CECILIA 2050

OPTIMAL EU CLIMATE POLICY

Choosing Efficient Combinations of Policy Instruments for Low-carbon development and Innovation to Achieve Europe's 2050 climate targets

The sun also rises: Policy instruments to mitigate the adverse effects on competitiveness and leakage

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Table of Contents

List of Tables

List of Figures

LIST OF ABBREVIATIONS

BCA	Border carbon adjustment (import tariff on ‘embedded’ carbon)
CDM	Clean Development Mechanism
CGE	Computable General Equilibrium (model)
CEPII	Centre de recherche français dans le domaine de l'économie internationale
CO_2	Carbon dioxide

EFTA	European Free Trade Association (Iceland, Liechtenstein, Norway, Switzerland)
EIA	U.S. Energy Information Administration
EITE	Energy Intensive and Trade Exposed sectors
ER	Environmental Regulation
EU	European Union
EU ETS	EU Enmissions Trading System
EV	Equivalend Variation (welfare measure)
FMA	First Mover Advantage
GDynE	Dynamic GTAP-E model
GDP	Gross Domestic Product
GW	Gigawatt
GHG	Greenhouse gas
GWEC	Global Wind Energy Council
HS	Harmonised System (tariff line codes)
IAM	Integrated Assessment Model
IEA	International Energy Agency
IPPC	Intergovernmental Panel on Climate Change
GCAM	Global Change Assessment Model
GDyn	Dynamic GTAP model
GTAP	Global Trade Analysis Project (model)
GTAP-E	Global Trade Analysis Project (model) with Energy and Environment
IIASA	International Institute for Applied Systems Analysis
ICTSD	International Centre for Trade and Sustainable Development
Mt	Mega tonnes (million tonnes)
MUSD	Million United States' Dollars
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Squares
PH	Porter Hypothesis
ppm	parts pro million (measure of concentration)
PPML	Poisson Pseudo-Maximum Likelihood
PV	Photovoltaic
RCP	Representative Concentration Pathway (GHG emission scenario)
RD	Research & Development
SAM	Social Accounting Matrix
tCO_2	Tonnes of carbon dioxide (CO_2)
toe	tonnes of oil equivalent (measure of energy content)
UNCTAD	United Nations Conference on Trade and Development
USD	United States' Dollar

1 Executive summary

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. The unilateral imposition of stringent climate policies may produce distortive effects in terms of displacement and re-allocation of carbon intensive production processes to unregulated countries where no climate policies are in force, a phenomenon also known as carbon leakage. Using a 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 scenarios range from a global effort where all countries participate to reach the necessary emissions reductions in 2050 that are compatible with the 450ppm GHG concentration target, to a EU alone scenario, where only the EU achieves these necessary reductions (EU-ETS). For the latter scenario, three different anti-leakage measures are modelled, two measures implementing border carbon adjustments, where 'embedded' carbon in products is based on best available technology and actual foreign emissions (BCA_{bat} and BCA_{nobat} respectively), and one focussing on investing in energy efficiency and renewable energy through a 10% levy on carbon tax revenue (EERW).

The results show two interesting things. First, if all countries cooperate, there is obviously no carbon leakage and the economic effects for the EU are overall positive. There are small 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 planning 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, distinguishing the criteria environmental effectiveness, cost-effectiveness, and political feasibility reveal that the extra investment in energy efficiency and renewable scores relatively well on all criteria in contrast to the border carbon adjustment measures that score not so well, especially on the political feasibility criteria.

Apart from protecting the competitiveness of 'sunset' industries, like the energy-intensive industries (in the words of Hallegatte et al., 2013), the investment option may also enhance the international competitiveness of 'sunrise' industries such as the renewable energy technology industry. Our econometric model shows evidence of first mover advantage, sustained in the wind industry and at least for four years in the solar PV industry. These results are in line with other non-econometric studies.

Our conclusions are in line with the qualitative assessment of policy options to mitigate carbon leakage and adverse effects on competitiveness that was carried out in parallel to our research and that are reported in Deliverable 5.3a. The best policy to mitigate adverse effects on carbon leakage and competitiveness is to have an international agreement with broad cooperation. In the event of a lack of international cooperation, the second-best policy for the EU is to accelerate investments in energy efficiency and renewable energy, protecting the competitiveness of 'sunset' industries and enhancing the competitiveness of 'sunrise' industries.

2 Introduction

2.1 Background

The European Union (EU) has developed a strategy to mitigate climate change by cutting GHGs 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.

The unilateral imposition of stringent climate policies may produce distortive effects in terms of displacement and re-allocation of carbon intensive production processes to unregulated countries where no climate policies are in force, a phenomenon also known as carbon leakage. As was reported in Deliverable D2.8 of CECILIA2050 project (Kuik et al. 2014), empirical studies have as yet not revealed any evidence of carbon leakage and loss of competitiveness in sectors considered at risk of carbon leakage, such as cement, aluminium, and iron and steel (Reinaud, 2008; Ellerman et al., 2010; Sartor, 2012; Quirion, 2011; Branger and Quirion, 2013). A number of reasons for this lack of evidence was 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 ETS has been in force, and lastly because of the time lags before 'investment leakage' (a change in production capacities) materialises and becomes visible. For the case of the European iron and steel sector, another Deliverable of the CECILIA2050 project suggested that investment leakage could become substantial in the future, if left unmitigated (Kuik, 2015). Hence, it is natural that there is interest in policy instruments to mitigate adverse effects on competitiveness and carbon leakage.

In Deliverable 5.3a of the CECILIA2050 project, Turcea and Kalfagianni (2015) qualitatively assess a number of policy instruments to address competitiveness and carbon leakage, with a focus on the European steel sector. In agreement with the 'optimality' framework of CECILIA2050 (Görlach, 2013), they assess the policy instruments on environmental effectiveness, dynamic efficiency, and legal and political feasibility. The current policy instruments to avoid carbon leakage are 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 on their dynamic efficiency. 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. The legal feasibility of the policy instruments is high, although there are legal difficulties regarding the classification of waste gases from the steel industry, that complicate the benchmarking rules in that industry (Turcea and Kalfagianni, 2015). The evidence on the political feasibility is mixed. On the one hand, both (EU) policy-makers and the industry (e.g. Eurofer) consider free allocation and electricity cost compensation as effective and practical (Turcea and Kalfagianni, 2015, p. 55). On the other hand, there is public concern on the 'windfall profits' that free allowances generate in the sectors concerned. The design of the current policy instruments could be improved by putting a greater emphasis on conditionality and incentives for innovation.

Border carbon adjustments (BCA) are commonly regarded as effective in the literature (e.g., Böhringer et al., 2012), and they are characterised in the EU ETS Directive's preamble as an "effective carbon equalisation system" (EC, 2009, par. 25) and are 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] The dynamic efficiency of the BCA instrument is uncertain and would depend 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, for example with the international trade law of the World Trade Organization (WTO), needs further investigation. Its political feasibility is ambiguous. The steel sector is not particularly enthusiastic. The European association of steel producers, Eurofer, points out some of the technical obstacles mostly related to the long value chain of the steel sector: "Imposing a CO_2 tax on imports of crude steel would inevitably displace the problem to the next step of the value chain, namely hot rolled products, and so on down to fabricated products in which the amount of steel, its origin and carbon footprint would be almost impossible to trace back" (Eurofer, 2014, p. 58). Moreover, many observers do not regard border measures as a constructive means to incentivise 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).

A final policy instrument that is assessed by Turcea and Kalfagianni (2015) is direct support for European industrial innovation with the help of revenues from the sale of emissions allowances. The policy instrument is effective in the sense that it can prevent 'innovation investment leakage', i.e. preventing internationally operating companies to shift research, development and innovation (RDI) investments and market launch abroad. From a dynamic efficiency perspective, the approach would encourage industrial sector's successful transition to low carbon production, reduce costs to meet long term objectives and create technological advantage (EC, 2014c). There is political support for this policy instrument. The European Commission (EC, 2014b) as well as influential think-tanks such as the Centre for European Policy Studies (Nunez and Katarivas, 2014) and Climate Strategies (Neuhoff et al., 2014) embrace the approach. Industry might even accept higher carbon prices if revenues were recycled in this way (Turcea and Kalfagianni, 2015). In terms of legal feasibility, EU state aid rules need to be adjusted. Subsidies for innovation should be ensured not to be a distortion of internal EU competition. Compatibility with international trade law (WTO) should be further investigated.

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

In this Deliverable, we complement the essentially qualitative assessment of Turcea and Kalfagianni (2015) with a quantitative assessment. We follow the 'optimality' framework of CECILIA2050 project and try to quantify a number of indicators of environmental effectiveness, (dynamic) efficiency, and political feasibility with the help of CGE simulations of the effects of anti-leakage policy instruments on global emissions and international trade and competitiveness against the baseline of the common CECILIA2050 global scenarios over the period 2010-2050 (Zelljadt, 2014).

We add to the analysis an econometric estimation of the effect of direct support for renewable energy on 'first mover advantages' of renewable energy technology manufacturers on the global market place. Here we aim to assess whether investing in industrial innovation would not only protect, in the words of Hallegate et al. (2013), Europe's 'sunset' industries (energy-intensive industries) but also support its 'sunrise' industries (renewable energy). And we find, indeed, that the sun also rises in Europe.

2.2 Statement of purpose and contents of the report

This Deliverable report on research carried out for sub-task 5.2.2 and for certain elements of task 5.3 of the Description of Work of the EU FP7 project CECILIA2050. The methods used for the research in this Deliverable are of a quantitative nature, including dynamic CGE modelling and the estimation of an econometric model.

Following this introduction, the report is structured as follows: Chapter 3 reviews the economic modelling literature on anti-leakage policy instruments. Chapter 4 presents our dynamic CGE model and describes our main assumptions and data. Chapter 5 describes the baseline and the policy scenarios. Chapter 6 reports the simulation results. Chapter 7 presents our assessment of the anti-leakage policy options in terms of the CECILIA2050's optimality criteria. Chapter 8 presents our econometric assessment of the effect of renewable energy support policies on first mover advantages of renewable energy manufacturers on the global market place. Chapter 9 concludes. The following overview describes how the tasks outlined in the project's Description of Work have been implemented.

Sub-task 5.2.2 outline in the Description of Work	How the tasks have been implemented
Sub-task 5.2.2 will analyse from a political and legal perspective a range of options to address impacts on the competitiveness of European industries and leakage risks. This analysis will include both options that are already discussed in the policy domain, and novel options that will arise from the CECILIA2050 work. The team of researchers from VUA-IVM and Ecologic will study in this area both options that might be related to the design of existing policy instruments (including exemptions, free allocation under ETS, or inclusion of third-country operators in the scope of EU policies), and entirely new instruments and institutions, such as border tax adjustments. For all options, important considerations to be studied will be their effectiveness	Sub-task 5.2.2 has been implemented in two Deliverables. Deliverable 5.3a presents a qualitative analyses of the 'optimality' of a range of options, including current options (free allocation and compensation for electricity costs), potential improvement in the design of these options, and new instruments in the form of border tax adjustment and direct support for European industrial innovation with the help of revenues from the sale of emissions allowances. This deliverable includes an assessment of the political and legal feasibility of the options. This Deliverable, 5.3b, complements the analysis of 5.3a by a quantitative analysis with simulation of the GDynE model (the dynamic counterpart of the GTAP-E

in addressing the leakage risk, domestic political consequences, the legality under world trade law, and broader political consequences for the EU, e.g. in terms of transatlantic and North-South relations.

