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Analysis

Mitigation of adverse effects on competitiveness and leakage of unilateral EU climate policy: An assessment of policy instruments

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ABSTRACT

The European Union (EU) has developed a strategy to mitigate climate change by cutting greenhouse gas (GHG) emissions and fostering low carbon technologies. However, the risk of implementing unilateral policies is that distortive effects are generated at the global scale affecting world energy prices, international competitiveness and the geographical allocation of carbon intensive production processes. Using a dynamic CGE model, we assess the rate of carbon leakage and adverse impacts on competitiveness in a number of scenarios over the period 2010–2050. According to the model results, we highlight two major issues. First, in the case of a unilateral EU climate policy, carbon leakage and negative effects on competitiveness are quite serious. Anti-leakage measures can only mitigate leakage and adverse economic impacts on competitiveness in a limited way. On the contrary, an optimality analysis addressing the environmental effectiveness, cost-effectiveness and political feasibility of alternative policy solutions reveals that the EU long term decarbonisation strategy by investing in energy efficiency and renewable energy might ensure protection of vulnerable manufacturing activities while enhancing the competitiveness of technologically-advanced industries.

1. Introduction

The European Union (EU) has developed a strategy to mitigate climate change by cutting greenhouse gas (GHG) emissions while fostering low carbon technologies with an intermediate target in 2030. The adoption of this complex policy framework has been signed officially in October 2014 under the EU document "The Climate and Energy Policy Framework", briefly addressed as EU2030. Although the Conference of the Parties held in Paris in December 2015 (COP21) achieved progress towards a global climate mitigation policy with stringent abatement targets for large emitters, strong scepticisms remain in the EU debate concerning potential risks of too challenging unilateral targets adopted by the EU. In fact, even though members of the United Nation Framework Convention on Climate Change (UNFCCC) have reached the Paris Agreement to limit global warming below at least 2 °C, the agreement is based on a voluntary approach with absence of sanctions, and requires that 55 countries accounting for at least 55% of global emissions ratify it. In any case, this global agreement will enter into force only in 2020 but international leaders have also agreed to set more ambitious targets every 5 years, in order to ensure a dynamically effective long-term abatement strategy and to reach the global emissions peak early and a rapid reduction after that. This primary aim to reach the global peak of GHG as soon as possible is still based on the common but differentiated responsibilities principle, meaning that developing countries are allowed to reach it later than developed regions. The EU has already presented the intended Nationally Determined Contributions (NDCs) in line with the EU2030 strategy, but some doubts still remain, mainly because until a binding global agreement is in place, the unilateral imposition of mitigation policies may produce two types of distortive effects. First, if there are countries not involved in active mitigation, a carbon leakage effect might arise, in terms of displacement and re-allocation of carbon intensive production processes to unregulated countries where no climate policies are in force. Second, if the EU abatement targets are unilaterally settled as higher than the other countries' targets, the most vulnerable EU manufacturing sectors might face severe losses in economic competitiveness due to higher abatement costs.

Several empirical analyses have already addressed these two issues, without concluding unanimously in the direction of the existence or not of carbon leakage and competitiveness losses.

There are studies that have not revealed any evidence of carbon leakage and loss of competitiveness in the energy-intensive sectors considered at risk of carbon leakage such as cement, aluminium, and iron and steel (Reinaud, 2008; Ellerman et al., 2010; Okereke and McDaniels, 2012; Quirion, 2011; Sartor, 2012). A number of reasons

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for this lack of evidence are suggested, including the relatively short time period that makes robust empirical estimation difficult, the fact that firms are often compensated through policy packages (including free allocation of allowances), the relatively low price of carbon allowances over most of the period that the EU Emission Trading Scheme (EU-ETS) has been in force.

In contrast, there are recent analyses that reveal potential negative effects related to unilateral EU climate mitigation policies in a long term scenario approach. More importantly, such studies propose a wider range of evaluation criteria with the purpose of selecting the proper policy instruments relying on a multidimensional assessment exercise. Economists have tended to focus on the criteria of economic efficiency and its close relative, cost-effectiveness (Goulder and Parry, 2008). However, there are other important criteria for policy-makers, such as the distribution of benefits and costs, the ability to address uncertainties, and elements of political and administrative feasibility (e.g., Konidari and Mavrakis, 2007). Böhringer et al. (2012) evaluated anti-leakage instruments according to the criteria of efficiency and international equity. Görlach (2013) developed an ‘optimality’ framework that assesses policy instruments on the basis of environmental effectiveness, dynamic efficiency, and legal and political feasibility.

The policy instruments currently debated to avoid carbon leakage and reduce competitiveness losses might be classified twofold.

First, there are some already adopted (and legally feasible) solutions applied domestically, that consist in the free allocation of CO_2 emission allowances to sectors in danger of carbon leakage (EC, 2014a) and the temporary compensation for increased electricity prices (EC, 2012). While these policy instruments are deemed to be environmentally effective because of the announced future decrease of the total volume of allowances, there is doubt over their dynamic efficiency. In particular, while the benchmarking rules provide some incentive for innovation, there is limited evidence that the current policy instruments have stimulated innovation in the past and that they will provide a continuous incentive to innovation in the future in order to ensure dynamic efficiency.

Second, there are several proposals about protecting domestic industries from foreign competitiveness by adopting Border Carbon Adjustments (BCA). BCA are characterized in the EU-ETS Directive's preamble as an “effective carbon equalization system” (EC, 2009, par. 25) and defined in Art 10b as “the inclusion in the Community scheme of importers of products which are produced by the sectors or subsectors determined in accordance with Article 10a”.[1] BCA are commonly regarded as effective in the literature (Böhringer et al., 2012), nonetheless they are not free of limitations. Among the main criticisms, BCA are subject to the risk of shifting the cost of emission abatement from developed to developing countries through trade mechanisms, and the fact that BCA might be used as “green protectionism” and thus jeopardise abating efforts in emerging countries (Babiker and Rutherford, 2005; Evenett and Whalley, 2009; Holmes et al., 2011). Moreover, many observers do not regard border measures as a constructive means of incentivising third countries to engage in climate friendly business; on the contrary, “border measures are likely to trigger retaliatory measures by trading partners” (Eurofer, 2014, p. 58). The BCA policy design also requires determining which goods and sectors to include and how to calculate the amount of CO_2 associated with exports of specific goods: this complexity and the high cost of implementation explain why BCA are almost never adopted (Condon and Ignaciuk, 2013). Therefore, the dynamic efficiency of the BCA instrument is uncertain and depends on its exact design, particularly with respect to the determination of the carbon embodied in products, based on an average, predominant or best available technology (Bednar-Friedl et al., 2012). Its legal feasibility, especially with the international trade law of the World Trade Organization (WTO), needs further investigation and its political feasibility is ambiguous.

An alternative policy instrument that has not yet been adopted but that it seems highly valuable is the direct support for European industrial innovation with the help of revenues from the sale of emissions allowances (Neuhoff et al., 2014; Nunez and Katarivas, 2014). The policy instrument could be effective in the sense that it could prevent ‘innovation investment leakage’, i.e. preventing internationally operating companies from shifting research and development (RD) investments and market launch abroad. From a dynamic efficiency perspective, the approach would encourage the industrial sector's successful transition to low carbon production, reduce costs to meet long term objectives and create technological advantage (EC, 2014b). In terms of legal feasibility, EU state aid rules need to be adjusted. Subsidies for innovation should not be a distortion of internal EU competition.

In this paper, we are mainly interested in evaluating the potential gains associated to this last alternative policy solution, that to the best of our knowledge has not yet been assessed and compared to the other two well-established policy solutions. In order to follow the recent evaluation exercises developed by the international literature, we apply the ‘optimality’ framework by Görlach (2013) and quantify a number of indicators of environmental effectiveness, (dynamic) efficiency and political feasibility with the help of ex-ante simulations of the effects of anti-leakage policy instruments on global emissions and international trade and competitiveness over the period 2010–2050 by using a dynamic Computable General Equilibrium Model (CGE) based on the GTAP framework dealing with climate and energy issues.

The rest of the paper is structured as follows. Section 2 reviews the economic modelling literature on anti-leakage policy instruments. Section 3 presents our dynamic CGE model, main assumptions and data and describes the baseline and the policy scenarios. Section 4 reports the simulation results. Section 5 presents our assessment of the anti-leakage policy options in terms of ‘optimality’ criteria and Section 6 concludes.

2. Review of Literature

The economic impact of energy and mitigation policies can be analysed using different applied models that can assess how the economy will react to any exogenous shock, such as the imposition or cut of tariff on imports, export subsidies, trade liberalization and the impact of price rises for a particular good or changes in supply for strategic resources such as fossil fuels. There are numerous examples of simulations of economic scenarios through bottom-up, top-down or integrated assessment models. In particular, dynamic computable general equilibrium (CGE) models are analytical representations of the interconnected exchanges that take place between all economic agents in the modelled economy based on observed data. The advantages of this kind of analysis are given by the fact that they can evaluate direct as well as indirect costs, spillover effects and economic trade-offs in a multi-region perspective.

