Perales, I., J. Valero-Gil, D. I. Leyva-de la Hiz, P. Rivera-Torres, and C. Garces-Ayerbe
573 (2021). Educating for the future: How higher education in environmental management affects
574 pro-environmental behaviour. *Journal of Cleaner Production* 321, 128972.
- 575 Tauque, K. M. R., C. Siwar, N. Chamhuri, and F. H. Sarah (2016). Integrating general environ-
576 mental knowledge and eco-label knowledge in understanding ecologically conscious consumer
577 behavior. *Procedia Economics and Finance* 37 39-45.

- 578 Tiezzi, S. (2005). The welfare effects and the distributive impact of carbon taxation on Italian
579 households. *Energy Policy* 33(12), 1597{1612.
- 580 Tol, R. S. (2020). The economic impacts of climate change *Review of Environmental Economics*
581 and Policy.
- 582 Vieira, L. C., M. Longo, and M. Mura (2021). Are the European manufacturing and energy sectors
583 on track for achieving net-zero emissions in 2050? an empirical analysis *Energy Policy* 156
584 112464.
- 585 Walsh, B., P. Ciais, I. A. Janssens, J. Penuelas, K. Riahi, F. Rydzak, D. P. Van Vuuren, and
586 M. Obersteiner (2017). Pathways for balancing CO2 emissions and sinks *Nature communi-*
587 *cations* 8(1), 1{12.
- 588 Wang, Q., K. Hubacek, K. Feng, Y.-M. Wei, and Q.-M. Liang (2016). Distributional effects of
589 carbon taxation. *Applied Energy* 184 1123{1131.
- 590 Wesseh Jr, P. K. and B. Lin (2019). Environmental policy and 'double dividend' in a transitional
591 economy. *Energy Policy* 134 110947.
- 592 Wier, M., K. Birr-Pedersen, H. K. Jacobsen, and J. Klok (2005). Are CO2 taxes regressive?
593 Evidence from the Danish experience. *Ecological Economics* 52(2), 239{251.
- 594 Wissema, W. and R. Dellink (2007). AGE analysis of the impact of a carbon energy tax on the
595 Irish economy. *Ecological Economics* 61(4), 671{683.
- 596 Zhang, Y.-J., H.-R. Peng, and B. Su (2017). Energy rebound effect in China's industry: An
597 aggregate and disaggregate analysis *Energy Economics* 61 199{208.
- 598 Zhang, Z., A. Zhang, D. Wang, A. Li, and H. Song (2017). How to improve the performance of
599 carbon tax in China? *Journal of Cleaner Production* 142, 2060{2072.

600 A Appendix

601 A.1 Data and definitions

602 The data sources employed to calibrate the model, from 2010 to 2018, are summarized below.

603 Social and National Accounts¹⁰ the Italian Institute of Statistics (ISTAT) provides data
604 about the inter-industry intermediate and international trade, including information about
605 the final demand, taxation, and value added (wages and profits). The data are consistent
606 with the NACE (Rev. 2) classification.¹¹ The ISTAT also provides data on the household
607 budget survey (HBS) that focuses on consumption expenditure behaviours of households
608 residing in Italy (see <https://www.istat.it/en/archivio/180353>
609 Eurostat, the survey is based on the harmonized international classification of expendi-
610 ture voices (Classification of Individual Consumption by Purpose { COICOP) to ensure
611 international comparability.

612 Energy Accounts: the energy data come from two datasets. The ISTAT-PEFA reports the
613 matrices of supply and demand of energy fluxes (in terajoules) by source for each (NACE)
614 industry and for households, for the years 2014 and 2015. In particular, the demand for
615 energy is split into two parts, a matrix (B) which supplies total use { including final use,
616 losses, non-energy use, and for transformation { of energy, and a matrix(Q) which reports
617 the share of polluting energy that generates CO₂ emissions. We integrate these data with
618 those from the International Energy Agency (IEA) and EUROSTAT's energy balance to
619 obtain final energy use and the actual amount of CO₂ emissions by source and industry,
620 including the residential sector, from the Air Emission Account (AEA).¹²

621 Labour market data: productivity, skill-specific wages and employment by industry, fixed
622 capital stock and capital productivity and hours worked are obtained from the EU-KLEMS
623 project database for Italy.¹³

624 Government Balance¹⁴: ISTAT collects detailed information on public expenditure, debt
625 and revenues from taxation. See Table A2.1 for the list of revenues and expenditures.