Elements of task 5.3 outline in the Description of Work

Using integrated assessment models, this task will look at the global effects of EU policies, in the context of the scenarios described in Task 5.1, on countries outside the EU. Possible pathways for such effects include: ….. (c) spill-over impacts of low carbon technology developments resulting from EU policies, (d) distributive and output impacts of measures such as border tax adjustment on the exporting countries.

model). The quantitative analysis focuses on effectiveness, dynamic efficiency, and political feasibility of the options, paying particular attention to transatlantic and North-South relations.

Deliverable 5.3b also implements elements of task 5.3, particularly pathways (c) spill-over impacts of low carbon technology developments resulting from EU policies (see Chapter 8), and (d) distributive and output impacts of measures such as border tax adjustment on the exporting countries (see Chapter 6).

3 Review of economic (modelling) 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 liberalisation 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, especially in the fields of international trade, agriculture and land use and climate change policies. Whatever the approach chosen, and depending on the issue under investigation, a particular aspect to take into account is the role of behavioural parameters that determine the price-responsiveness of economic agents and the effects of the modelled policy scenarios.

In particular, computable general equilibrium (CGE) models are analytical representations of the interconnected exchanges taking place among 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 and intertemporal 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 selecting alternative scenarios of climate policies considering different policy measures and interventions, in a global dimension or across regions and economic sectors.

There are several alternative policy options to mitigate climate change and its related negative externalities, in both economic and environmental terms. In particular, the EU has established a market-based mechanism (the EU ETS) as the core mean to achieve the targeted GHGs emissions reduction according to the Kyoto Protocol. However, one of the risks of imposing unilateral climate policies (in a fragmented international approach) is to generate distortive effects among particularly vulnerable economic sectors or across regions (Borghesi, 2011). 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 (for example in term of production costs or competitiveness). This could also lead to variations in terms of comparative advantages, especially for energy intensive and trade exposed (EITE) sectors. In fact, in an interconnected global market, carbon leakage may occur, according to which a unilateral policy may result in a shift in the production locations with an increase of carbon intensive production in non-regulated countries, partially annulling the GHGs reduction achieved in abating countries (Copeland and Taylor, 2004). In the CECILIA2050 project, carbon leakage has been discussed in several Deliverables (Branger and Quirion, 2013; Kuik et al., 2014; Kuik, 2015). The main conclusion is that empirical studies have as yet not revealed any evidence of carbon leakage and loss of competitiveness, but that it cannot be excluded that it will happen in the future, especially through the channel of 'investment leakage'.

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 border carbon adjustment 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 border carbon adjustment is 14% (5%-25%) and 6% with border carbon adjustment (-5%-15%). Holding all other parameters constant, border carbon adjustment reduces carbon leakage by 6%-points. In the meta-analysis, the effectiveness of border carbon adjustment 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 border adjustments are based on domestic or foreign CO_2-intensities.

Fischer and Fox (2012) compare three variants of border carbon adjustment (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 border carbon adjustment, 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 border carbon adjustment 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) use a CGE model to compare three policy instruments to mitigate adverse effects on competitiveness and leakage: border carbon adjustment, output-based allocation, and exemptions for EITE industries. They compare these instruments for different coalitions of abating countries and for 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% to 21% at abatement rates of 10% to 30% relative to the benchmark emission levels of the coalition countries. Full border carbon adjustment 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 the simulations of Böhringer et al. (2012), output-based allocation and exemptions are less effective because they do not offset the comparative disadvantage of EITE industries as much as the border carbon adjustments, partly because they do not compensate for increased electricity costs. In terms of global efficiency, border carbon adjustment is also best. It achieves this economic superiority at an equity cost, however. In contrast to output-based allocation and exemptions, border carbon adjustment shifts a large part of the carbon abatement burden to non-coalition countries. Border carbon adjustments 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, S209).

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 (Caron, 2012; Alexeeva-Talebi et al., 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), trade elasticities (Branger and Quirion, 2014), and the underlying theory of international trade (Balistreri and Rutherford, 2012), to name but a few.

For the long term perspective, there are a number of assessment 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 Research and Development (RD) investments and new technology options are of crucial importance.

Given market failures, environmental externalities and additional goals next to GHG emissions abatement, additional and (partly) overlapping measures could be justified. Hence, a combination of policies to mitigate concentration of GHG emissions and, at the same time, to promote RD activities, support technology or improve energy security may be appropriate (Goulder, 2013; Fischer and Newell, 2008). For example, Fischer and Newell (2008) conclude that an optimal portfolio of climate measures (as emissions trading system, performance standard, fossil power tax, green quota and subsidies for renewables energy production and RD) may allow reaching the abatement targets at lower costs than any single policy alone would imply. Furthermore, in 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 on the possible consequences that overlapping regulation may have, in term of adverse effects on efficiency and effectiveness, is rich and complex. It can be optimal with respect 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 it is a broad concept that has to account for a high level of uncertainty (technological, organizational, social) in a dynamic perspective. Görlach (2013) tries to answer to the questions of what 'optimal' in this case means and summarises three criteria to assess the performance of policies: 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 of the selected tools not being able to deliver the awaited results (political, legal and administrative feasibility).

As emphasised by Flanagan et al. (2011), the tools adopted in a single policy setting should be designed in order to respect at least three characteristics: i) the overall policy mix needs to be comprehensive, ensuring the extensiveness and exhaustiveness of its elements (variety); ii) instruments should be synergic, in order to maximize and exploit potential complementary effects among different policy elements (consistency); iii) there must be coherence among the different in-force policy tools where the objective of each instrument should be in line with the others (coherence).

The quality of the policy mix should be also considered from a geographic perspective, where a strong international coordination is crucial. Finally, different conclusions may arise from differences in level of aggregation with respect to the individual measure or the mitigation policy mix, in the general context of public policy and considering the spatial level, as the differences in target among Members States or the coexistence of European-wide and national regulation.

Moreover, in the complexity of the policy mix, when reasoning about the coherence between objectives and instruments, it also has to 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. Finally, further questions concern the optimality of the policy mix in a dynamic rather than a static context and investigation about whether significant differences exist, depending on the timing of introduction of mitigation measures and of the phases of technological innovation and diffusion. In this respect, when accounting for the possibility of overlapping regulation in a long time horizon, it can occur that a well-designed policy mix, other than mitigate climate change, can generate positive spillover effects on innovation and technology paths (Costantini et al., 2014).

4 Methodology

4.1 An overview of the GDynE model

The recursive-dynamic version (GDynE) of the GTAP (Global Trade Analysis Project) model, as described in Golub (2013), builds on the comparatively-static energy version of the GTAP model: GTAP-E (Burniaux and Truong, 2002; McDougall and Golub, 2007) in combination with the dynamic GDyn model (Ianchovichina and McDougall, 2000).

The GTAP model has a so-called ‘nested’ Constant Elasticity of Substitution (CES) production function, where inputs into production are combined in different ‘nests’. In the standard GTAP model, primary production factors (labour, capital, land) are first combined into a value added nest, and this value added nest is then combined with an aggregate intermediate input nest. In model simulations the combination of the inputs depends on their relative prices, given the elasticity of substitution in the specific nest. In the comparatively-static GTAP-E model an energy-capital nest is added to the production function. First, energy is combined with capital and then the energy-capital composite is combined with labour and land in the value added nest. Energy itself is composite good that is a combination of electricity and non-electricity, where non-electricity is a combination of coal and non-coal, and non-coal is comprised of natural gas, crude oil, and oil products. Energy demand is explicitly specified and there is substitution in both the factors and fuels mixes. Data on CO_2 emissions are introduced through social account matrices (SAM) and are region and sector specific. The model allows for the simulation of market-based instruments, such as carbon taxes and emission trading.

GDyn is a recursive-dynamic model that preserves the standard features of the GTAP and enhances the investment side of the model, allowing a better representation of long-term policies. It introduces international capital mobility. Regional capital stocks include capital stock physically located within the region as well as financial assets from abroad, and there is a Global Trust acting as intermediary for all the international investment. Physical capital is owned by firms and households hold financial assets directly in local firms and, through the Global Trust, they hold equity of foreign firms. Households own land and natural resources, which they lease to firms. The Global Trust holds equity in firms in all regions.

Time is an explicit variable in the model equations and a dynamic representation of specific developments in the global economy can be represented. In particular, in each period the financial intermediary distributes the global funds between regions according to investors’ expectations. Hence, capital progressively moves to regions with high (expected) rates of return where the gap between expected and actual rates of return falls period after period. This is particularly relevant given that both the energy efficiency and the renewable targets imply the introduction of a specific form of technical change that is transmitted by capital investment. A further interesting line of research that could benefit from this dynamic framework can focus on the coherence between the targets of the different EU climate policies (EU2020, EU2030, EU Roadmap to 2050).

Technological change might be modelled alternatively as exogenous or endogenous. In the case of endogenous technical change it is necessary to develop specific modules (as in the case of energy efficiency or renewable energies) in order to simulate also the financial mechanisms of RD activities. In the case of exogenous technical change, it could be modelled only in terms of the production function in industrial sectors as general input or output augmenting technical change, without the possibility to disentangle invention, innovation and diffusion activities.

To conclude, the GDynE model merges the dynamic properties of GDyn with the detailed representation of the energy system from GTAP-E. Therefore, it is appropriate for long-term projections, given the properties of the dynamic model, and it is specifically suited for energy and environmental policy analysis, with special attention to energy substitution in production and consumption (Golub, 2013). It provides time paths for both CO_2 emissions and the global economy, and allows capturing the impacts of policies in term of abatement costs and distributive effects between regions and sectors. It also allows giving a complete assessment of the economic impacts of climate policy options, with a detailed analysis on the effects in terms of changes in bilateral relationships, with particular focus on those between EU and the rest of the world.

The GDynE model adopted here uses the last version of the GTAP-Database (GTAP-Database 8.1, updated to 2007), together with the latest version of the additional GTAP-Energy data on CO_2 emissions.

4.2 Model improvements

The GDynE model adopted for this assessment 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 Border Carbon Adjustment (BCA) according to the modelling approach developed by Antimiani et al. (2013) for a static setting. Goods imported by EU from the rest of the world that are not already subject to carbon taxation (thus excluding energy commodities) are taxed in the final demand equation for the imported good as follows:

$$Y_1 = \eta_Y p_Y - \tau_{Y1} \quad (1)$$

where Y_1 is the demand for the imported good, which corresponds 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 any CBA is generally defined as:

$$\tau_{Y1} = \mathrm{f}(p_Y, \tau_C) \quad (2)$$

where τ_C is the ad valorem equivalent of a carbon tax in level, as a function of the specific carbon tax or carbon allowance price (CTAX) and the carbon content of the taxed sector (given by the ratio of CO_2 emissions to value added). Depending on which carbon content is adopted (based on a BAT approach 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 Antimiani et al. (2014). In this case, we assume that part of the revenue from carbon taxation or the revenue of the sale of allowances, directly finances RD activities aiming to promote improvements in energy efficiency and increases in the productivity of renewables. We assume that a portion of total carbon tax revenue (CTR) is directed towards financing RD activities in energy efficiency, in a input-augmenting technical change manner, and towards investments to increase 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 (measured in equivalent variation (EV)) of the regional household.