The assessment of the potential impacts of climate change policy and mitigation measures is an essential input to policy decisions regarding the climate system (Burton et al., 2002). In the perspective of providing a comprehensive analysis of alternative policies, several global models combining economic and social data with climate and technology information have been developed. In general, these models try to deal with the high level of uncertainty in the costs of mitigation policies, generally over a long time horizon. They help select alternative scenarios of climate policies by considering different policy measures and interventions in a global dimension or across regions and economic sectors.

[1] The sectors and subsectors determined in accordance with Article 10a are those that are at risk of carbon leakage.

There are several alternative policy options to mitigate climate change. However, if abatement efforts are played unilaterally, there is the risk of generating distortive effects among particularly vulnerable economic sectors or across regions. Energy intensive sectors are vulnerable to increases in energy prices and, consequently, climate change policies that affect energy prices may generate deeper negative impacts on energy intensive sectors than on less energy intensive sectors. This could also lead to variations in terms of comparative advantages, especially for energy intensive and trade exposed (EITE) sectors. Indeed, in an interconnected global market, carbon leakage may occur according to which a unilateral policy may result in a shift in the production location with an increase of carbon intensive production in non-regulated countries, partially annulling the GHG reduction achieved in abating countries (Copeland and Taylor, 2004).

A small but rapidly expanding literature has analysed policy instruments to mitigate carbon leakage and adverse impacts on competitiveness. Several potential 'anti-leakage' measures have been identified, including international sectoral agreements, cost containment measures, free or output-based allocation of allowances, and border adjustment measures (Grubb and Neuhoff, 2006; Houser et al., 2008; Kuik and Hofkes, 2010).

Branger and Quirion (2014) carry out a meta-analysis of recent BCA studies. They collect 25 studies from the period 2004–2012, providing 310 estimates of carbon leakage. They find that the mean rate of carbon leakage without BCA is 14% (5%–25%) and 6% (−5%–15%) with BCA. Holding all other parameters constant, BCA reduces carbon leakage by 6% points. In the meta-analysis, the effectiveness of BCA is most sensitive to the inclusion of all manufacturing sectors (instead of only EITE sectors) and export rebates. Remarkably, the meta-analysis suggests that the effectiveness is less sensitive to whether the BCA are based on domestic or foreign CO_2-intensities.

Fischer and Fox (2012) compare three variants of BCA (a charge on import, rebate for exports, and full border adjustment) and output-based allocation. They simulate a USD 50 carbon tax in the US, Canada, and Europe, respectively. They conclude that full BCA, especially when it is based on foreign carbon intensities, would be the most effective policy for avoiding leakage, although the ability of anti-leakage measures to enhance global emissions depends on sector and country characteristics. They further argue that when BCA would not be feasible because of legal (WTO) or practical considerations, output-based allocation could in most circumstances achieve the bulk of the gains in terms of mitigating carbon leakage.

Böhringer et al. (2012) adopt a CGE model to compare three policy instruments used to mitigate adverse effects on competitiveness and leakage: BCA, output-based allocation, and exemptions for EITE industries. They compare these instruments for different coalitions of abating countries and different abatement targets. They show that the rate of carbon leakage increases with the abatement target and decreases with the size of the abatement coalition. In the smallest coalition, EU27 plus EFTA countries, the rate of leakage varies between 15% and 21% at abatement rates of 10% to 30% of the benchmark emission levels of the coalition countries. Full BCAs that level the playing field between domestic and foreign producers of EITE goods are most effective in decreasing carbon leakage: they decrease leakage by more than a third. In their simulations output-based allocation and exemptions are less effective because they do not offset the comparative disadvantage of EITE industries as much as the BCAs, partly because they do not compensate for increased electricity costs.

In contrast to output-based allocation and exemptions, BCA shifts a large part of the carbon abatement burden to non-coalition countries. BCAs therefore "fare poorly when our welfare measures account for even a modest degree of inequality-aversion and there is no mechanism in place to compensate losers under the border-tax-adjustment regime" (Böhringer et al., 2012, p.209).

The assessment of the size of carbon leakage and the effectiveness of anti-leakage measures is affected by many model characteristics and assumptions, including the type of economic model (Branger and Quirion, 2014), sectoral aggregation (Alexeeva-Talebi et al., 2012; Caron, 2012), inclusion of process emissions (Bednar-Friedl et al., 2012), assumptions on the supply of fossil energy (Sinn, 2008), endogenous technological change and diffusion (Gerlagh and Kuik, 2014), elasticity parameters (Antimiani et al., 2013) and the underlying theory of international trade (Balistreri and Rutherford, 2012).

For the long term perspective, there are a number of assessments of possible solutions to reach the defined GHG targets and the induced economic effects. Hübler and Löschel (2013) analyse the EU roadmap to 2050 in a CGE framework considering alternative unilateral and global policy scenarios, with and without the inclusion of the Clean Development Mechanism (CDM) and equalization of permits price across sectors (ETS and non-ETS) and world regions. They conclude that RD investments and new technology options are of crucial importance. In this respect, we need to recall that other than the ETS, there are different types of environmental policies and measures in place or at least discussed by the literature. Market-based instruments may take also the form of taxes or subsidies, typically designed with the aim to achieve abatement targets and incentive innovation, ensuring efficiency and cost-effectiveness (Fullerton et al., 2010). Environmental taxes are relatively easy to enforce and may provide worthy solutions with respect to resource allocation, but if unilaterally applied may also induce trade distortion and affect international distribution and competitiveness. Concerning environmental subsidies, while they may produce the same effect in term of emissions price, they could also induce an increase in the level of output (contrary to taxes that increase the firms' costs) and, perhaps, also of emissions. On the other hand, command-and-control measures and direct regulation, as the introduction of quotas and standards, are alternative policy options that, if properly designed and beside their high enforcement costs, can guarantee the prescribed abatement with a low level of uncertainty, but not at the least cost (Oates and Baumol, 1975).

Although all the aforementioned measures ultimately aim at the achievement of the same goal of reducing GHG emissions, and given the existence of market failures, externalities and additional environmental goals next to emissions abatement, combining (partly) overlapping measures could be justified. According to Oates and Baumol (1975), there are several examples of complex environmental problems that should be better solved by adopting an "optimal policy package" that combines different instruments, including direct controls and voluntary initiatives.

To this purpose, Christiansen and Smith (2012) analyse the effect of a combined use of environmental taxes and direct regulation in term of suitability to control externalities. They show that, while in some cases the use of taxation alone should be preferred, different types of distortions can be reduced with the introduction of further regulatory measures. They also explicitly abstract from the additional contribution of taxes in term of potential government revenue, which relates to the well-known "double-dividend" issue (Goulder, 1995; Bosquet, 2000; Patuelli et al., 2002; Fernández et al., 2011).[2] Moreover, combining the use of taxes with direct regulation, but also with subsidies for investment in abatement technology, helps reducing the uncertainty about abatement costs (Christiansen and Smith, 2015).

Hence, a combination of policies to mitigate concentration of GHG emissions and, at the same time, promote RD activities, support technology or improve energy security may be appropriate (Fischer and Newell, 2008; Goulder, 2013). For example, Fischer and Newell (2008) conclude that an optimal portfolio of climate measures

[2] A similar argument applies to the revenues from the auction of tradable permits.

(such as emissions trading system, performance standard, fossil power tax, green quota and subsidies for renewables energy production and RD) may allow the abatement targets to be reached at lower costs than any single policy alone would imply. Furthermore, in the presence of market distortions, "[i]f differential emission pricing or/and overlapping regulation can sufficiently ameliorate initial distortions then the direct excess costs from a first-best perspective can be more than offset through indirect efficiency gains on initial distortions" (Böhringer et al., 2009, p. 304).

Indeed, the debate over the optimal policy mix and the possible consequences that overlapping regulation may have, in terms of adverse effects on efficiency and effectiveness, is rich and complex. It can be optimal with regard to economic theory, abatement costs or economic competitiveness, but conclusions derived from applied models should also consider the (partial or general equilibrium) scale dimension. Taking the EU targets as given, the optimality is strictly linked to cost-effectiveness, but at the same time is a broader concept that has to account for a high level of uncertainty (technological, organizational, social) in a dynamic perspective. Görlach (2013) tries to answer the questions of what 'optimal' in this case means and summarizes three criteria to assess the performance of policies: environmental effectiveness, cost effectiveness and practical feasibility. The optimal solution would be able to induce the required emission reduction, at the least cost (with respect to the overall time horizon, thus ensuring static and dynamic efficiency), accounting for the risks of the policy not being implemented as designed and the selected tools not being able to deliver the awaited results (political, legal and administrative feasibility).