¹⁰The Italian Input-output tables can be found here: <https://www4.istat.it/it/archivio/210298>

¹¹The detailed classification is available on <https://rb.gy/l6ouec>

¹²A detailed description of the energy balance is found <https://ec.europa.eu/eurostat/web/energy/data/energy-balances> here while data on greenhouse gas emissions are available <https://ec.europa.eu/eurostat/web/environment/emissions-of-greenhouse-gases-and-air-pollutants/air-emissions-accounts>

¹³The data are available http://www.euklems.net/index_analytical.shtml

¹⁴Available <https://www.istat.it/it/archivio/finanza+pubblica>

626 A.1.1 COICOP-NACE Bridge matrix

627 We decided to implement the RAS algorithm to overcome the inconsistencies when passing from
628 CPA to NACE, since it has been proved to be efficient and highly reliable when a matrix must
629 be balanced to respect given constraints (see Distefano et al., 2020, for an explanation). Indeed,
630 the RAS algorithm is a simple iterative process of bi-proportional adjustment that rescales the
631 initial matrix in order to respect the total values by columns and rows (of our IO matrix) until
632 it converges toward a unique non-negative matrix.

633 The step-by-step procedure can be summarised as follows:

- 634 i download the matrix A_0 of final demand composition in CPA-COICOP terms from (Cai
635 and Vandyck, 2020; Cazcarro et al., 2020);
- 636 ii create the vector r of total household demand from Eurostat IO data. Note that r will
637 represent the row-constraint of RAS, i.e. the row sum of the new matrix after-RAS must
638 equal r ;
- 639 iii compute the vector \bar{s} as the column sum of A_0 ;
- 640 iv calculate the scalar coefficient $\alpha = \frac{\sum_i r_i}{\sum_i \bar{s}_i}$ to clean out any inconsistency between the total
641 consumption in COICOP and NACE categories. This step is necessary because RAS
642 requires that total by row equals total by column;
- 643 v calculate the RAS column-constraints $\bar{s} = \alpha \bar{s}$;
- 644 vi run the RAS algorithm departing from A_0 , given row (r) and column (\bar{s}) constraints to
645 obtain the new bridge matrix: $A = rA_0\bar{s}$;
- 646 vii normalize the matrix A with respect to the NACE classification in order to obtain the
647 unitary conversion factor from COICOP to NACE, i.e. the matrix $B^c = A \hat{\delta}^{-1}$, where the
648 hat stands for diagonal matrix. Hence, knowing the total households demand for a given
649 COICOP product (f^c) we can construct the vector of NACE final demand (f) associated
650 to every industry as $f_i = b_i^c f^c$, where $\sum_i b_i^c = 1$.

651 A.2 Tables

Table A2.1: Government balance: revenue and expenditure sources.

| Expenditures | Revenues |
|--|------------------------------------|
| Government consumption | Value added tax |
| Wages | Labour taxes |
| Investment | Corporate income tax |
| Interest on public debt | Progressive income tax |
| Pensions | Aggregate social contribution |
| Unemployment benefits | Tax on financial income and wealth |
| Sickness, disability and family benefits | Carbon tax |

See the Supplementary Information of D'Alessandro et al. (2020) for more details.