The share to be taken from the CTR, 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. It has to be noticed that in this work, the x% of CTR is not uniformly applied to all regions because this mechanism is active only for the EU, while in all the 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 nominal 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.

In mathematical terms, total revenue from CO_2 taxation is computed as:

$$CTR = \mathrm{CO}_2 \cdot CTAX \quad (3)$$

where CTR is the revenue in EU resulting from a tax on a target level for CO_2 emissions and CTAX is the domestic level of carbon tax. Finally, CO_2 is the amount of taxable emissions in the EU.

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

$$CTRD = \alpha \cdot CTR \quad (4)$$

where α is the exogenous x% defined by policy makers.

The amount of CTRD used for financing RD activities and contributing to domestic welfare must be detracted from the EV as follows:

$$EVnew = EV - CTRD \tag{5}$$

Having introduced the RD financing mechanism only in the EU, the value of the EV will be unvaried in all other countries except for the EU, which is the only region where CTRD has a value different from 0. Indeed, α will be equal to the x% defined by policy makers in the EU and zero for all other countries.

The total amount of CTRD can be used for improving technical change in energy efficiency ($CTRD_{EE}$) and for improving technical change in renewable energies ($CTRD_{RW}$). The choice of the share of total CTRD to be directed towards energy efficiency or renewables is exogenously given, as part of the 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 during last ten years (2003-2012) 60% is directed towards energy efficiency (β) and 40% to renewable energies (γ). Accordingly:

$$CTRD_{EE} = \beta \cdot CTRD \tag{6}$$

$$CTRD_{RW} = \gamma \cdot CTRD \tag{7}$$

where $(\beta + \gamma) = 1$.

The relationship between technical change in energy efficiency and $CTRD_{EE}$ is modelled in a very simple way. An elasticity parameter, $R_{EE}(i, j)$, is taken in order to transform RD efforts (Mln USD) into technical progress in energy efficiency. We adopted a differentiated value for R_{EE} for energy inputs (i) that influence produced commodities (j) in a uniform way. Such an approach represents a standard modelling choice when sectoral empirical estimates are not given.

The final equation for translating RD efforts into technical progress in energy efficiency is thus given by:

$$t_{EE}(i,j) = R_{EE}(i,j) \cdot CTRD_{EE} \tag{8}$$

where $t_{EE}(i, j)$ is the technical energy efficiency gain in input i as a result of funds allocated to RD in energy efficiency that uniformly influence productivity in all sectors j. In this paper, we have assumed that all RD efforts are directed towards improvements in energy efficiency in the production function, considering that the diffusion path of technologies is not affected by technical barriers.

The elasticity parameter has been calibrated according to latest reports by ENERDATA considering the sectoral efficiency gain (EE gains) and the public RD investment in energy efficiency (RD_{EE}) during the last decade, as an average value between industry, residential sector and transport. In mathematical terms:

$$R_{EE}(j,r) = EE\ gains / RD_{EE,t-1} \quad (9)$$

It is worth noting that, by working in a dynamic setting, this is a quite conservative assumption, since it could be the case that in the next decade efficiency gains might change across final uses and technologies. In order to better shape such a dynamic pattern, it will be necessary to link the macro CGE model to bottom-up energy models, which is out of the scope of the current work, but may be considered for further work.

The second technology option is to use CTRD to finance the increasing production of renewable energy services. In this case, a share of CTRD devoted to technology options is directed toward financing the technical change in renewable energies production. Here, from a pure modelling approach, we introduce an improving technical change measure in the electricity sector, given by $el_{RW}(j)$ (we ignore biofuels and other non-electricity renewable sources):

$$el_{RW}(j) = [R_{RW}(j)] \cdot CTRD_{RW} \quad (10)$$

where $R_{RW}(j)$ represents the reactivity of the electricity sector to RD investments. The reactivity parameter is calibrated with regard to the last ten years of investment in RD activities in renewable energies (RD_{RW}) and the corresponding increase in installed capacity in renewable electricity in OECD countries, as the numerator in the following formula (IEA energy balance dataset available online):

$$R_{RW}(j,r) = \frac{(C_t - C_{t-1})}{C_{t-1}} / RD_{RW\ t-1} \quad (11)$$

5 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 the 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 distinguish 20 industries with special attention to manufacturing industry, in fact 10 out of them are manufacturing sub-sectors (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, other than Agriculture, Transport (also distinguishing Water and Air transport) and Services, energy commodities have also been 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 ILO (for aggregate labour) with those provided by the GTAP Macro projections (where skilled and unskilled labour forces are disentangled).

With respect to 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.[2]

In the reference case, with current policies only, CO_2 emissions are given as an endogenous output of the model. In fact, we projected the global economy from 2007 to 2010, with CO_2 emissions being exogenously in order to replicate the current distribution among regions based on current data. To this purpose, the calibration criteria are built on the continuation of existing economic and technological trends, including short term constraints on the development of oil and gas production and moderate climate policies.

When considering the global policy options (emission trading, carbon tax, carbon tariff, RD efforts in energy efficiency and renewable energies in electricity production), these are all based on a CO_2 pathway that respects the 450PPM scenario developed by IEA (and RCP 2.6 by IPCC).

The emission target settled for the EU in the 450PPM pathway is also consistent with the 2030 target recently adopted by the European Parliament, consisting in a reduction of CO_2 emissions of 40% by 2030 with respect to 1990 levels. This means that, by reaching the target to 2030 of cutting emission by 40% with respect to 1990 level, the EU is on track with respect to the 450PPM objective for 2050.

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, which allows all countries to trade emissions until an equilibrium price is

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

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, which is equivalent to the permit price level if EU countries are singled out and the whole economy is involved into 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.[3]

The third policy option includes a Border Carbon Adjustment (BCA) based on the carbon content of traded goods, only accounting for the direct emissions therefore excluding indirect emissions associated to the production process of all intermediates. In order to quantify the embedded carbon from non-abating countries production, we consider two alternatives approaches, based on the importer or exporter carbon content of traded commodities. In the first case, we apply a best available technology (BAT) approach in the importing country. In this case, 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.

Then we 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 by 27% in 2030 with respect to a current policy scenario. With respect to the latter, and considering the specific GDynE model features, we have modelled only a part of the EU2030 strategy, namely the share of 40% of electricity produced by renewable sources by 2030 (EC, 2014c), 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 necessary to respect the 450ppm concentration target for the EU CO2 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 at a global emissions trading system (GET);

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

4. The 450PPM target where only EU reduces emissions with a domestic market-based policy based on ETS (EU-ETS);
5. The 450PPM target where only 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 (BCA_{bat})
6. The 450PPM target where only 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 (BCA_{nobat})
7. The 450PPM target where only 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 respect by 2030 the EU2030 target of 27% in energy efficiency and 40% in renewable electricity (EERW).

6 Results

The CO_2 emissions pathways in the seven scenarios here adopted are described in Table 1. The emissions trend in BAU is consistent with baseline scenarios provided by main international organization as IEA and IPCC, as well as calibrated with the other models used in CECILIA2050 project. 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 aiming at reaching 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 compatible with a 450PPM scenario.

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

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 respect to 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, reaching 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 to an international emission trading system, it is confirmed that a global agreement with permit trading is more cost-effective. 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, it becomes increasingly costly to reach the climate targets. 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 higher than the price in EU-ETS.

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

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 (BCA_{bat} and BCA_{nobat}). 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 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 reducing the carbon leakage rate only by 1%-point in the case of a BAT approach and by 6%-points by 2050 when the second carbon content option is taken.

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

By 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. The amount of RD investments gathered in this scenario is described in Table 4.

The distribution between energy efficiency and renewable energy technological options is here taken as exogenously given, and it is fixed with respect to the current level. Future research is needed to find a dynamically optimal distribution between the options.

As a general remark, it is worth mentioning that by adopting a fixed 10% levy of total carbon tax revenue, the amount of RD necessary 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 to the actual value of RD investments in 2010, thus suggesting that the carbon tax revenues can indeed boost RD in this direction.

Table 4 RD flows in EU27 with 10% CTR levy (Mln USD)

Scenario: EERW	2015	2020	2025	2030	2035	2040	2045	2050
ENERGY EFFICIENCY	2,623	4,489	11,514	18,079	18,945	19,345	20,254	19,325
RENEWABLE ENERGY	1,749	2,993	7,676	12,052	12,630	12,897	13,503	12,883

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 an increase of 30% of energy efficiency by 2030 with respect to a BAU case, is 60.44 toe of energy consumption for each million USD of GDP at the EU level (Table 5).

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 not negligible rebound effect on energy prices, which might be explained by the behaviour of energy markets in a unilateral climate policy.

Table 5 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

The reduction in energy demand by the EU does not influence the 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 with respect to the EU-ETS policy option. Given the rigidity of energy demand, this directly brings an increase in energy consumption with respect to 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 6). When trade policy measures complement the emissions mitigation policy, the EU faces a slight increase in GDP losses with respect to the ETS case. This clearly reveals that the adoption of carbon tariffs cannot help reducing the cost of combating climate change and might 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 necessary 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.

Table 6 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

More generally, by comparing scenarios with a unilateral EU climate policy with those scenarios representing a global abatement strategy, the GDP losses for 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. This is explained by the expected dynamics of technology development, combined with the relative economic structure and the energy mix of the EU in comparison to the rest of the world. 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 might explain the negotiations deadlock due to those countries that will face the major part of the climate burden. Bu 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 output and export values of the manufacturing sector (Tables 7 and 8).

Table 7 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

Figures obtained for export flows in the manufacturing sector at the aggregate level are particularly interesting. Losses for EU industries in terms of international competitiveness on the international markets are high also in the case of a global agreement. If the targets are achieved by implementing an international permits scheme such losses appear to be reduced.

If a unilateral EU climate strategy is adopted by implementing an ETS system, by 2040 export flows face a strong reduction with respect to BAU and higher than in the other global deal cases. Protective measures based on BCA cannot ensure full protection for European industries. On the contrary, they might 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 should rely on trade measures, only by implementing export subsidies as a form of full adjustment would it be feasible to restore a level playing field, but such measures are extremely difficult to get accepted in the multilateral trade agreement context.