Moreover, in the complexity of the policy mix, when reasoning over the coherence between objectives and instruments, it should also be noted which regulation covers certain economic activities (and which not), the potential feedbacks among them, and how well a measure works in practice, especially the EU-ETS. For this purpose, the public choice approach adopted by Gawel et al. (2014) emphasizes that if the EU-ETS is scrutinized under real conditions of market failures, its cost and environmental effectiveness is weaker than expected in economic theory. Accordingly, a complimentary policy measure, as a support to renewable energies, may contribute to improving the efficiency of the EU climate strategy.

Finally, further questions concern the optimality of the policy mix in a dynamic rather than a static context and investigation into whether significant differences exist, depending on the timing of the introduction of mitigation measures and the phases of technological innovation and diffusion (Costantini et al., 2014).

3. Methodology

3.1. Model Details for Assessing the Impacts of EU Climate Policy

The recursive-dynamic version (GDynE) of the GTAP-E (Global Trade Analysis Project — Energy) model, as described in Golub (2013), builds on the comparatively-static energy version of the GTAP-E (Burniaux and Truong, 2002; McDougall and Golub, 2007) in combination with the dynamic GDyn model (Ianchovichina and McDougall, 2000). The GDynE model adopted here uses the GTAP-Database 8.1, together with the additional GTAP-Energy data on CO_2 emissions. With respect to the model version available from the GTAP official website, the GDynE model adopted for this paper contains two policy options modelled for the evaluation of the EU climate policy mix, a carbon border tax and the investments in RD for energy efficiency and renewable energy.

The first one introduces a BCA according to the modelling approach developed by Antimiani et al. (2013) for a static setting, where equations are expressed in log linear form in order to represent the effects in terms of percentage change. The lower-case letters refer to derivatives whereas upper-case letters refer to variables in level. The equation representing the influence of a BCA on the final good domestic demand is settled in order to impose a BCA only on goods imported by EU from the rest of the world that are not already subject to carbon taxation (thus excluding energy commodities). Accordingly, while changes in the demand for the domestic product (y) can be synthesized as function of price elasticity ($\eta_Y < 0$) and price changes (p_Y) as:

$$y = \eta_Y p_Y \tag{1}$$

changes in the level of the final demand for the imported good are formally expressed as follows:

$$y_1 = \eta_Y(p_Y + \tau_{Y1}) \tag{2}$$

where y_1 is the changes in the demand for the imported good, which corresponds to the same good produced domestically (Y), whose demand elasticity and price are represented by η_Y and p_Y. The BCA (τ_{Y1}) is applied as an ad valorem equivalent only to that portion of good Y imported from outside EU (y_1). The ad valorem equivalent of the BCA is generally defined as a function of the market price of the good (p_Y), the specific carbon tax or carbon allowance price (C_{TAX}) imposed to the emitters in the form of an excise and the carbon content of the taxed sector (CC_Y), given by the ratio of CO_2 emissions to value added:

$$\tau_{Y1} = f(p_Y C_{TAX}, CC_Y) \tag{3}$$

with

$$\frac{\partial \tau_{Y1}}{\partial p_Y} < 0; \frac{\partial \tau_{Y1}}{\partial C_{TAX}} > 0; \frac{\partial \tau_{Y1}}{\partial CC_Y} > 0 \tag{4}$$

Depending on which carbon content is adopted (based on a Best Available Technology (BAT) in Europe or on the real carbon intensity of the exporting country), the ad valorem equivalent changes according to the specific value assumed.

The second policy option introduces a mechanism to directly finance RD in energy efficiency and renewable sources in the electricity sector, according to Markandya et al. (2015). We assume that part of the revenue from carbon taxation (CTR) or the revenue from the sale of allowances directly finances RD activities aiming to promote improvements in energy efficiency, in an input-augmenting technical change manner, and increases the installed capacity of renewable energy. In this second case, investment efforts must be interpreted as output-augmenting technical change. In the standard version of the model, the revenue from carbon taxation is considered as a source of public budget that directly contributes to domestic welfare and it is usually modelled as a lump sum contributing to the welfare of the regional household.

The share to be taken from the CTR (γ in Fig. 1) collected through a carbon tax or an emissions trading scheme, that is directed towards RD activities is exogenously given, meaning that it is independent from the total amount of CTR gathered.[3] It should be noted that in this work, the x% of CTR is not uniformly applied to all regions because this mechanism is only active for the EU, whereas in all other regions the share is zero.

Obviously, while the x% is exogenous, the total amount of CTR directed to RD activities (CTRD) is endogenously determined by the emission abatement target and the carbon tax level. This means that, when RD activities are transformed into efficiency gains or into an increase in renewable energy, the final effects on the economic system will influence the carbon tax level (for a given abatement target) and, consequently, the CTRD total amount. The amount of CTRD used for financing RD activities and contributing to domestic welfare must be detracted from the Equivalent Variation (EV) measure. Having introduced the RD financing mechanism only

[3] In Fig. 1, the carbon tax level and the parameters in the white boxes are exogenously determined. See also Appendix I for further details on the model specification.

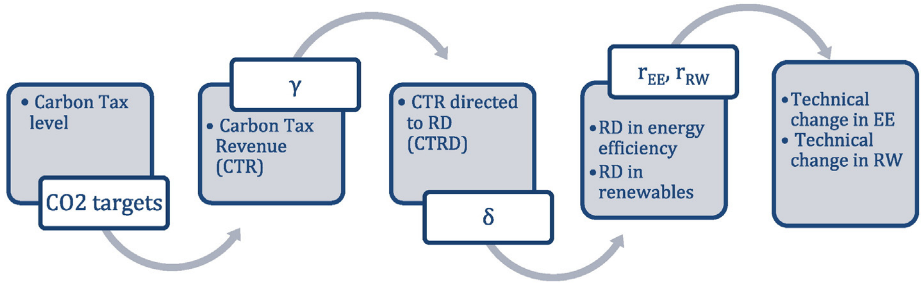


Fig. 1. Model representation of the RD financing mechanism.

in the EU, the value of the EV will be changed only for the EU with respect to the functioning of the CTRD.

The total amount of CTRD can be used for improving technical change in energy efficiency and in renewable energies. The choice of the share of total CTRD to be directed towards energy efficiency or renewables is exogenously given (δ in Fig. 1), as part of the EU policy options for the climate strategy. The current distribution of total public budget in EU for RD activities in EE and RW (IEA database) is that on average over ten years (2003–2012) 60% was directed towards energy efficiency and 40% towards renewable energies.

The relationship between technical change and RD expenditures is modelled according to two elasticity parameters in order to transform RD efforts (mln USD) into technical progress in energy efficiency and renewable energy. In this paper, we assume that all RD efforts directed towards improvements in energy efficiency in the production function are not affected by technical barriers. The elasticity parameter for energy efficiency (r_{EE}) has been calibrated according to latest reports by ENERDATA (2014) considering the sectoral efficiency gain and the public RD investment in energy efficiency during the aforementioned decade, as an average value between industry, residential sector and transport. In the case of renewable energy, we introduce an improving technical change measure in the electricity sector, according to a reactivity parameter (r_{RW}) that is calibrated with regard to the same ten years of investment in RD activities in renewable energies and the corresponding increase in installed capacity in renewable electricity in EU countries.[4]

3.2. Baseline and Policy Scenarios

We employ a time horizon to 2050 in order to perform a long term analysis of climate change policies in a world-integrated framework. As a standard modelling choice, we work with 5-year periods.

As far as country and sector coverage is concerned, we consider 20 regions and 20 sectors. With respect to the former, we distinguish between developed (Canada, European Union, Former Soviet Union, Japan, Korea, Norway, United States, Rest of OECD) and developing countries (Brazil, China, India, Indonesia, Mexico, African Energy Exporters, American Energy Exporters, Asian Energy Exporters, Rest of Africa, Rest of America, Rest of Asia and Rest of Europe).

Considering the sectoral aggregation, we identify 20 industries with special attention paid to the manufacturing industry (Food, beverages and tobacco; Textile; Wood; Pulp and paper; Chemical and petrochemical; Non-metallic Minerals; Basic metals; Machinery equipment; Transport equipment and Other manufacturing industries). Moreover, in addition to Agriculture, Transport (also distinguishing Water and Air transport) and Services, energy commodities were also disaggregated in Coal, Oil, Gas, Oil products and Electricity.