Table A2.2: Official classification of Individual consumption expenditure of households by purpose (COICOP). Note that here we keep a higher breakdown with respect to the original COICOP 01-12 classification in order to obtain 18 categories as indicated by the codes reported in the second column.

| Numb. | COICOP code | Description |
|-------|--------------------|---|
| 1 | CP01 | Food and non-alcoholic beverages |
| 2 | CP02 | Alcoholic beverages and tobacco |
| 3 | CP03 | Clothing and footwear |
| 4 | CP04.1 | Actual rentals for housing |
| 5 | CP04.3 + CP04.4 | Regular maintenance, repair and other services of the dwelling |
| 6 | CP04.5 | Electricity, gas and other fuels |
| 7 | CP05 | Furnishings, household equipment and routine maintenance of the house |
| 8 | CP06 | Health |
| 9 | CP07.1 + CP07.2 | Purchase of vehicles + Operation of personal transport equipment |
| 10 | CP07.3 | Transport services |
| 11 | CP08 | Communications |
| 12 | CP09 | Recreation and culture |
| 13 | CP10 | Education |
| 14 | CP11 | Restaurants and hotels |
| 15 | CP12.1 + CP12.3 | Personal care |
| 16 | CP12.4 | Social protection + |
| 17 | CP12.5 + CP12.6 | Insurance + Financial services n.e.c. |
| 18 | CP12.7 | Other services n.e.c. |

See [https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Classification_of_individual_consumption_by_purpose_\(COICOP\)](https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Classification_of_individual_consumption_by_purpose_(COICOP)) for a detailed description of the COICOP classification.

Table A2.3: Official classification sectoral activities (NACE Rev. 2). Note that here we make an aggregation in order to obtain 29 sectors as indicated by the codes reported in the second column.

| Numb. | NACE Rev. 2 code | Description |
|-------|------------------|---|
| 1 | A) | Agriculture, Forestry and Fishing |
| 2 | B) | Mining and quarrying |
| 3 | C) | Manufacturing |
| 4 | C19) | Manufacture of coke and refined petroleum products |
| 5 | C33) | Repair and installation of machinery and equipment |
| 6 | D35.1) | Electric power generation, transmission and distribution |
| 7 | D35.2) + D35.3 | Manufacture of gas; distribution of gaseous fuels through mains + Steam and air conditioning supply |
| 8 | E) | Water supply; sewerage, waste management and remediation activities |
| 9 | F) | Construction |
| 10 | G) | Wholesale and retail trade |
| 11 | G45.2+G45.4) | Sale, maintenance and repair of motor vehicles and motorcycles and related parts and accessories |
| 12 | H49) | Land transport and transport via pipelines |
| 13 | H50) | Water transport |
| 14 | H51) | Air transport |
| 15 | H52) | Warehousing and support activities for transportation |
| 16 | H53) | Postal and courier activities |
| 17 | I) | Accommodation and food service activities |
| 18 | J) | Information and communication |
| 19 | K) | Financial and insurance services |
| 20 | L) | Real estate activities |
| 21 | M) | Professional, scientific and technical activities |
| 22 | M72) | Scientific research and development |
| 23 | N) | Administrative and support service activities |
| 24 | O) | Public Administration and Defence |
| 25 | P) | Education |
| 26 | Q) | Human health and social work activities |
| 27 | R) | Arts, entertainment and recreation |
| 28 | S) | Other services activities |
| 29 | S95) | Repair of computers and personal and household goods |

See the RAMON - Reference And Management Of Nomenclatures, from Eurostat, for a detailed description of the NACE Rev. 2 classification.