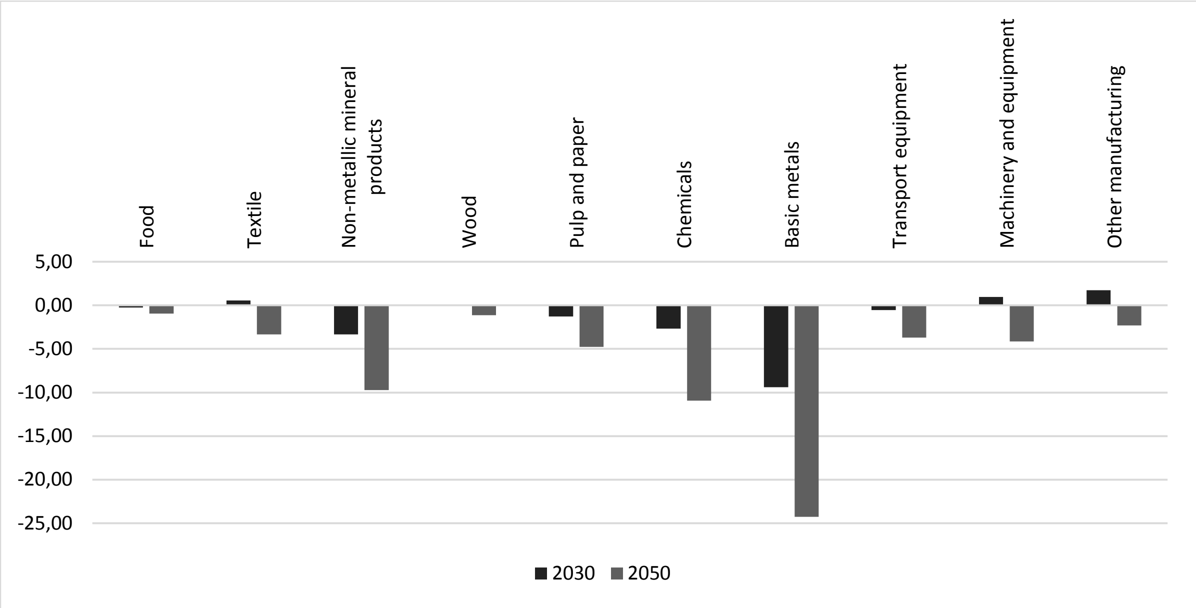
By contrast, when RD efforts in more efficient technologies and alternative energy sources are exploited, by 2035 export flow losses start to decrease with respect to the other unilateral policy mix strategies.

Energy-intensive sectors are most adversely affected by emissions reduction achieved by a unilateral EU-ETS policy. In Figure 1 we report changes in export flows in the case of a pure ETS policy with respect to the baseline scenario for manufacturing sectors for the periods 2030 and 2050.

Table 8 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

Figure 1 Changes in export flows in EU-ETS w.r.t. BAU for EU27 (%)



For the sake of simplicity we report export changes trends only for two periods, in order to trace some first results referring to the final dates of the EU2030 policy and the 450PPM target. The basic metal sector (which includes iron and steel industries) faces a negative change in export flows with respect 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 as machinery and equipment would 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 turns 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-metalic minerals (including cement and clinkers) from the rest of the world also declines in the long term (Figure 2). 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 (Figure 3), 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 (which is the only feasible in terms of WTO compatibility) 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 (Figure 4), 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 those technologically advanced sectors which constitute the engine of economic growth for Europe. This might well explain why GDP losses associated with such policy mix strategies are even larger than in the pure mitigation policy approach as in EU-ETS scenario.

Figure 2 Changes in export flows in EU-ETS w.r.t. BAU for the rest of the world (non-EU27) (%)

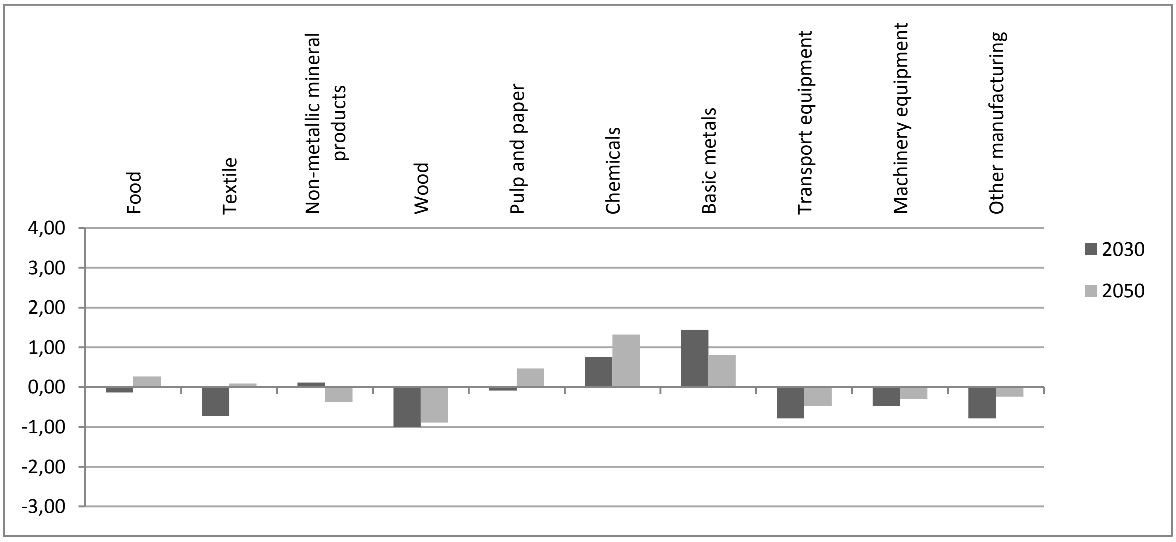
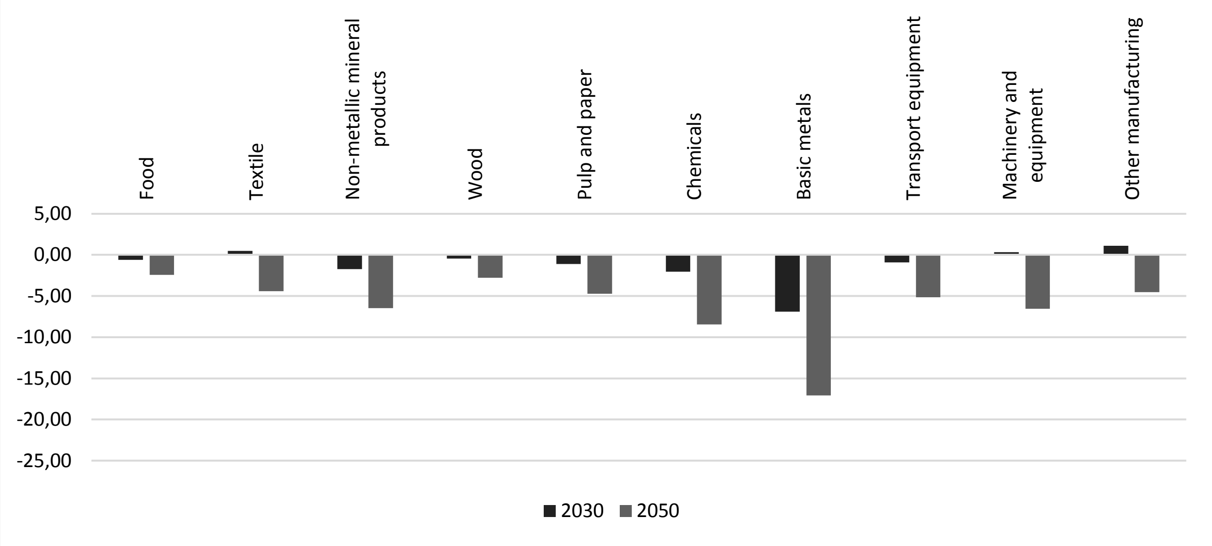
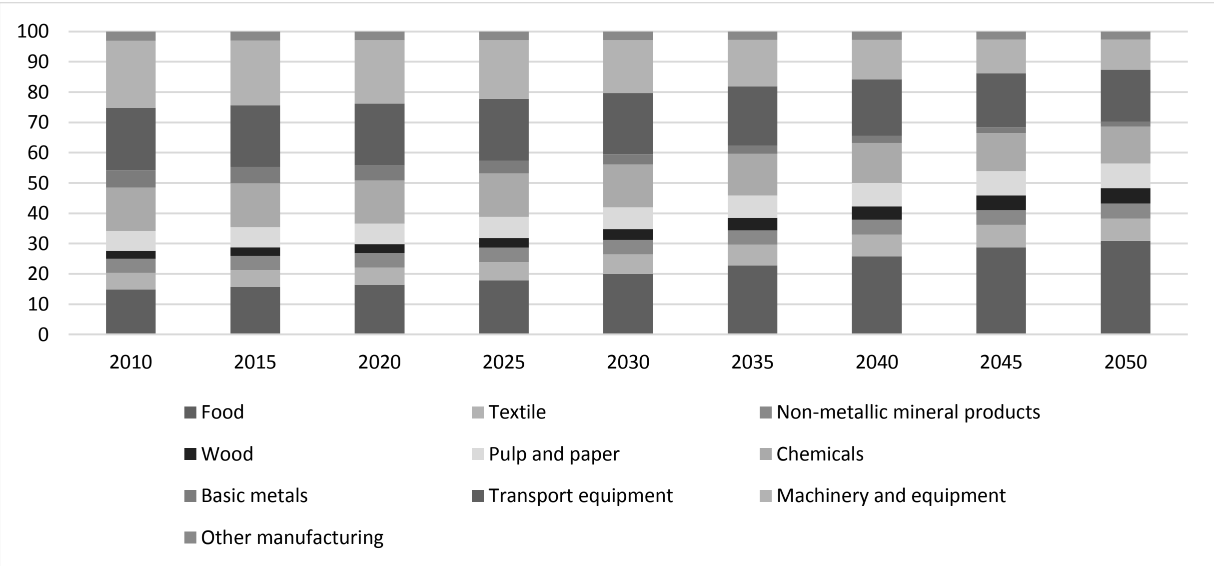


Figure 3 Changes in export flows in BCA_{bat} w.r.t. BAU for EU27 (%)



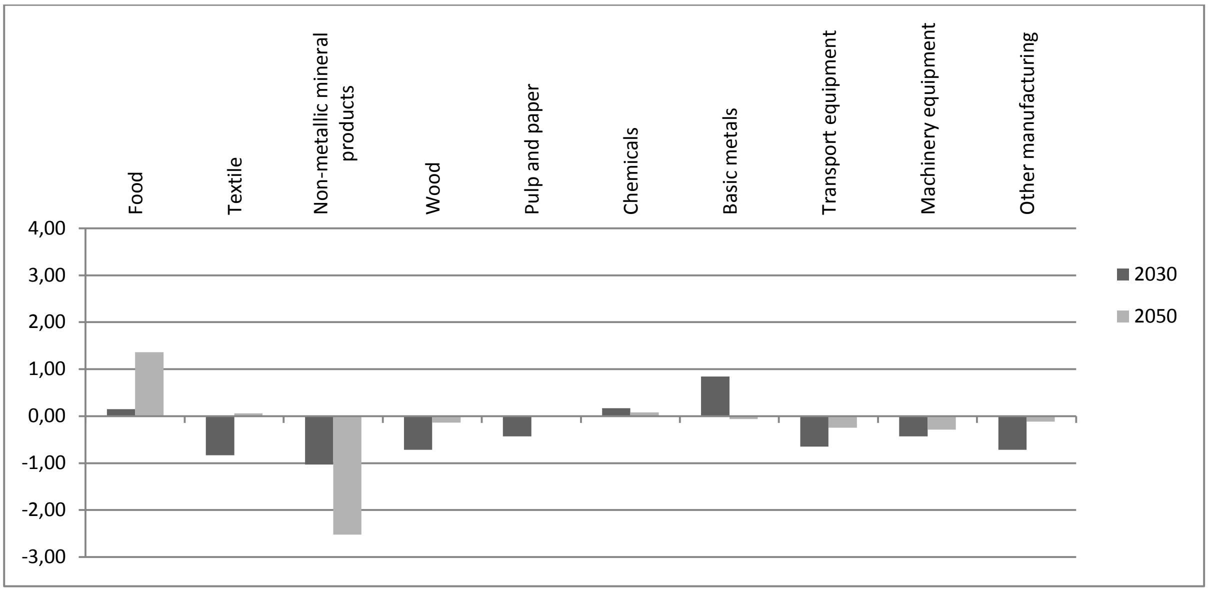
The export gains of the rest of the world that would be the result of the EU ETS policy, are largely undone by the BCA measures, especially in the long run (Figure 5). The exports of non-metallic minerals even decrease with respect to BAU. If BCA rates were to be based on foreign carbon intensities (BCA_{nobat}), 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).