The projections for macro variables such as GDP, population and labour force are given by the combination of several sources. Projections for exogenous variables are taken as given by major international organizations. GDP projections are taken from the comparison of the reference case for four main sources, the OECD Long Run Economic Outlook, the GTAP Macro projections, the IIASA projections used for the OECD EnvLink model and the CEPII macroeconomic projections used in the GINFORS model. Population projections are taken from the UN Statistics (UNDESA). Projections for the labour force (modelled here as skilled and unskilled) are taken by comparing labour force projections provided by the ILO (for aggregate labour) with those provided by the GTAP Macro projections (where skilled and unskilled labour forces are disentangled).

With respect to the calibration of CO_2 emissions, in the reference scenario, the model presents emissions by 2050 in accordance with the CO_2 projection given by International Energy Agency in the World Energy Outlook 2013 and Energy Information Administration (EIA). In order to have calibrated emissions in accordance with a specific EU perspective, emissions provided by IAM climate models such as GCAM in a 'Do-nothing' scenario for EU countries are also compared with GDynE output.[5]

When considering the climate policy options, these are all based on a CO_2 pathway that respects the 450PPM scenario developed by IEA (and RCP 2.6 by IPCC).

The policy options here described (Fig. 2) have been selected according to the criterion of minimizing the number of simulations, in order to picture a range of results able to provide sufficient information for the purpose of the current analysis. The two standard market-based policy options considered refer to a domestic carbon tax, where every country reduces its own emissions internally, and to an international emissions trading system that allows all countries to trade emissions until an equilibrium price is reached. In order to simplify the analysis, by modelling EU as an aggregate, the two market-based policy options (carbon taxation and emission trading) are equivalent when an emissions target is imposed only in the EU in the case of unilateral climate policy. Indeed, the carbon tax in the whole EU corresponds to the minimum cost for achieving the target that is equivalent to the permit price level if EU countries are singled out and the whole economy is involved in ETS. As a benchmark, we also provide results from a scenario where every region in the world has an abatement target and implements a domestic mitigation policy in the form of a carbon tax.[6]

The third policy option includes a BCA based on the carbon content of traded goods, only accounting for the direct emissions, therefore

[4] Because it was beyond the scope of the present work to deal with uncertainty and risks in innovation financing, we follow very conservative assumptions in this regard. In other words, we assume that the response in term of technical change, in both EE and RW domains, due to an increase in the public RD investment, is the same as those registered in the last decade. Further development should incorporate at least some of the critical issues at stake in this regard. Few examples are the amount of investment needed with respect to the abatement potential, the timing of the abatement, the differences in term of resource needed, impact on competitiveness (and economic performance) or the uncertainty in the future costs of climate change with respect to damages, technological costs and financial constraints.

[5] The 'Do-nothing' scenario is coherent with IEA Current Policies and the RCP 6.0 from IPCC scenarios.

[6] In all scenarios where the emissions target is given to the EU only, emissions levels for all the other countries are endogenously given by the model in order to verify to what extent a unilateral climate policy may induce a carbon leakage effect.

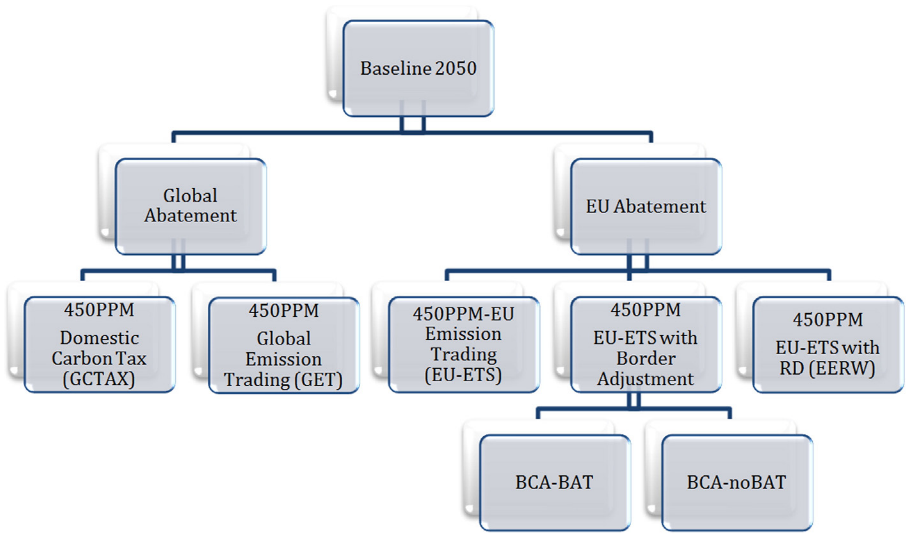


Fig. 2. GDynE baseline and policy scenarios.

excluding indirect emissions associated with the production process of all intermediates. In order to quantify the embedded carbon from non-abating country production, we consider two alternative approaches, based on the importer or exporter carbon content of traded commodities. In the first case, we apply a BAT approach in the importing country, and the carbon content for each good produced within the EU is applied to imported goods coming from non-abating economies. The second one considers the effective carbon content of the imported goods, thus relying on the production technique applied by the producing country. This second method could introduce a high degree of uncertainty for exporting countries and lead to a heterogeneous treatment and a relative penalty for less developed economies.

We then consider an increase in energy efficiency and in the share of renewable energies in the energy mix. In the former case, we consider the target declared by the EU2030 strategy that refers to an improvement in energy efficiency of 27% in 2030 with respect to a current policy scenario. With respect to the latter, and considering the specific GDynE model features, we only modelled a part of the EU2030 strategy, namely the 40% share of electricity produced by renewable sources by 2030 (EC, 2014b), without considering other renewables used in other sectors. The model setting is chosen in order to respect the 2030 target, while continuing to be effective up to the final 2050 time horizon. As a result, the increasing levels of abatement targets required to respect the 450PPM concentration target for the EU CO_2 emissions trajectory would produce increasing values for carbon tax revenue and increasing amount of RD investments in energy efficiency and renewable energy.

Summing up, scenarios included in the analysis are:

1. the baseline up to 2050 (BAU);
2. the 450PPM target where all countries globally achieve the emissions level by applying country-specific domestic carbon taxes (GCTAX);
3. the 450PPM target where all countries achieve the emissions level by participating in a global emissions trading system (GET);
4. the 450PPM target where only the EU reduces emissions with a domestic market-based policy based on ETS (EU-ETS);
5. the 450PPM target where only the EU reduces emissions with a domestic market-based policy based on ETS and a carbon tariff proportional to carbon tax based on a BAT approach (BCAbat);
6. the 450PPM target where only the EU reduces emissions with a domestic market-based policy based on ETS and a carbon tariff proportional to carbon tax based on the carbon content of the imported good (BCAnobat); and
7. the 450PPM target where only the EU reduces emissions with a domestic market-based policy based on ETS combined with the increase of energy efficiency and the production of electricity with renewable sources financed through a 10% levy on carbon tax revenue, calibrated in order to comply with by 2030 the EU2030 target of 27% in energy efficiency and 40% in renewable electricity (EERW).

4. Results

The CO_2 emissions pathways in the seven scenarios here adopted are described in Table 1. First, the emissions levels in all scenarios where only the EU adopts a climate strategy up to 2050 are equalized, since the core of this study is to assess the cost of alternative policy solutions that aim to reach the same climate target. As a benchmark, it is worth mentioning that the EU emissions level in the GCTAX scenario, where all countries at the global level respect a target by implementing a domestic carbon tax policy, is exactly the same as in the unilateral EU climate policy cases, since the EU2030 and 2050 climate targets settled by the European Commission coincide with an emissions trend that is compatible with a 450PPM scenario.

The unit cost for abating one ton of CO_2 in each period of the simulation exercise is reported for the six alternative policy scenarios in Table 2. If all countries implement domestic policies in order to be on track with a 450PPM pathway (GCTAX), the cost in terms of carbon tax is extremely high for all countries. For the EU, this carbon tax level is increasing over time as targets become more binding, and will reach

Table 1
CO_2 emissions for EU27 (MTons).

Scenarios	2015	2020	2025	2030	2035	2040	2045	2050
BAU	3517	3314	3197	3117	3015	2946	2862	2835
GCTAX	3343	2967	2466	1996	1637	1358	1119	940
GET	3413	3131	2795	2439	2050	1705	1384	1139
EU-ETS	3343	2967	2466	1996	1637	1358	1119	940
BCAbat	3343	2967	2466	1996	1637	1358	1119	940
BCAnobat	3343	2967	2466	1996	1637	1358	1119	940
EERW	3343	2967	2466	1996	1637	1358	1119	940

Source: our elaboration on GDynE results.

Table 2
Carbon tax level for EU27 (USD per ton of CO_2).

Scenarios	2015	2020	2025	2030	2035	2040	2045	2050
GCTAX	13	26	103	206	269	340	457	582
GET	7	10	45	106	175	232	345	443
EU-ETS	10	17	71	140	172	208	265	309
BCAbat	10	17	71	140	172	207	265	309
BCAnobat	10	17	72	142	174	210	268	312
EERW	12	22	67	127	160	195	249	289

Source: our elaboration on GDynE results.