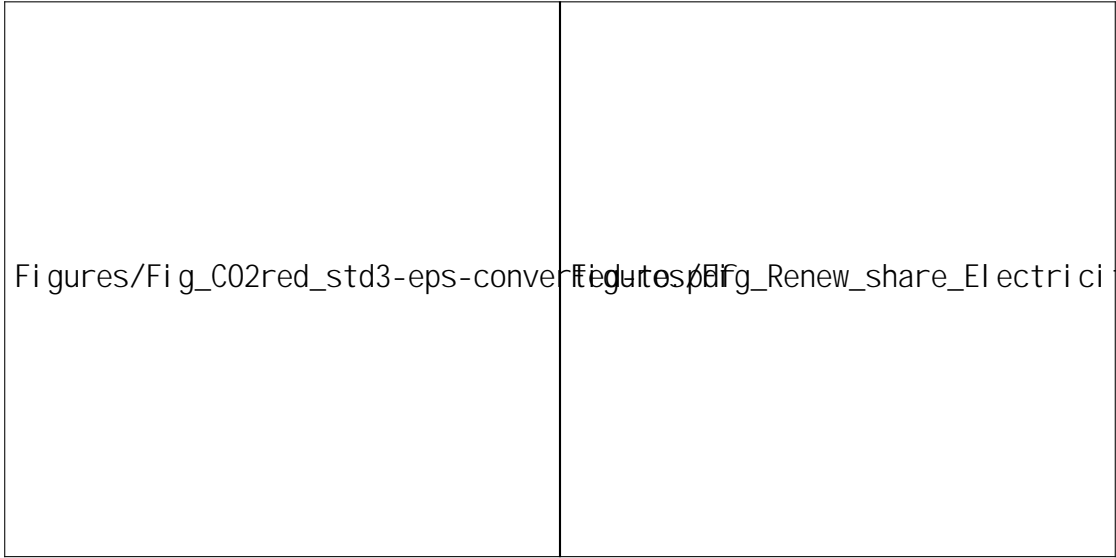
652 A.3 Disaggregated results

653 In order to provide a more detailed explanation, we also report the change in the number of
654 employees by skill in the two key macro-sectors that are directly affected by the CT , i.e. the
655 *Energy* and the *Transport* sectors.¹⁵ As expected, the *Energy* sector (top panels of Figure
656 A3.1) is slightly negatively affected by the introduction of carbon tax. The impact is greater
657 inasmuch consumers and firms adapt to the policy. From the demand-side if consumers have the
658 possibility to reallocate their consumption bundle, then they reduce the use of energy-intensive
659 commodities that are becoming more costly. From the supply-side, if firms innovate towards more
660 energy efficient technologies then they reduce the energy use per unit of input. The combination
661 of these two effects generates an overall contraction in energy production that reflects in lower
662 employment. Notably, the most affected category are the low skilled workers (light red areas).
663 By contrast, the *Transport* sector followed an opposite trend, with an increasing number of
664 workers in each scenario. This can be partly explained by the level of aggregation of our model:
665 changes in intermediate-inputs and energy-saving technologies required does not alter the level
666 of transportation inasmuch as if alternative means of transports (e.g., electric cars and public
667 transports) were included. Again, the last scenario ($CT +$) results in a lower increase, for similar
668 reason as those explained above. However, in this case the middle class seems more negatively
669 affected.

670 We also analyse the effect of carbon tax on private energy consumption: this is possible
671 by taking advantage of our novel approach underpinned on the COICOP-NACE bridge matrix
672 (as explained in Section 2). Figure A3.2 compares the share of private consumption in energy
673 products (COICOP classification) across groups (g). In line with the available literature (Huang
674 et al., 2020; Okonkwo, 2021), they emerge three interesting facts: i) lower skill levels and worse
675 occupational status determine higher shares of energy consumption, ii) when the economy is
676 flexible and the agents adapt to accommodate to the CT the expenditure in energy products
677 falls, and iii) higher levels of innovations entails higher total energy production. Point *a1*) is
678 mostly due to the fact that poorer people must allocate a higher percentage of their income
679 to the energy consumption that is a necessary commodity. It suggests that, if the economy is
680 rigid, the CT might have a regressive effect in terms of consumption instead of income because it
681 generates higher real energy costs. Point *a2*) relates to the households' possibility to reshape their
682 consumption bundle to face the increase in energy prices. In the long-run the share drastically
683 decrease reaching similar percentages (3-4%) in every group. This means that a responsive
684 behaviour of household and firms might narrow the inequalities on the consumption side, mostly
685 when necessary goods are considered. A similar pattern is observed when we introduce the
686 assumption of a faster technological progress (). However, in this case the level of energy

¹⁵*Energy* includes the NACE sectors B, C19, D35 and E, while *Transport* is composed by air, land, transport sectors (from H49 to H53). See Table A2.3 in the Appendix for a description.