Figure 4 Manufacturing value added composition in BAU for EU27 (%)



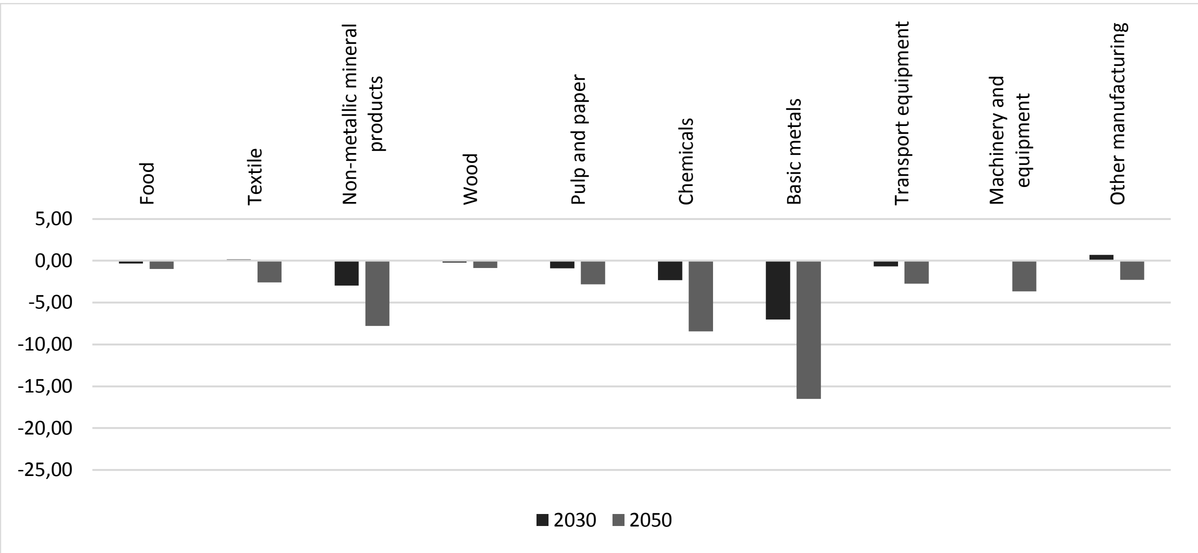
Turning to the policy mix strategy including green technological efforts, results are much more encouraging than for the trade protection option (Figure 6). The export flow losses for fragile sectors such as basic metals and chemicals are reduced reaching a maximum of -16.5% (which is still a large loss) for basic metals and a -8.4% for chemicals, which results in an improvement with respect to the pure ETS-based mitigation policy option which is quite similar to that obtained via a BCA measure.

Figure 5 Changes in export flows in BCA_{bat} w.r.t. BAU for the rest of the world (non-EU27) (%)



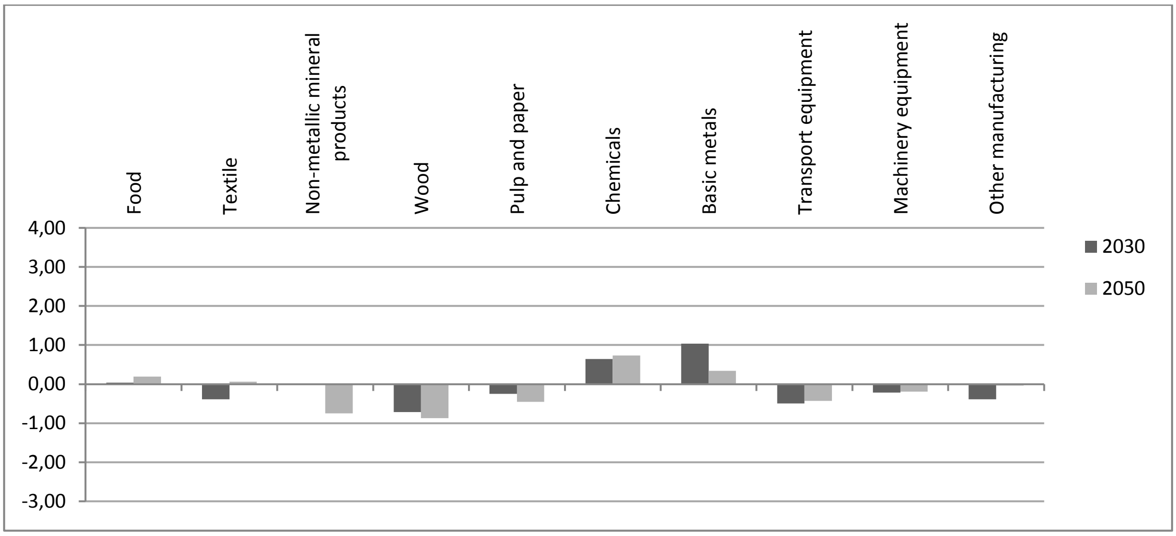
Most importantly, it is also worth noting that the technology-intensive sectors here reported as machinery and equipment and transport equipment face by 2050 a reduction in export losses with respect to the ETS case. This means that this policy mix strategy leads to a generalized improvement in international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

Figure 6 Changes in export flows in EERW w.r.t. BAU for EU27 (%)



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 of exports of other industries (except for food that increases its exports) are relatively small (Figure 7).

Figure 7 Changes in export flows in EERW w.r.t. BAU for the rest of the world (non-EU27) (%)



7 Optimality assessment

The CECILIA2050 project aims to identify ‘optimal’ mixes of climate policy instruments, with a view to achieving Europe’s climate targets for 2050. In assessing different policy instruments, CECILIA2050 adopts a broad notion of optimality, which does not only analyse what looks best in theory, but also what is the most expedient way forward under real-life constraints (Görlagh , 2013). The following ‘criteria’ of optimality are distinguished:

- 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?

In their qualitative assessment of anti-leakage policy instruments, Turcea and Kalfagianni (2015) operationalize these criteria with a number of measurable indicators. We will complement the assessment of Turcea and Kalfagianni (2015) by proposing 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 9).

Table 9 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/MUSD
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)	MUSD

Environmental effectiveness of the anti-leakage measures is measured by the change in carbon leakage in 2050 in %-point, 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 in domestic political feasibility and international political feasibility. The indicator for domestic political feasibility is change in competitiveness of the EITE sector, measured by the change in exports of 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 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 also use the indicator 'Rawls' justice' that measures the change in GDP of the poorest regions in our set of regions.

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 decrease 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 1,322 Mt (Table 10).

Table 10 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	-1,094	-1,322
Cost effectiveness	CO_2-price 2030	USD/tCO2	140	140	142	127
	CO_2-price	USD/tCO2	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	MUSD	-3,262	-2,992	-4,935	-2,496

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 hand, the energy-intensity under EERW is (slightly) higher. It must be assumed that EERW does not necessarily lead to a decrease of energy intensity but it 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 BCA_{nobat} 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: representative of the EITE sector may prefer BCA_{nobat} protection, while those of the broader manufacturing industry may prefer the EERW measure.

From the 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 BCA_{nobat} measure, since the GDP loss for this latter scenario is the highest w.r.t. BAU.

In the next chapter, we will argue that the EERW policy cannot only mitigate competitiveness losses of EITE sectors, it can also actively enhance the competiveness of the renewable energy manufacturing industry by providing it sustained first mover advantages in the global market place.

8 First Mover Advantage in the Renewable Energy Industry: Evidence from a Gravity Model

8.1 Introduction

Porter (1991) and Porter and Van der Linde (1995) contested the established paradigm that strict environmental regulation (hereafter ER) was necessarily harmful for business, and claimed that 'properly crafted' regulation could enhance competitiveness through innovation. Jaffe and Palmer (1997) further introduced three variations of the Porter Hypothesis (hereafter PH): the weak version (properly designed ER fosters innovation), the strong version (properly designed ER increases competitiveness, i.e. benefits of innovation can outweigh compliance costs), and the narrow version (flexible, i.e. market-based or performance based policies give greater incentives to innovate than prescriptive, command-and-control policies). While for the narrow PH, a general consensus prevails among economists, the other two versions have been contested on theoretical grounds, especially the strong version which conflicts with the vision of profit-maximizing firms. The past twenty years have seen the development of theoretical justifications[4] of the PH along with empirical studies testing its validity (Lanoie et al. 2008, 2011). Ambec et al. (2013) give a comprehensive review of the PH and conclude in particular that, thanks to patent data analysis (Popp et al. 2011, Dechezleprêtre et al. 2011, Johnstone et al. 2010), evidence of the weak version is fairly clear, while results are mixed for the strong version (at the firm or country level). However they warn that most previous studies have not adequately accounted for the dynamic nature of the PH, which is crucial as innovations often take several years to develop.

The impact of environmental policies on competitiveness is likely to be very different across sectors. Hallegatte et al. (2013) distinguish sunset sectors (such as energy-intensive industries) and sunrise sectors[5] (such as the renewable energy sectors).

This Section investigates a side effect of domestic environmental regulation on sunrise sectors: the potential First Mover Advantage (hereafter FMA) in the new eco-industries markets and the related export opportunities for pioneering countries (Beise and Rennings 2005).

In their seminal paper, Lieberman and Montgomery (1988) identify four sources for FMA: technological leadership (through the experience curve), pre-emption of scarce assets, buyer switching costs (which imply that late entrants must invest extra resources to attract

[4] Theoretical justifications include (Ambec et al. 2013): (i) behavioural arguments, involving the rationality of managers who miss good investment opportunities; (ii) market failures: market power, asymmetric information and R&D spillovers; (iii) organizational failures: information asymmetries or conflicting goals within the company.

[5] Many sectors actually present some characteristics of sunset sectors and some characteristics of sunrise sectors, such as the automotive industry.

customers away from the first-mover firm) and imperfect information of buyers regarding product quality (so that buyers may rationally stick with the first brand they encounter that performs the job satisfactorily). There are several examples of FMA, when countries pioneered the adoption of a product and national companies became global leaders, such as cellular phones in the Nordic countries, personal computer in the US or airbag in Germany (Beise 2004). In the case of renewable energies, new markets have emerged not only in developed countries but also in developing countries "tunnelling through the Environmental Kuznets Curve" (Munasinghe 1999). Lovely and Popp (2008) studied the diffusion of regulation on the case of coal-fired power plants and showed that developing countries regulated sooner (at a lower per capita income) than did early adopters.