582 USD per ton of CO_2 by 2050. By comparing this carbon tax level with the permits' price obtained in the GET scenario (443 USD), where all countries participate in an international emission trading system, the fact that a global agreement with permit trading is more cost-effective is confirmed.

Turning to a unilateral EU climate strategy, it is worth mentioning that by relying on the EU-ETS, the level of the permits' price by 2050 is about 309 USD per ton. The reduced unitary cost in comparison to global participation (GCTAX, GET) is fully explained by the dynamic CGE approach here adopted. When all countries at the global level must compete for acquiring inputs on the international markets to substitute fossil fuels, reaching the climate targets becomes increasingly costly. The increased competition on alternative inputs directly influences the marginal abatement costs by pushing up prices in the international markets for all goods and this explains why after 2030, the permits' price in GET is increasingly more than the price in EU-ETS.

The effect on permits' price in the case of unilateral EU climate policy complemented by trade competitiveness protection represented by the imposition of a BCA designed for ensuring a level playing field is almost negligible, whatever carbon content approach is adopted (BCAbat and BCAnobat). This means that the introduction of trade protection measures does not influence the marginal abatement costs of reaching the emissions target.

It is also worth mentioning that the carbon leakage rate, calculated as the ratio between the increase in CO_2 emissions by the rest of the world with respect to the BAU scenario and the emissions reduction by the EU (EU-ETS) is high and increasing over time, resulting in a rate of 16% in 2015 up to a rate of 49% in 2050 (Table 3).

When adopting protective measures based on trade protection policies, the carbon tax level remains stable with a small increase when the carbon content of the imported goods is adopted as a weighting criterion for the tariff imposed by the EU. More importantly, these trade protection measures allow the carbon leakage rate to be reduced by only 1%-point in the case of a BAT approach and by 6%-points by 2050 when the second carbon content option is taken.

In contrast, when the technological change policy is evaluated (EERW), the leakage rate is increasingly reduced starting from 2030, reaching −18%-points by 2050 with respect to the EU-ETS scenario. Furthermore, it is worth mentioning that starting from 2025 the marginal abatement cost for reaching a given target starts to decrease until reaching a difference with the pure ETS policy of 20 USD per ton of CO_2 by 2050.

As a general remark, it is worth mentioning that by adopting a fixed 10% levy of total carbon tax revenue, the amount of RD required to ensure the successful achievement of the three policy goals (reduction in carbon emissions, improve in energy efficiency, and increase in renewable energy quota) is augmented by 50% in 2015 compared with the actual value of RD investments in 2010, thus suggesting that the carbon tax revenues can indeed boost RD in this direction.

Table 3
Carbon leakage rate (%).

Scenarios	2015	2020	2025	2030	2035	2040	2045	2050
EU-ETS	15.68	22.31	28.37	35.30	40.99	45.47	46.73	48.63
BCAbat	15.35	21.91	27.75	34.52	40.10	44.53	45.70	47.59
BCAnobat	13.43	19.30	24.12	30.12	35.16	39.24	40.03	42.26
EERW	18.13	23.98	25.71	28.50	30.48	31.55	30.50	30.25

Source: our elaboration on GDynE results.

Table 4
Energy intensity for EU27 (toe per mln USD).

Scenarios	2015	2020	2025	2030	2035	2040	2045	2050
BAU	124.48	104.88	91.81	82.41	74.01	66.98	60.67	56.19
GCTAX	121.43	98.62	77.81	60.44	47.43	37.59	29.76	24.17
GET	122.66	101.73	84.63	69.57	55.57	44.18	34.63	27.82
EU-ETS	121.15	98.63	78.59	62.31	50.14	40.76	33.39	28.28
BCAbat	121.17	98.67	78.67	62.42	50.27	40.90	33.53	28.42
BCAnobat	121.19	98.71	78.76	62.57	50.48	41.19	33.87	28.86
EERW	121.22	98.76	79.04	63.27	51.46	42.23	34.99	29.79

Source: our elaboration on GDynE results.

In order to compare results in terms of energy intensity achievements, the broad energy intensity level, calculated by the dynamic GDynE model and compatible with the EU2030 target of reaching a 27% increase in energy efficiency by 2030 with regard to a BAU case, is 60.16 toe of energy consumption for each million USD of GDP at the EU level (Table 4).

The energy intensity level obtained by the pure ETS policy strategy reaches the value of 62.31 toe per mln USD in 2030, which is higher than the EU2030 target. More importantly, when complementing the ETS with trade protection measures, the energy intensity slightly increases in both carbon content approaches. By imposing a 10% levy on carbon tax revenue in EU to be directed towards RD flows in energy efficiency and renewable energy in the electricity sector, the carbon price is reduced (hence denoting a reduction in total abatement costs paid by the EU) but the energy intensity level (63.27 toe per mln USD) is higher than the expected target and even higher than the energy intensity achieved in the EU-ETS scenario. This last result denotes a non-negligible rebound effect on energy prices, which may be explained by the behaviour of energy markets in a unilateral climate policy.

The reduction in energy demand by the EU does not influence international energy prices. By investing in energy efficiency and renewables, the internal costs for energy consumption (given by the combination of the international market prices for energy and the domestic carbon tax) are reduced compared with the EU-ETS policy option. Given the rigidity of energy demand, this directly leads to an increase in energy consumption compared with the ETS policy option alone. This is not necessarily a negative effect since the increase in energy consumption is fuelled by renewable sources.

The economic gains obtained by fostering green technologies in the energy sector are here presented in terms of the reduction in GDP losses with respect to BAU when the EERW scenario is compared with the other policy mix strategies (Table 5). Hence, EU incentives to RD in green energy technologies together with a reduction in the carbon tax level (at least from 2025, although in the previous periods differences in tax levels are almost negligible), ensure better results in term of higher GDP for the entire 2015–2050 period with respect to the other non-global options.

Table 5
GDP changes w.r.t. BAU for EU27 (%).

Scenarios	2015	2020	2025	2030	2035	2040	2045	2050
GCTAX	0.10	0.36	0.63	0.99	1.80	2.91	4.23	5.81
GET	0.08	0.37	0.95	1.95	3.20	4.35	5.27	6.12
EU-ETS	−0.09	−0.27	−0.82	−1.80	−2.89	−3.91	−4.79	−5.52
BCAbat	−0.09	−0.27	−0.82	−1.81	−2.91	−3.93	−4.82	−5.54
BCAnobat	−0.09	−0.28	−0.82	−1.83	−2.96	−4.02	−4.98	−5.78
EERW	−0.08	−0.24	−0.62	−1.29	−2.01	−2.68	−3.27	−3.77

Source: our elaboration on GDynE results.

When trade policy measures complement the emissions mitigation policy, the EU faces a slight increase in GDP losses in relation to the ETS case. This clearly reveals that the adoption of carbon tariffs cannot help to reduce the cost of combatting climate change and may increase the heavy burden in abating countries. The small increase in GDP losses is fully explained by the CGE approach here adopted. When imposing tariffs on import flows, firms face an increase in import prices for inputs required for the production process, thus resulting in a further production cost to be sustained domestically. This leads to a further deterioration of international competiveness, especially for manufacturing sectors.

More generally, by comparing scenarios with a unilateral EU climate policy with scenarios representing a global abatement strategy, the GDP losses for the EU in the former cases become GDP gains in the latter. The international economic linkages depicted in GDynE reveal that in the case of a global deal, whatever mitigation measure is adopted, the EU would achieve substantial economic gains by participating in an international climate agreement. The abatement costs for achieving climate targets for the other countries are larger than for the EU, transforming the climate burden for the EU into an economic growth opportunity. This result may explain the negotiations deadlock caused by the countries that will face the major part of the climate burden. However, it also should encourage the EU to continue to work towards a global agreement since the unilateral solution is extremely costly and inefficient from an environmental point of view.

This result is also valid when comparing the effects on the export and output values of the manufacturing sector (Table 6 and Table A1 in Appendix II). Figures obtained for export flows in the manufacturing sector at the aggregate level are particularly interesting (Table 6). Losses for EU industries in terms of international competitiveness on the international markets are high also in the case of a global agreement. If targets are achieved by implementing an international permits scheme, these losses appear to be reduced.

If a unilateral EU climate strategy is adopted by implementing an ETS system, export flows will face a strong reduction with respect to BAU by 2040. Protective measures based on BCA cannot ensure full protection for European industries. On the contrary, they may bring further economic costs to the industrial sector since export flows decrease at a slightly higher rate when BCA are implemented in comparison to a pure ETS solution without BCA. This means that, if complementary policies rely on trade measures, a level playing field can only be restored by implementing export subsidies as a form of full adjustment, but such measures are extremely difficult to get accepted in the multilateral trade agreement context.