687 consumption lies at a slightly higher shares. This outcome seems in line with the literature on
688 the “energy rebound effect” related to technological progress (Zhang et al., 2017): innovations
689 for energy efficiency improvements lead to a decline in the real cost of energy and, at the same
690 time, boosts economic growth; then, the combination of these two drivers might lead to and
691 increase of total energy demand and consumption.

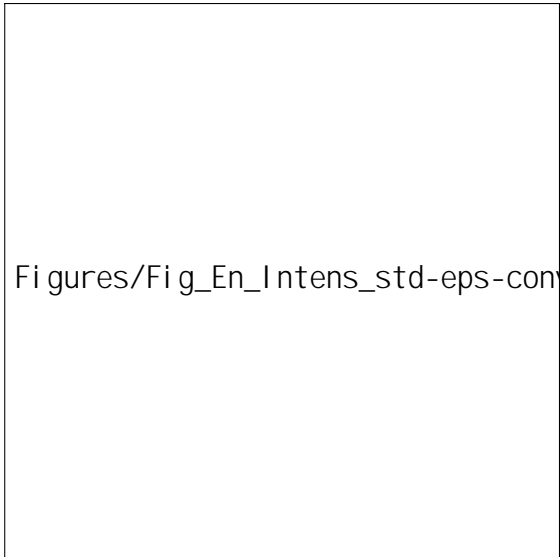


Figures/Fig_CO2red_std3-eps-converted-to.pdf

Figures/Fig_Renew_share_Electricity_std-eps-converted-to.pdf

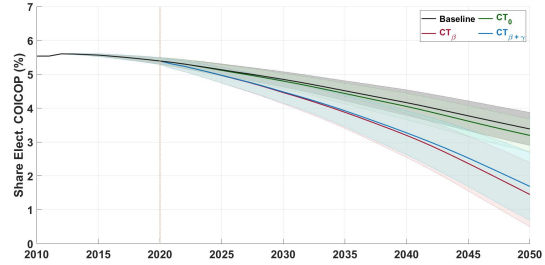
(a) Carbon emissions

(b) Clean electricity



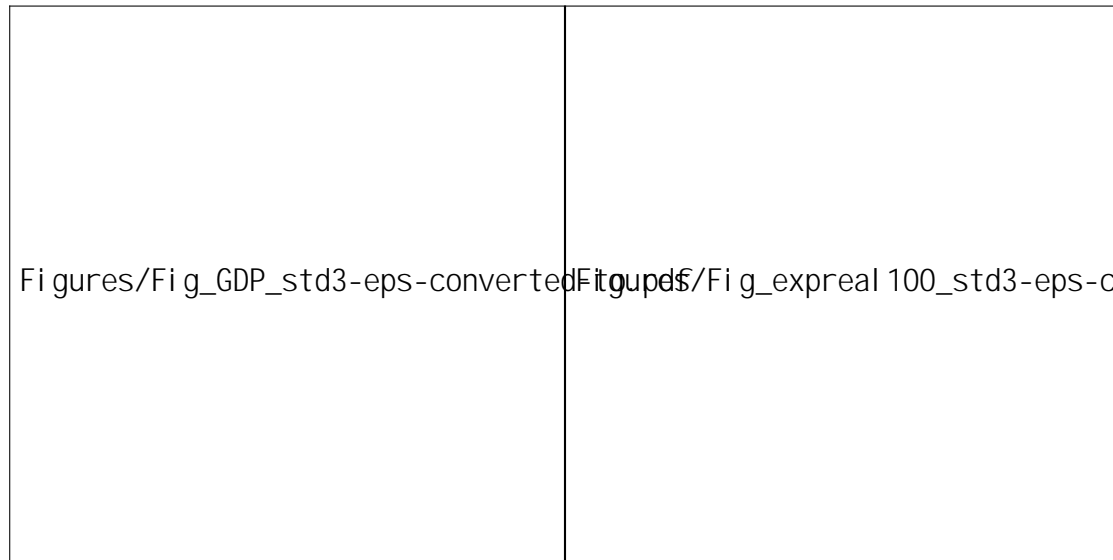
Figures/Fig_En_Intens_std-eps-converted-to.pdf