Building new competitive industries is a strong argument for policy leaders for promoting renewable energy policies, both in developed and emerging countries. Recently, the tremendous investments in renewable energy capacities in China (Schmitz 2013) and to a smaller scale in Korea (Fankhauser et al. 2013) may have been more driven by the «green race» rush than by climate change mitigation concerns. However the comparative advantage of climate pioneers (or conversely late movers) is not established. Domestic demand-pull policies also induce innovation in foreign countries as it was shown by Peters et al. (2012) for the solar PV industry and Dechezleprêtre and Glachant (2014) for the wind industry.

Further, differences among countries are likely to lessen through the diffusion of knowledge and technologies (Keller 2004, Dechezleprêtre et al. 2011). Trade is an important channel (Copeland 2012), but technological transfer can also be achieved by licensing arrangements, mergers and acquisitions or joint development as shown in the Chinese and Indian wind industry by Lewis (2007, 2011). Finally, there are also second-mover advantages (Cleff and Rennings 2012, Voituriez and Balmer 2012), such as freeriding on first-mover investments, less incumbent inertia, and leapfrogging (Fudenberg et al. 1983) allowed by reduced market, technological and regulatory uncertainty. As Pegels and Lütkenhorst (2014) put it, the question is whether it is «the early bird that catches the worm or the second mouse that gets the cheese».

Algieri et al. (2011) and Sawhney and Kahn (2012) studied renewables technologies trade from the point of view of the US[6] with simple models but with great product detail.

While Algieri et al. (2011) set aside policies and only consider price and income elasticities in the solar photovoltaic sector (hereafter solar PV), Sawhney and Kahn (2012) find that domestic renewable power generation of the exporting countries play a significant positive role in export performance.

Lund (2009) establishes a statistical correlation between large domestic markets and large export shares in the wind industry.

The closest studies to ours are Costantini and Crespi (2008), Costantini and Mazzanti (2012), Groba (2014) and Groba and Cao (2015) which all four investigate the impact of

[6] For which trade data at the 10 digits level is more reliable than at the global level.

environmental regulation on renewable energy technologies exports with a gravity model, and find some evidence of the Porter Hypothesis. We will try to expand their results on several aspects. First, our regression covers the period 1995-2013, five to six years more, which may matter as renewables industries evolve extremely quickly. Second, our dataset is more comprehensive on sectoral and geographical coverage: we focus on both wind and solar PV, and use balanced dataset of 49 (for wind) and 40 (for PV) countries comprising major developed and emerging countries[7]. Third, we use a different variable proxying the stringency of renewable energy policies and pay particular attention to the dynamic nature of the PH to test a potential First Mover Advantage.

8.2 Empirical Model

8.2.1 Gravity Model

The gravity model of trade is the «workhorse» of the applied international trade literature (Shepherd 2013, Head and Mayer 2014), used in thousands of studies, mostly investigating the impact of policies like tariffs and regional agreements on trade. The importance of geography and national borders in trade (highlighted by the 'missing trade' (Trefler 1995) and the McCallum puzzle (1995)) gives empirical strength to this model, which is applied not only to goods but also to trade in services (Kimura and Lee 2006), immigration (Lewer and Van den Berg 2008) or knowledge flows through patent citations (Peri 2005, Picci 2010).

It is named after an analogy to Newton's law:

$$T_{o,d} = G \times \frac{M_o^{\beta_1} M_d^{\beta_2}}{D_{od}^{\beta_3}} \tag{12}$$

The trade flow from country o (origin) to country d (destination) is positively linked to the economic masses of the two countries, M_o and M_d and negatively linked to the distance between them D_{od} (which refers to geographical distance but also other trade barriers). The model is then log-linearized for estimation.

First developed by Tinbergen (1962) as an intuitive explanation of bilateral trade flows, this model was dismissed for long for lacking theoretical foundations (Bergstrand 1985), whereas it was providing robust empirical findings (Leamer and Levinsohn 1995). The first attempt to give micro-foundation to the gravity model can be traced back to Anderson (1979), which was followed by successful attempts to derive the gravity equation from different structural models (Bergstrand 1985, 1990, Helpman and Krugman 1985, Deardorff 1998). However it was only in the early 2000's with two prominent articles (Eaton and Kortum 2002, Anderson and van Wincoop 2003) that the gravity model was finally acknowledged as theoretically-grounded. More recently, the convergence with the heterogeneous firm literature (Helpman et al. 2008, Melitz and Ottaviano 2008) finally achieved to provide recognition to the gravity

[7] Costantini and Crespi (2008) and Costantini and Mazzanti (2012) use aggregated renewables and energy savings technologies or «high tech» sectors, Groba (2014) is only on solar PV and importers belong to the OECD, Groba and Cao (2015) is centred on China.

model in the field of international trade. This turning point led to considerable number of publications and change in estimation methods. In their famous ‘gravity with gravitas’ model, Anderson and Van Wilcoop (2003) introduced multilateral resistance terms of trade, which can be captured by importer and exporter fixed effects[8] (Feenstra 2002, Redding and Venables 2004).

8.2.2 Model specification

The dependent variables are bilateral export flows for wind and solar PV goods, from country *o* to country *d* at time *t*. We clearly separate wind and solar PV industries in the regression in order to reduce aggregation biases as suggested by Anderson and Yotov (2012). We use a balanced dataset of 49 and 40 countries for wind and solar PV respectively (see Table in Appendix). The choice of countries is data-driven: we kept countries which either had significant installed capacities (virtually all installed capacities are in these countries) or are big exporters (in the world top 20 of exporters, such as Malaysia for solar PV).

The subsets of countries represent at least respectively 85% and 90% of world trade for wind and solar PV goods[9] corresponding to our HS classification. The time period of the study is 1995-2013 (though because of lags estimation often starts in 1996 or 1997).

The estimated model is:

$$\ln(T_{o,d,t}) = \beta_0 + \beta_1 \ln(GDP_{o,t}) + \beta_2 \ln(GDP_{d,t}) + \beta_3 \boldsymbol{G_{o,d,t}} + \beta_4 RDEMAND_{d,t} \\ + \beta_5 RPOLICY_{o,t-3} + \alpha_o + \alpha_d + \alpha_t + \varepsilon_{o,d,t} \qquad (13)$$

The variables are (see Appendix for the list of variables):

- $T_{o,d,t}$ is the bilateral export flow of wind or solar PV goods. Section 2c details how data is collected and computed.
- GDP, in nominal rather than real terms (Shepherd 2013, Baldwin and Taglioni 2006), are used to proxy economic masses. They are taken from the World Development Indicator database of the World Bank.
- $\boldsymbol{G_{o,d,t}}$ is a vector of variables for geography.The main geographical variable is 〖DIST〗_(o,d) which is the geographical distance weighted by population between two countries as computed by CEPII (Mayer and Zignago 2011).We also use common variables used in gravity models:〖LANG〗_(o,d),〖COLONY〗_(o,d),〖RTA〗_(o,d,t) and 〖CONTIG〗_(o,d) are dummy variables for respectively common language, past colonial relationship, regional trade agreements and contiguity (common border).These variables are also taken from the CEPII database (data end in 2006 but the historical, cultural and geographical variables will not change and we assume that 〖 RTA〗 _(o,d,t) is invariant thereafter).

[8] Omitting them is considered as the «gold medal mistake» by Baldwin and Taglioni (2006).

[9] Own computation from Comtrade.

- $RDEMAND_{d,t}$ is the demand for wind or solar goods in the destination country. We expect that an increase in demand in the destination country will lead to more exports. The demand includes mainly new installed capacity, but also a rough estimation of maintenance and replacement of old installations. We use a threshold of minimum demand because very small demands may be unreliable due to measurement errors, while null demand would be dropped out of the sample as we express them in logarithm to be coherent with the main variable. More precisely we have $RDEMAND_{d,t} = \log(\max(D_{min}, D_t))$ where $D_t = [K_t - K_{t-1}] + \delta_1 K_{t-1}, K_t$ being the installed capacity D_{min} and $\delta_1$take values of 5 MW and 0.5% for wind and 2.5 MW and 0.25% for solar PV[10]. We extracted annual installed wind capacities from the interactive map on the website[11] of the Global Wind Energy Council (GWEC) which is the world association of the wind industry and from Enerdata (2014) (as there is no equivalent displayed figure) for the solar PV industry.
- 〚RPOLICY〛_(o,t) is a proxy of the effectiveness of renewable energy policies in the country of origin. It is our main explanatory variable since the purpose of the study is to investigate the linkage between home renewable policies and export performance. There is strong evidence that pollution control technologies are mainly adopted because of regulation rather than by technology diffusion (Kerr and Newell 2003, Snyder et al. 2003, Kirkegaard et al. 2010, Horbach et al. 2012). Therefore renewable capacities investments are primarily induced by dedicated policies (Popp et al.2011). However renewable energy policies are hardly comparable across countries (even a given feed-in tariff can hide different incentives because of network junction pricing for example). This is why we consider that installed capacities (in proportion of the size of the electric sector in the country) are the best proxy to compare them. 〚RPOLICY〛_(o,t) is then equal to the share of solar PV or wind installed capacity at year t relative to the total capacity of the electric sector (in percentage points). As for $RDEMAND_{d,t}$, we use a threshold, defined as 0.01% for both Wind and PV. The temporal delay used in the main regression is three years because it provides the best statistical results, but we try different lags of this variable to study temporal effects.

As errors are likely to be correlated by country-pair in the gravity model context (Moulton 1990), we provide robust standard errors clustered by geographical distance (Shepherd 2013). We also use directional (for source and destination country) fixed effects to model multilateral resistance terms (Anderson and van Wincoop 2003, Feenstra 2002) as common best practice, as well as time fixed effects to capture exogenous shocks common to all countries (such as the price of oil, or recessions).

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[10] Those are guestimates, but changing them does not change significantly the results. First, data is piecemeal for decommissioned capacity. In the EU 324 MW were decommissioned in 2013 (EWEA 2014) out of 106 454 installed MW in the beginning of this year (so 0.3%). Data for maintenance (replacing parts of wind turbines for example) is even harder to estimate.

[11] http://www.gwec.net/global-figures/interactive-map/.

A much-discussed issue of in the gravity model is the treatment of the many zeros that appear in bilateral trade flows. In its simplest form (OLS), as the logarithm of zero is undefined, zero observations are dropped from the sample, leading to potentially biased estimates. Due to our reduced samples in terms of countries, the proportion of zeros is not very large: 6% for wind and 2% for solar PV. The two most used alternative estimators are the Poisson Pseudo-Maximum Likelihood (PPML) developed by Santos Silva and Tenreyro (2006, 2011) and the Heckman Sample Selection Estimator developed by Helpman et al. (2008). In this study we use present results for both estimation methods. For the Heckman Sample Selection method, we use the geographical variables (except the distance) only for the sample selection equation.

8.3 Trade data in renewable energy technologies

Data from export flows in the solar and wind industries are extracted from the UNCTAD COMTRADE database. A caveat for using trade data is that the matching between 6-digit HS codes and renewable energy technologies is far from being perfect. Indeed HS codes are related to components for which the usage is unknown: the same components may be used in renewable energy or other industries. In addition the categories may be relatively wide and correspond to several products. Following Wind (2008), the International Centre for Trade and Sustainable Development (ICTSD) identified HS 6-digits product category codes according to the different renewable energy sectors (Jha 2009, Vossenaar and Jha 2010).