In contrast, when RD efforts in more efficient technologies and alternative energy sources are exploited, export flow losses will start to decrease in relation to the other unilateral policy mix strategies by 2035. In fact, while from 2015 to 2030 the results show tiny differences among the unilateral EU abatement strategies (except for 2025 and 2030 where export losses are larger in the EERW scenario in comparison to the non-global scenarios), from 2035 sustaining green energy technologies ensures a continuous reduction in export losses. The fact that the EERW scenario becomes increasingly convenient in the medium-long run is due to the fact that investment in RD in sustainable technologies foster a restructuring of the economic system, and results of this process sustaining the low-carbon transition may take some years to be achieved.[7]

Table 6
Manufacturing exports changes w.r.t. BAU for EU27 (%).

Scenarios	2015	2020	2025	2030	2035	2040	2045	2050
GCTAX	−0.47	−0.92	−2.00	−3.07	−3.57	−3.24	−4.17	−4.88
GET	−0.25	−0.52	−1.59	−2.66	−2.42	−0.85	−0.32	0.30
EU-ETS	−0.13	−0.39	−0.99	−1.92	−3.08	−4.20	−5.06	−5.54
BCAbat	−0.13	−0.39	−1.00	−1.95	−3.16	−4.35	−5.29	−5.87
BCAnobat	−0.13	−0.39	−0.97	−1.86	−3.00	−4.11	−4.99	−5.55
EERW	−0.11	−0.38	−1.05	−1.96	−2.92	−3.81	−4.44	−4.79

Source: our elaboration on GDynE results.

Energy-intensive sectors are most adversely affected by emissions reduction achieved by a unilateral EU-ETS policy. In Fig. 3 we report changes in export flows in a pure ETS policy with respect to the baseline scenario for manufacturing sectors for the periods 2030 and 2050. The basic metal sector (which includes iron and steel industries) faces a negative change in export flows in relation to BAU that reaches 25% by 2050. Chemical industries also face a large reduction reaching a 10% loss by 2050. The less energy-intensive sectors such as machinery and equipment will experience a small increase in export flows in 2030 due to a relative higher competitive advantage gained as a result of the increased production costs for energy-intensive industries, but such a gain will turn into a loss by 2050.

The exports of the rest of the world partially show a mirror-image, especially for basic metals, chemicals and paper products. This reflects the increase in relative competitiveness in the manufacture of carbon-intensive products by the rest of the world. However, the exports of non-metallic minerals (including cement and clinker) from the rest of the world also decline in the long term (Fig. A1 in Appendix II). This reflects the fact that the trade effects are not a zero-sum game, but that domestic demand is also affected by the EU ETS policy, shrinking global demand and negatively affecting the export opportunities of all countries.

By complementing the mitigation policy with trade measures (Fig. 4), some gains in export capacity are achieved for the two energy-intensive sectors (basic metals and chemicals), but it is also worth noting that in the case of a BCA based on a carbon content computed with a BAT approach the transport equipment and machinery and equipment sectors, which include the best technologically performing firms in the EU, as well as a large share of total manufacturing value added (Fig. A2 in Appendix II), face a reduction in export flows which exceed the losses resulting from the pure ETS policy strategy. This means that protecting fragile energy-intensive sectors could damage the technologically advanced sectors that constitute an engine of economic growth for Europe.

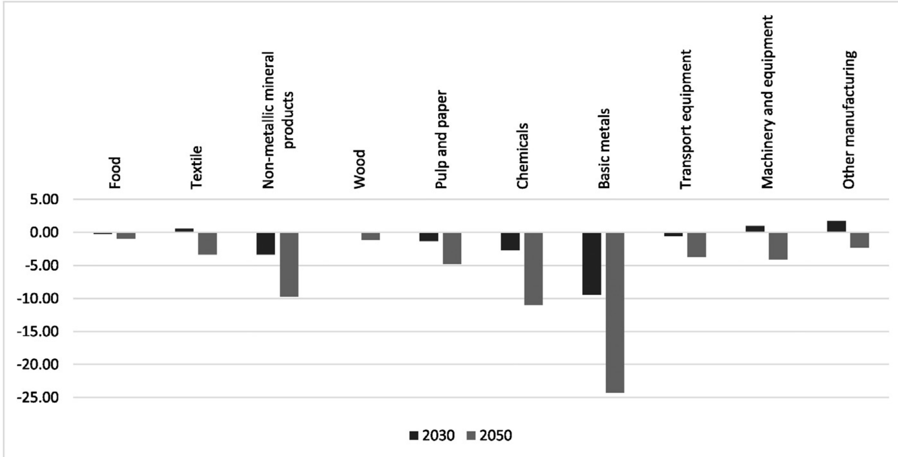
The export gains of the rest of the world that would be the result of the EU ETS policy are largely undone by the BCA measures, especially in the long run (Fig. A3 in Appendix II). The exports of non-metallic minerals even decrease with respect to BAU. If BCA rates were based on foreign carbon intensities (BCAnobat), exports of basic metals, chemicals, pulp and paper and non-metallic minerals from the rest of the world would fall by 3% to 7.5% (not shown).

Turning to the policy mix strategy including green technological efforts, results are much more encouraging than for the trade protection option (Fig. 5). The export flow losses for fragile sectors such as basic metals and chemicals are reduced reaching a maximum of −16.5% (which is still a large loss) for basic metals and −8.4% for chemicals which results in an improvement over the pure ETS-based mitigation policy option which is quite similar to that obtained via a BCA measure.

Most importantly, it is also worth noting that the technology-intensive sectors here reported such as machinery and equipment and transport equipment face a reduction by 2050 in export losses compared with the EU-ETS case. This means that this policy mix strategy leads to a generalized improvement in the international competitiveness of EU industries, without harming the sectors that constitute the core of industrial growth.

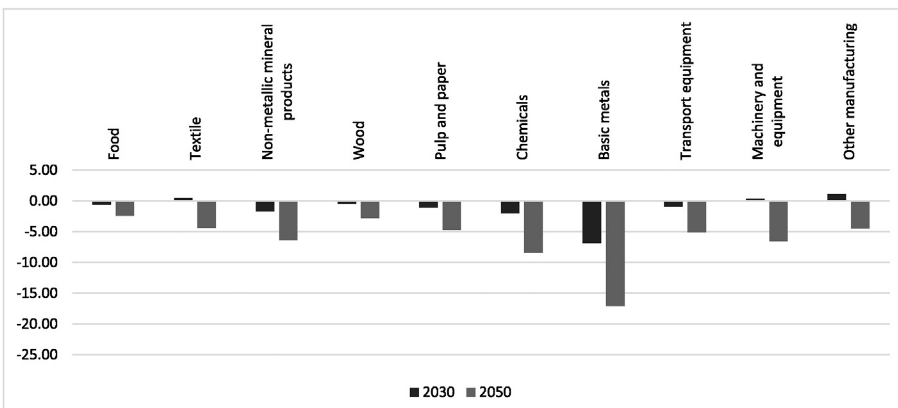
Therefore, by comparing Figs. 3–4–5 we note that the EERW policy implies a general reduction in the sectoral export losses, with respect to the ETS scenario but also to the BCAbat option, and it also ensures better performances especially in term of export of technology-intensive sectors. In this respect, we also need to recall that BCA measures act as climate measures but explicitly affect the trade relationships among

[7] A similar pattern can be identified in terms of carbon leakage, where in the EERW scenario results are worse in the first periods but become increasingly better in the later ones. Moreover, when considering energy intensity, we also need to recall that even if the EERW and the BCA options may be characterized by the same intensity, the former implies lower CO_2 emissions due to the increasing role of renewable energy sources in electricity production.



Source: our elaboration on GDynE results.

Fig. 3. Changes in export flows in EU-ETS w.r.t. BAU for EU27 (%). Source: our elaboration on GDynE results.



Source: our elaboration on GDynE results.

Fig. 4. Changes in exports in BCAbat w.r.t. BAU for EU27 (%). Source: our elaboration on GDynE results.

countries, in this case favouring EU export. On the other hand, the EERW is primarily directed to affect the internal technological structure, and its impact on international competitiveness depends on the magnitude of the innovation efforts.[8]

For the rest of the world, the green technology strategy seems to be the least disturbing protection strategy. While the effects on exports are not as favourable as under the EU ETS policy without protection measures, the exports of basic metals and chemicals slightly increase with respect to BAU and the decreases in exports of other industries (except for food that increases its exports) are relatively small (Fig. A4 in Appendix II).

5. Optimality Assessment

To assess the alternative policy instruments used to mitigate the adverse effects on competitiveness and carbon leakage, we apply the 'optimality' framework of Görlach (2013). This framework distinguishes the following criteria:

- Environmental effectiveness: is the policy achieving its objectives?
- Cost effectiveness: is the policy achieving its objectives at least costs — both in the short and long term?
- Feasibility: what is the risk of policy failure — both for administrative, legal and political reasons?