(c) TPES-to-GDP ratio



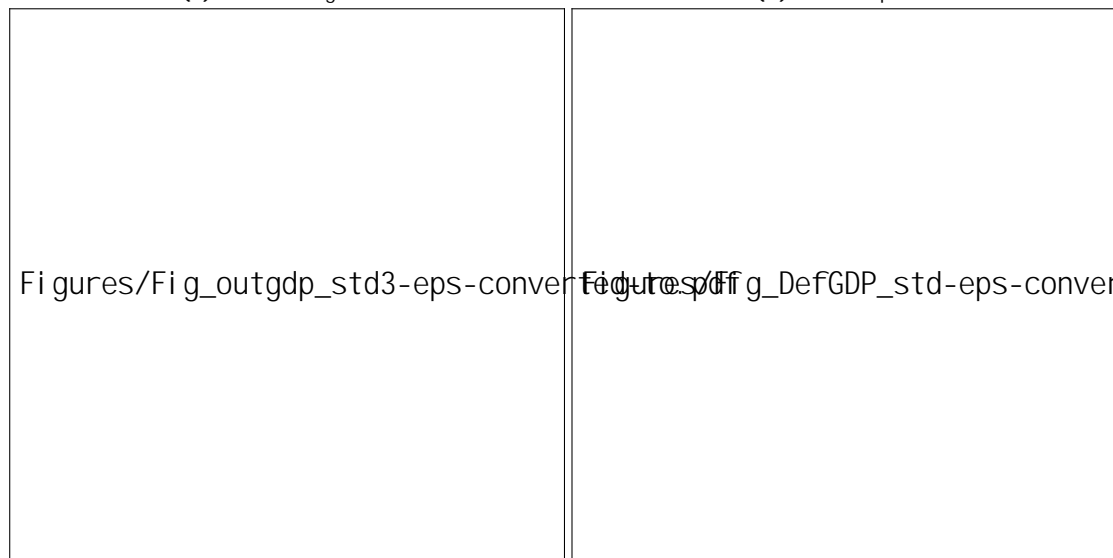
(d) Households' energy consumption

Figure 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 $CT_{\beta+\alpha}$ (blue). The following indicators are considered: (a) CO_2 emissions normalized with respect to 1990, (b) percentage of renewable energy sources in the electricity 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.



(a) Economic growth

(b) Total exports



(c) Economic efficiency

(d) Public deficit-to-GDP rate

Figure 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^- (red), and CT^+ (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.



Figure 4: Scenario analysis: Inequality and labour market. Comparison – from 2010 to 2050 – of the numerical outcomes under the Baseline (black) and the other three scenarios: CT_0 (green), CT (red), and CT_+ (blue). The following indicators are considered: (a) Gini index, (b) labour productivity index, (c) number of employees (in millions), and (d) unemployment rate. The Gini index (top panel 4a) measures the degree of inequality in the income distribution, from a minimum value of 0% (no inequality) to 100% (maximum inequality). Panel (4c) 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.