Their product categorization is displayed in the Appendix[12]. Because of multiple-use products, the aggregated trade flows of these categories are likely to be overestimated and only partially correlated to «real» trade flows corresponding to renewable energy technologies.

In this study, we focused on HS codes which are most likely to contain renewable energy supply technologies only. To do so, we used the detailed methodology of Jha (2009) to sub-selected product categories (with * in the Appendix). In the wind sector, selected categories correspond to towers (730820), blades (841290) and parts of the engine (850164, 850231 and 850300).

In the solar sector, the two selected categories correspond roughly to PV cells and inverters[13] representing then a good approximation of trade in the solar PV sector (hereafter we will use the term solar PV rather than solar). Total trade flows with this specification correspond to 32% and 62% of the wide classification for respectively wind and solar.

Another common problem of trade data is the mismatch between importer and exporter data. Because of measurement errors, reported exports from country A to country B may differ from reported imports in country B from country A. Usually data from imports are considered more reliable as countries spend more resources in measuring imports to

[12] The original categorization is made by HS 2007 codes. We used UN Stats conversion tables to extract trade data up to 1995.

[13] HS 854140 also includes light-emitting diodes, unrelated to solar PV products (Kirkegaard et al. 2010).

implement tariffs. However the point is reversed in the EU because of the way VAT is collected (Baldwin and Taglioni 2006). In our case, the mismatch was more important for the solar PV industry (reported imports around 10% higher than reported exports) than for the wind industry (similar amounts). We took the maximum of reported flows as common practice in the field of international trade.

Figure 8: Exports of wind good in selected countries (France, Japan, Spain, Denmark, USA, China and Germany). RoD=Rest of the Dataset

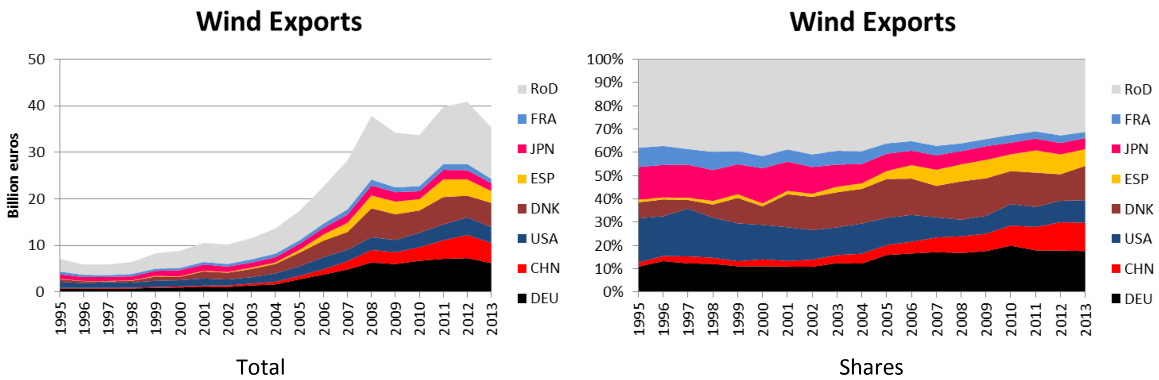
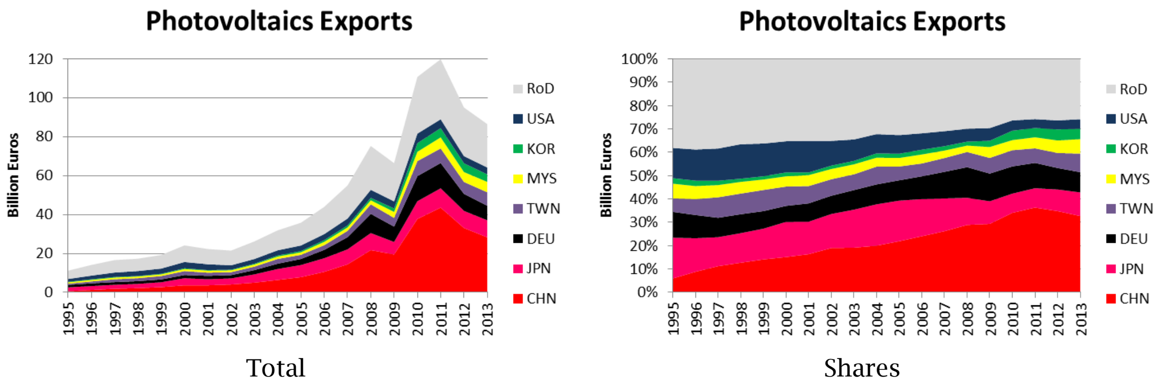


Figure 9: Exports of solar PV good in selected countries (USA, Korea, Malaysia, Taiwan, Germany, Japan and China). RoD=Rest of the Dataset



Figures 8 and 9 display exports of solar PV and wind goods, representing explicitly only the top 7 exporters[14]. Because our HS classification only partially reflect the «true» trade in renewable goods, variations are more relevant than absolute values in the following. Wind exports were around 5 billion US dollars at the end of the 1990's and almost doubled in the beginning of the 2000's. Then they increased sharply (threefold increase) up to 2008 then stayed approximately around this order of magnitude with some fluctuations due to the financial crisis and the subsequent recession. Photovoltaics exports exhibit a more important increase: from around 20 billion US dollars at the beginning of the 2000's, they increased significantly after 2005 (three years later than for wind goods). Slightly hit by the recession,

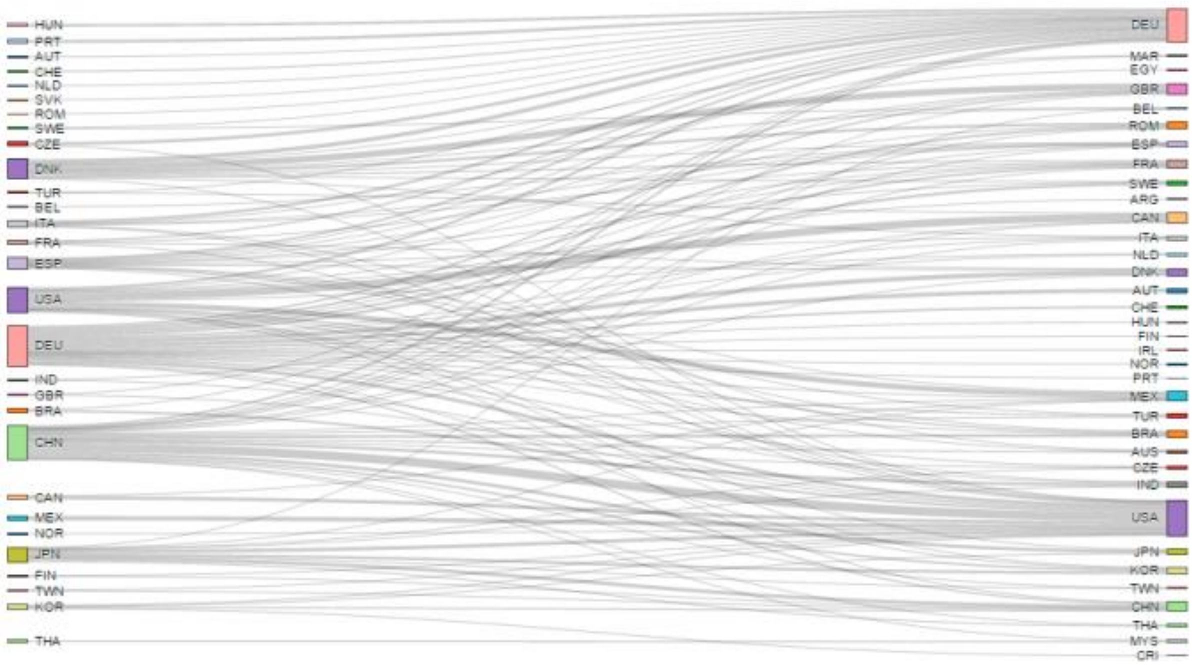
[14] Only exports of our country dataset are represented.

they nearly doubled between 2009 and 2010. In 2011, they reached 120 billion US dollars (a six times increase in less than ten years) but further decreased in 2012 and 2013 (85 billion US dollars).

In terms of market shares, the top 7 exporters account for around 60% of total exports of wind goods in our dataset. Japan, the US and France lost market shares during the last decade. China gained continuously market shares from a couple percent of world exports to about 10%, and three European countries (Germany, Denmark and Spain) increased their market shares especially before 2010 (in 2008 they accounted for about 35% of exports).

In the solar PV industry, the top 7 exporters represent between 60 and 70% of world exports. China which was already among the top exporters in the early 2000s with a 15% market share, doubled its position in 2011, being the world leader by far. The US and Japan lost substantial market shares during the last decade while Korea and Malaysia improved significantly after 2008.

Figure 10: International trade of renewable energy goods in 2013 with Sankey diagrams: wind.



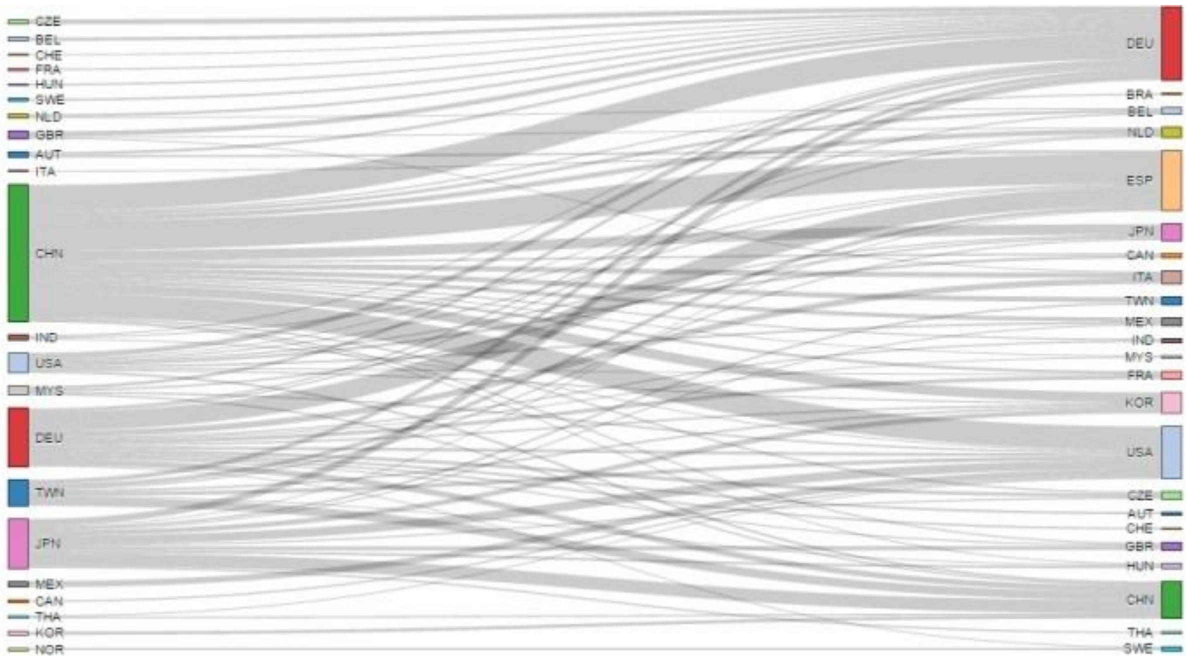
Because trade flows are bilateral, information about exporters only give a partial view of international trade. Additional insights are provided in Figures 10 and 11 with Sankey diagrams.[15]

First, international trade is highly concentrated, with a few bilateral trade flows representing a significant amount of total trade. In addition, the concentration is noticeably higher in the PV sector than in the Wind sector. At their highest level of international trade (2011 for solar PV and 2012 for Wind), 10% of the country pairs in the dataset accounted for 85% of total

[15] Only the top bilateral flows accounting for the three quarters of total trade of our classification are represented.

trade for both PV and wind. However the top 5 bilateral trade flows represented 24% of total trade for PV compared to 12% for wind. Even with a high concentration, the global picture is still complex, as there is a very high number of potential bilateral trade flows. Further, trade flows are to a large extent bi-directional (large exporters are very often large importers as well, such as Germany), showing the presence of intra-industry trade.