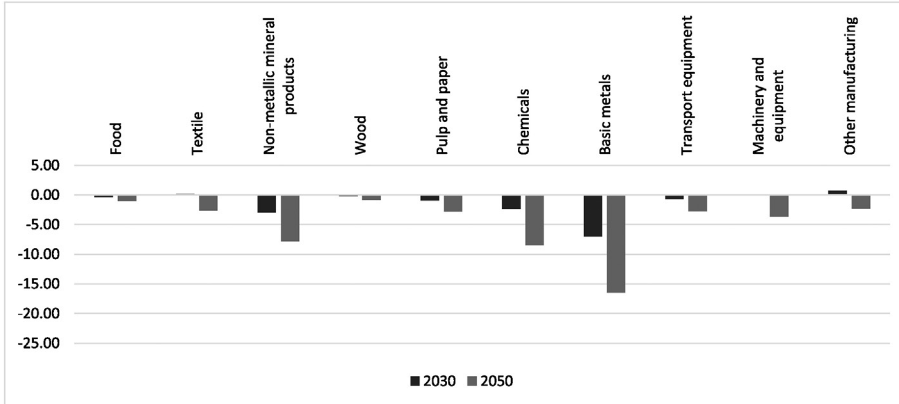
We propose a set of quantifiable indicators that can be directly derived from the GDynE model. The indicators focus on environmental effectiveness, static and dynamic efficiency, and political feasibility (Table 7).

Environmental effectiveness of the anti-leakage measures is measured by the change in carbon leakage in 2050 in %-points and the ultimate environmental effect: the change in global CO_2 emissions in 2050 (in Mt).

Cost effectiveness is measured in the short and long term. For the *short term*, the indicator 'CO_2-price in 2030' is used for the static efficiency of the policy. For the *long term*, we are interested in the dynamic efficiency of the policy and use the indicators 'CO_2-price in 2050' and 'Energy-intensity in 2050'. We assume that a dynamically efficient policy would spur 'green' technological innovation thereby reducing both the carbon price and the energy-intensity of production.

Political feasibility is divided into domestic political feasibility and international political feasibility. The indicator for domestic political feasibility is change in competitiveness of the EITE sector, measured by a change in exports in the iron and steel sector (as the most affected EITE sector). We have two indicators for international political feasibility. The first is the effect of the anti-leakage policies on the burden

[8] In this case, we model the impact of RD in green energy technologies without differentiating across sectors, while in further development at least the distinction between high-tech and low-tech sectors should be investigated.



Source: our elaboration on GDynE results.

Fig. 5. Changes in exports in EERW w.r.t. BAU for EU27 (%). Source: our elaboration on GDynE results.

sharing of costs between the EU and the rest of the world. It is assumed that a policy is *less* politically feasible the more it shifts the burden of compliance (in terms of GDP) to the rest of the world. To highlight the position of the poorest countries, we use the indicator 'Rawls' justice' that measures the change in GDP of the poorest regions in our set of regions (Ralws, 1971).

In terms of *environmental effectiveness*, all anti-leakage measures show improvements to the basis EU ETS policy on both indicators. The rate of leakage and global emissions decreases. In terms of environmental effectiveness, the gains with the BCA_{bat} measure are very modest, the rate of carbon leakage decreases from 49% to 48%. The largest gains are made in the EERW policy option where the rate of leakage decreases by 19%-points and global emissions decrease by 1322 Mt (Table 8).

In terms of *cost effectiveness*, static efficiency in 2030, measured by the CO_2 price, is approximately equal between the basis EU ETS policy and the two BCA options. Static efficiency is higher for the EERW policy option. The impact on dynamic efficiency shows a mixed pattern. On the one hand, the CO_2 price in 2050 is substantially lower for the EERW policy option, but, on the other, energy-intensity under EERW is (slightly) higher. It should be assumed that EERW does not necessarily lead to a decrease in energy intensity but does lead to a larger share of primary energy being renewable.

In terms of *political feasibility*, all anti-leakage measures improve the competitiveness of the EITE industry in comparison to the EU ETS policy without such measures. The BCAnobat policy offers the largest degree of protection to the EITE sectors. The competitiveness of the whole manufacturing sector is most improved by the EERW anti-leakage policy. The evidence for domestic political feasibility is therefore mixed: representatives of the EITE sector may prefer BCAnobat protection, whereas those representing the broader manufacturing industry may prefer the EERW measure.

From an international perspective, the two BCA measures shift the carbon compliance burden to the rest of the world. Here, the Rawls' justice criterion is based in terms of total GDP and the poorest region's GDP is given by the sum of GDP values at 2050 in the BAU scenario for all regions representing developing countries excluding emerging economies and energy exporters. From an international perspective, the EERW anti-leakage measure is likely to meet less resistance than both BCA measures, especially the BCAnobat measure since the GDP loss for this latter scenario is the highest w.r.t. BAU.

6. Conclusions

The European Union has developed a strategy to mitigate climate change by cutting GHG emissions and fostering low carbon technologies. However, the risk of implementing unilateral policies is that distortive effects are generated at the global scale that affect world energy prices, international competitiveness and the geographical allocation of carbon intensive production processes. Using an adjusted dynamic CGE model, we assess the rate of carbon leakage and the adverse impacts on competitiveness in a number of scenarios over the period 2010–2050.

The results show two interesting aspects. First, if all countries cooperate, there is obviously no carbon leakage and the economic effects for the EU are overall positive. There are adverse effects on the competitiveness of EU manufacturing sector, but especially if international emissions trading is allowed, these effects are very small and decline towards the end of the planned horizon. Second, without international cooperation, carbon leakage and the adverse effects on competitiveness become quite serious. Anti-leakage measures can mitigate leakage and adverse effects on competitiveness to some extent. An 'optimality' analysis, based on environmental effectiveness, cost effectiveness, and political feasibility criteria reveals that the extra investment in energy efficiency and renewable scored relatively well on all criteria in contrast with the BCA measures which scored not so well, especially on the political feasibility criteria.

Table 7
Criteria and indicators of optimality.

Criterion	Indicator (1st level)	Indicator (2nd level)	Unit
Environmental effectiveness		Carbon leakage in 2050 (w.r.t. BAU)	%
		Global emissions in 2050 (w.r.t. BAU)	Mt
Cost-effectiveness	Static efficiency	CO_2-price in 2030	USD/tCO_2
	Dynamic efficiency	CO_2-price in 2050	USD/tCO_2
		Energy-intensity in 2050	toe/mln USD
Political feasibility	Competitiveness	ΔExport basic metals in 2050 (w.r.t. BAU)	%
		ΔExport manufactures in 2050 (w.r.t. BAU)	%
	Burden sharing ratio	$\Delta GDP_{EU}/\Delta GDP_{non\text{-}EU}$ in 2050 (w.r.t. BAU)	
	Rawls' justice	$\Delta GDP_{poorest\ region}$ in 2050 (w.r.t. BAU)	mln USD

Table 8
Quantitative assessment of optimality.

Criterion	Indicator	Unit	EU ETS	BCA_{bat}	BCA_{nobat}	EERW
Environmental effectiveness	Carbon leakage	%	49	48	42	30
	Global emissions	Mt	−973	−993	−1094	−1322
Cost effectiveness	CO_2-price 2030	USD/tCO_2	140	140	142	127
	CO_2-price	USD/tCO_2	309	309	312	289
	Energy intensity	toe/MUSD	28	28	29	30
Political feasibility	Exports basic metals	%	−24.3	−17.0	−10.3	−16.5
	Export manufactures	%	−5.5	−5.9	−5.6	−4.8
	Burden sharing		−1.92	−1.92	−2.08	−1.77
	Rawls' justice	mln USD	−3262	−2992	−4935	−2496

Source: our elaboration on GDynE results.

As a general conclusion, the best policy to mitigate adverse effects on carbon leakage and competitiveness is obviously to have an international agreement with broad cooperation. However, while for EU countries the achievement of global binding abatement targets would be more beneficial than the unilateral solution, the extended stagnation in international climate change negotiations suggests that the existence of many groups of countries with different and critical issues at stake has prevented the achievement of a binding global agreement.

However, in the event of a lack of international cooperation, the second-best policy option for the EU is to accelerate investments in energy efficiency and renewable energy, protecting the competitiveness of energy-intensive industries and enhancing the competitiveness of technology-advanced industries. This allows turning the costs of abatement policies into long term benefits thanks to dynamic efficiency obtained by stimulating investments in innovation activities financed through carbon tax revenues. These benefits could be rather greater in the case of a global climate solution, where dynamic efficiency gains through green innovation in energy might ensure increased competitiveness into international markets.