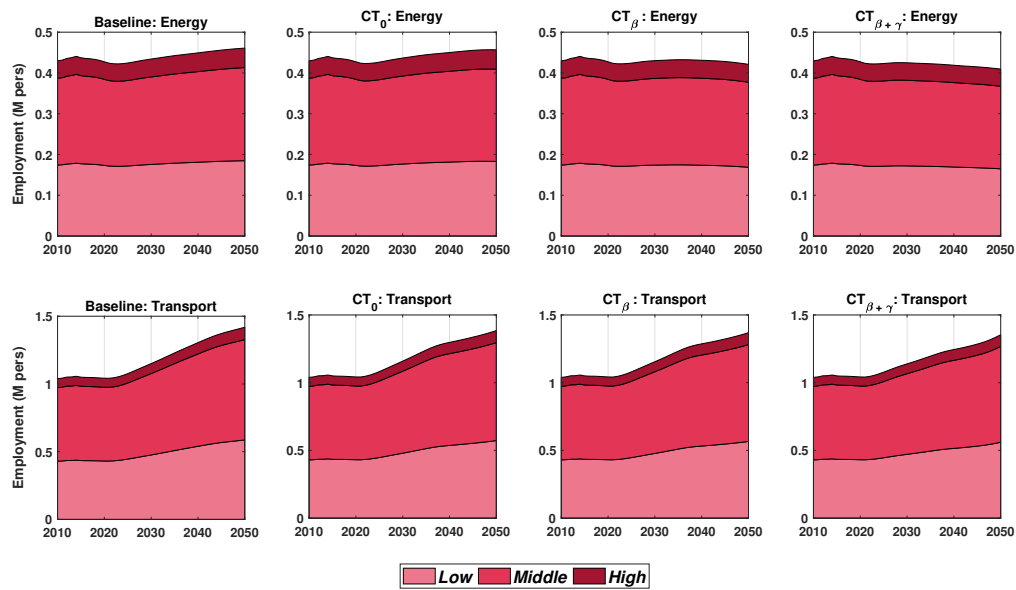


Figure A3.1: Scenario analysis: employment by skill. Comparison of the share of private consumption for energy products (COICOP classification) from 2010 to 2050 (every 10 years) under the Baseline (blue) and the other three scenarios: CT_0 (orange), CT_β (yellow), and $CT_{\beta+\gamma}$ (violet). They are compared 12 population groups defined by the combination of three educational levels (low, medium, high) and four occupational statuses (employed, unemployed, inactive, retired).

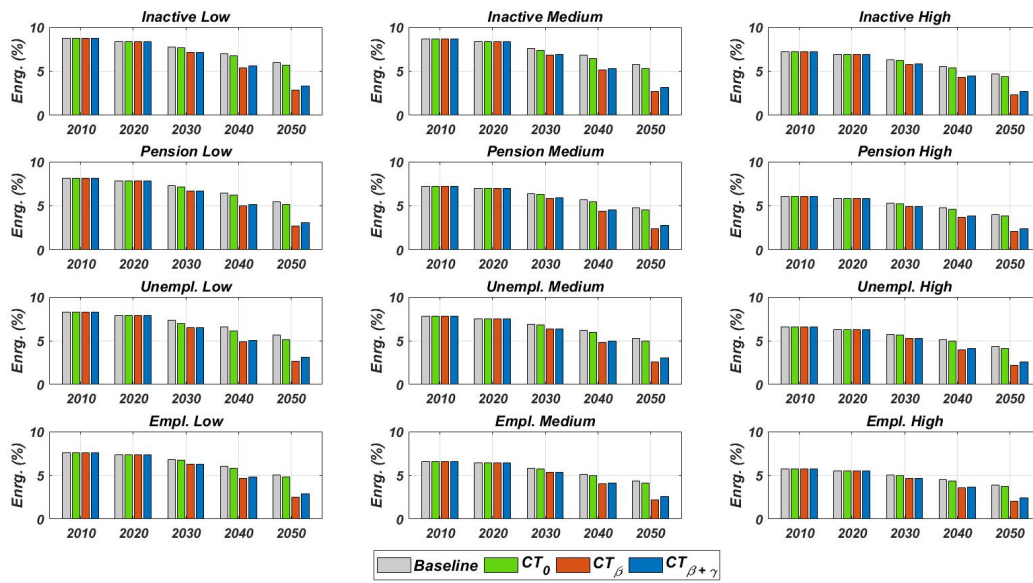


Figure A3.2: Scenario analysis: share of household's energy consumption. Comparison of the share of private consumption for energy products (COICOP classification) from 2010 to 2050 (every 10 years) under the Baseline (grey) and the other three scenarios: CT_0 (green), CT_β (red), and $CT_{\beta+\gamma}$ (blue). They are compared 12 population groups defined by the combination of three educational levels (low, medium, high) and four occupational statuses (employed, unemployed, inactive, retired).