Findings discussed in this paper are obviously affected by several limitations, mainly driven by the necessity to adopt specific assumptions in the modelling exercise, that could be addressed in future research activities.

The first issue refers to the adoption of differently designed quantitative targets for selected regions, more coherent with the ongoing bargaining positions in the climate negotiations. This will help better acknowledging the causes behind the uncertainty in a decisive and compulsory climate regime and thus will allow designing new compensatory mechanisms enabling to escape the deadlock.

The second potential research line could be to investigate different model settings for the representation of the technological pathways in energy green energy technologies, including evolutionary trajectories in R&D returns to scale and adoption and diffusion paths, that should be carefully taken by empirical studies on this topic.

The third option could be given by the inclusion of an analytical treatment of the impact of incentives on the demand side, thus also representing the role of consumers and demand side policies on the green energy sustainability transition.

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Appendix I. Model specification of the EERW scenarios

Given the CO_2 abatement target and the associated level of carbon tax C_{TAX}, the total carbon tax revenue (CTR) from the amount of taxable emissions (CO_2) is given by:

$$CTR = C_{TAX}\ CO_2 \quad (1)$$

The amount of CTR directed to RD activities is defined as:

$$CTRD = \gamma\ CTR \quad (2)$$

where γ represents the exogenous percentage rate defined by policy makers.

The total amount of CTRD finances both energy efficiency and renewable energies technologies and also in this case the distribution of the overall funds between the two technological domains is exogenously given, as part of the policy options for the climate strategy. Accordingly:

$$RD_{EE} = \delta\ CTRD \quad (3)$$

$$RD_{RW} = (1-\delta)CTRD \quad (4)$$

where δ represents the share of RD directed towards input-augmenting technical change in energy efficiency.

RD efforts are then transformed into technical change outcomes according to a simple formulation:

$$tc_{EE} = r_{EE}\ RD_{EE} \quad (5)$$

$$tc_{RW} = r_{RW}\ RD_{RW} \quad (6)$$

where r_{EE} and r_{RW} are two reactivity parameters representing the elasticities of technical change with respect to RD efforts in energy efficiency and renewables, respectively, calculated on the basis of historical statistics.

Appendix II. Additional tables and figures from simulations

Table A1
Manufacturing value added changes w.r.t. BAU for EU27 (%).

Scenarios	2015	2020	2025	2030	2035	2040	2045	2050
GCTAX	0.03	0.34	0.62	1.24	1.88	2.78	3.17	4.07
GET	0.03	0.35	0.69	1.43	2.00	2.28	2.26	2.77
EU-ETS	0.02	−0.14	−0.30	−0.85	−1.62	−2.16	−2.49	−2.70
BCAbat	0.03	−0.13	−0.28	−0.76	−1.44	−1.90	−2.15	−2.28
BCAnobat	0.03	−0.11	−0.21	−0.54	−0.96	−1.13	−1.04	−0.87
EERW	0.01	−0.13	−0.25	−0.61	−1.08	−1.38	−1.54	−1.64

Source: our elaboration on GDynE results.

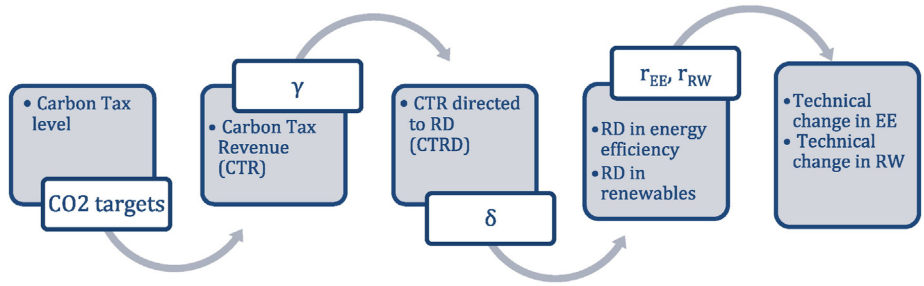


Fig. A1. Changes in exports in EU-ETS w.r.t. BAU for the rest of the world (non-EU27) (%). Source: our elaboration on GDynE results.

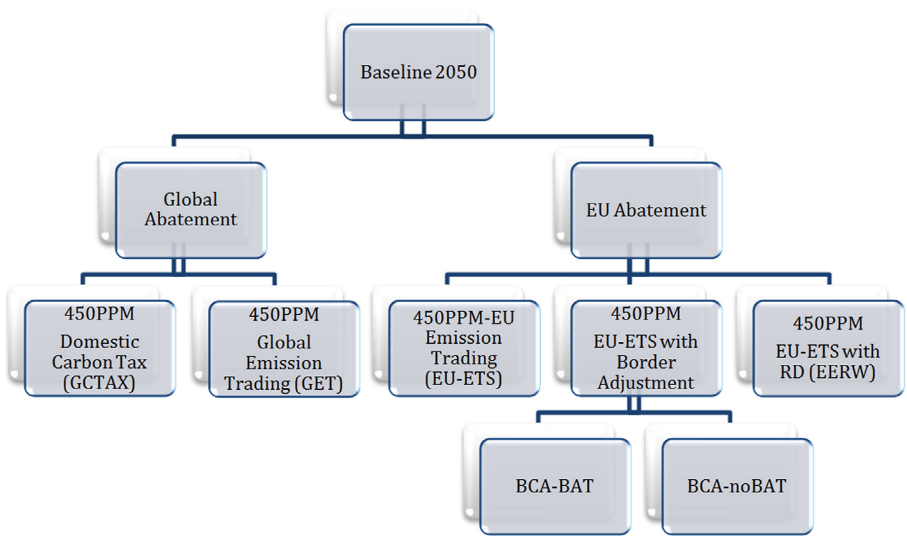
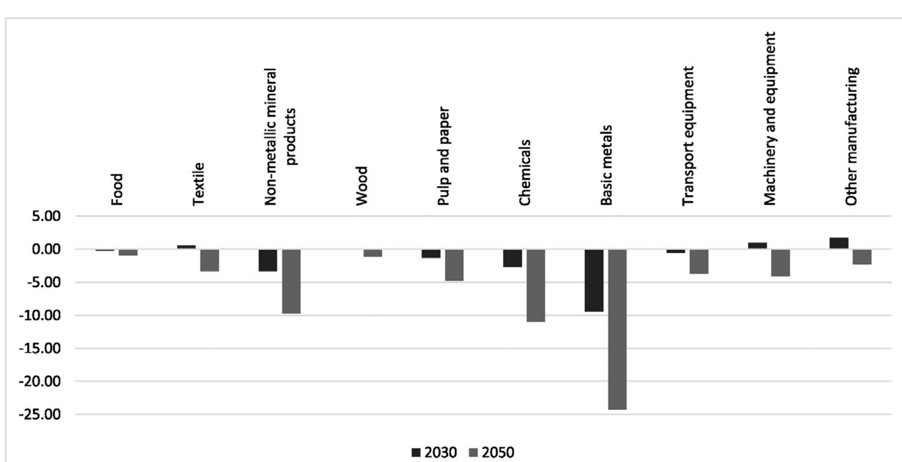
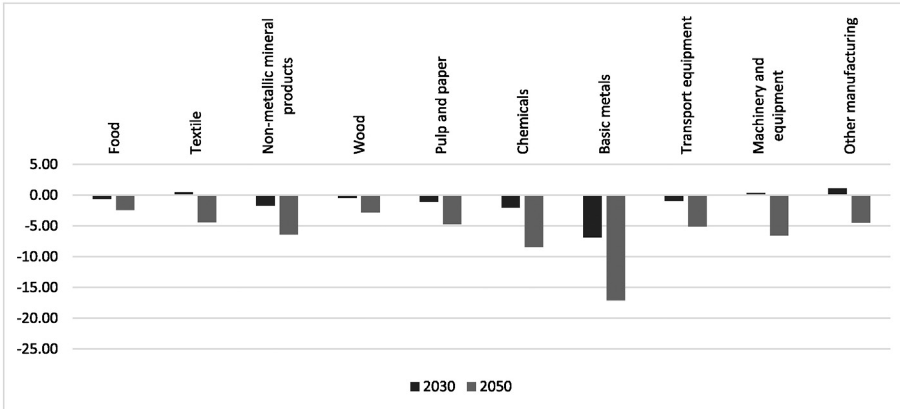


Fig. A2. Manufacturing value added composition in BAU for EU27 (%). Source: our elaboration on GDynE results.



Source: our elaboration on GDynE results.

Fig. A3. Changes in exports in BCAbat w.r.t. BAU for the rest of the world (non-EU27) (%). Source: our elaboration on GDynE results.



Source: our elaboration on GDynE results.

Fig. A4. Changes in exports in EERW w.r.t. BAU for the rest of the world (non-EU27) (%). Source: our elaboration on GDynE results.

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