Figure 11: International trade of renewable energy goods in 2013 with Sankey diagrams: PV.



8.4 Results

Results of the model in reduced form are displayed in Table 11. An advantage of the gravity model is that the values of its coefficients are easy to interpret: they correspond to elasticities as it is a log-log regression. The GDP of the country of origin, 〚GDP〛_o, is always statistically significant with an elasticity of around +1.The GDP of the country of destination, 〚GDP〛_d, is also statistically significant (except for wind with the PPML estimation), with a lower elasticity (about one third lower). The elasticity of distance is negative, with estimates in line with those of the trade literature (Kepatsoglou et al. 2010, Head et al. 2013), suggesting that even for these high value goods, distance is a serious impediment for trade. Further, trade in wind goods is more sensitive to distance than trade in solar PV goods (elasticity of -1/-1.5 versus -0.7/-1.1), and the Heckman two steps estimation gives higher elasticities than the PPML estimation.

Table 11: Main results

VARIABLES	(1) PV Heckman	(2) PV PPML	(3) Wind Heckman	(4) Wind PPML
$GDP_{o,t}$	1.344***	0.939***	1.046***	1.124***
	(0.0971)	(0.140)	(0.111)	(0.110)
$GDP_{d,t}$	0.942***	0.691***	0.510***	0.0765
	(0.0922)	(0.126)	(0.0977)	(0.130)
$DIST_{o,d}$	-1.162***	-0.709***	-1.554***	-1.011***
	(0.0413)	(0.0510)	(0.0554)	(0.0452)
$RDEMAND_{d,t}$	0.154***	0.201***	0.150***	0.0669***
	(0.0129)	(0.0247)	(0.00918)	(0.0230)
$RPOLICY_{o,t-3}$	0.146***	0.0479***	0.0640***	0.0842***
	(0.0153)	(0.0150)	(0.0128)	(0.0111)
Exporters FE	Yes	Yes	Yes	Yes
Importers FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	31,622	28,080	48,162	42,336
R-squared		0.784		0.682

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Note: variables are logged except $RPOLICY_{o,t-3}$

The variable of demand in the destination country, 〚RDEMAND〛_d, is statistically significant with the expected sign, both for wind and solar PV. The estimated value is slightly higher for PV goods than for wind goods (0.15/0.20 versus 0.07/0.15). It means that everything else hold constant, if a country doubles its yearly installed capacity (for example installing 100 MW instead of 50 MW in the previous year), its imports are going to increase by 8% (=$2^{0.11}$-1) for wind goods and by 13% for solar PV goods. Most of the demand is then provided by local production.

Our variable of interest, $RPOLICY_o$, gives robust results indicating a first mover advantage.

For both industries, the estimated coefficients are statistically significant at the 1% level for both estimators. The estimated values are quite similar for the PV industry for both estimators: 0.06 and 0.08. However they don't have the same order of magnitude for the Wind industry (0.15 for the Heckman estimator and 0.05 for the PPML estimator). The interpretation of these results, taking the results from the Heckman estimator, is as follows: everything else hold constant, a country where wind power represented 10% of electric capacities three years earlier will have exports 112%[16] higher than a country where wind power represented 5% of electric capacities. The figure would be 35% for PV under the same configuration.

In Table 12 we test the robustness of the results by removing China from the dataset, and testing two time periods, before and after 2003 (we only display estimations with the

[16] $= e^{5\times0.15} - 1$

Heckman methodology). Except the estimation of the elasticity of 〖GDP〗_o for the wind industry, results are robust when China is removed from the dataset. Further, the elasticities of GDP are much lower or insignificant after 2003, mainly for the PV industry but also to a lesser extent for the wind industry. The estimation of the distance elasticity remains invariant. The estimation of the elasticity of $RDEMAND_{d,t}$ increases noticeably after 2003 (especially for the PV industry), probably revealing a growing internationalization of the renewable goods market. Finally, the parameter $RPOLICY_{o,t-3}$ is only significant after 2003 for the PV industry but remains stable for the wind industry. Possible explanations are (i) that the estimation period (six years because of the lag is too short for a statistically significant effect to emerge, or (ii) that before 2003 the PV market was not internationalised enough, or (iii) that at that time a significant part of subsidies were targeted at domestic industries.

Table 12: Robustness Tests

VARIABLES	(1) PV Heckman	(5) PV Heckman No China	(6) PV Heckman Before 2003	(7) PV Heckman After 2003	(3) Wind Heckman	(8) Wind Heckman No China	(9) Wind Heckman Before 2003	(10) Wind Heckman After 2003
$GDP_{o,t}$	1.344***	1.210***	1.452***	0.254**	1.046***	0.609***	0.671***	0.522***
	(0.0971)	(0.114)	(0.164)	(0.116)	(0.111)	(0.116)	(0.178)	(0.123)
$GDP_{d,t}$	0.942***	0.907***	1.309***	0.0322	0.510***	0.593***	1.074***	0.0316
	(0.0922)	(0.106)	(0.143)	(0.114)	(0.0977)	(0.100)	(0.141)	(0.122)
$DIST_{o,d}$	-1.162***	-1.197***	-1.152***	-1.173***	-1.554***	-1.557***	-1.529***	-1.561***
	(0.0413)	(0.0449)	(0.0421)	(0.0465)	(0.0554)	(0.0593)	(0.0586)	(0.0603)
$RDEMAND_{d,t}$	0.154***	0.162***	0.0861**	0.138***	0.0640***	0.0707***	0.0575***	0.0735***
	(0.0129)	(0.0138)	(0.0421)	(0.0135)	(0.0128)	(0.0130)	(0.0188)	(0.0148)
$RPOLICY_{o,t-3}$	0.146***	0.145***	-0.519	0.0659***	0.0654***	0.0657***	0.0723***	0.0699***
	(0.0153)	(0.0156)	(0.446)	(0.0134)	(0.00799)	(0.00816)	(0.0124)	(0.0157)
Exporters FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Importers FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	31,622	30,050	19,142	15,600	48,162	46,206	29,346	23,520
Wald test of indep. eqns.	0.0006	0.0003	0.7674	0.0001	0.2698	0.0683	0.1692	0.0003

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Note: variables are logged except $RPOLICY_{o,t-3}$

Trying different lags (see Table 13), results remain robust for the wind industry: the first mover advantage is maintained during seven years (it diminishes in intensity after two years for the PPML estimation but peaks at four years for the Heckman estimation).

However for solar PV, estimates turn statistically non-significant after four or five years. In this respect, it is worth mentioning that including a five-year lag entails neglecting the policies implemented after 2008, a year at the end of which global PV capacity amounted to only 16 GW vs. 139 at the end of 2013 (EPIA, 2014). Thus it is not surprising that policies implemented up to 2008 are poor predictors of the trade dynamics in next five years.

Table 13: Temporal effects. Solar PV and Wind

	$RPOLICY_{o,t-1}$	$RPOLICY_{o,t-2}$	$RPOLICY_{o,t-3}$	$RPOLICY_{o,t-4}$	$RPOLICY_{o,t-5}$	$RPOLICY_{o,t-6}$	$RPOLICY_{o,t-7}$
PV Heckman	0.0516***	0.0547***	0.0659***	0.0503**	-0.0160	-0.0770	-0.159*
	(0.00781)	(0.00931)	(0.0134)	(0.0233)	(0.0381)	(0.0616)	(0.0890)
PV PPML	0.0361***	0.0403***	0.0479***	0.0668**	0.0819*	0.0625	0.0244
	(0.00794)	(0.00995)	(0.0150)	(0.0268)	(0.0459)	(0.0573)	(0.0743)
Wind Heckman	0.0560***	0.0643***	0.0699***	0.0728***	0.0708***	0.0634***	0.0508***
	(0.0146)	(0.0157)	(0.0157)	(0.0153)	(0.0144)	(0.0134)	(0.0130)
Wind PPML	0.0843***	0.0854***	0.0842***	0.0800***	0.0725***	0.0626***	0.0508***
	(0.0106)	(0.0107)	(0.0111)	(0.0120)	(0.0124)	(0.0130)	(0.0131)

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Note: variables are logged except $RPOLICY_o$

8.5 Discussion

Our econometric model shows evidence of first mover advantage, sustained in the wind industry and at least for four years in the solar PV industry. These results are in line with other non-econometric studies. Lewis and Wiser (2007), with a cross-country analysis, show that policies that support a sizable home market for wind power most likely result in the establishment of an internationally competitive wind industry. Pegels and Lütkenhorst (2014) find that in Germany the wind sector has a larger revealed competitive advantage than the solar sector. Voituriez and Balmer (2012) distinguish the conventional competition with sustained first mover advantage that has occurred in the wind industry from the hypercompetition and temporary advantage (D'Aveni et al. 2010) in solar PV.

Our quantitative study has the merit of a wide geographical and temporal coverage linked by common metrics, but is limited by the quality of the trade data. Unfortunately, getting more detailed trade data is impossible without losing our global coverage. The picture is more complex when looking at the firm level than just focusing on exports at the national level. Firms may outsource production of certain components while holding a significant share of the value added.[17] Further, several European firms (mostly small wind manufacturers) have served as sources of technology for firms based in China, India or South Korea through joint development (Lewis 2011). Suzlon, an Indian company has R&D units in Denmark, Germany and the Netherlands to benefit from local knowledge networks (Lewis 2007). These countries have then benefited to some extent from the development of companies abroad.

Demand-pull policies such as feed-in-tariffs have proved extremely efficient to foster renewables development and many countries have been implemented them to replicate pioneers' success. Yet, the trade deficit in PV cells in Germany and other European countries has led to an emotionally-charged debate (Kirkegaard et al. 2010, Pegels and Lütkenhorst, 2014). In this context, our results may allow a more informed debate. However, evaluating renewable policies focusing only on trade balance gives a very imperfect picture. Even if the

[17] The prominent example of such value capture is the iPod (Linden et al. 2007), where value added to the product through assembly in China is probably a few dollars at most.

technological leadership is not warranted, renewable energy policies still bring important benefits in terms of avoided greenhouse gas and local pollutant emissions. Moreover, even regarding employment, Voituriez and Balmer (2012) examined the value chains of wind and solar PV and find that the majority of jobs and value added are local. Then, even if a country were to import most of its renewable energy technologies, a significant number of jobs would be created locally, in installation and maintenance.

9 Conclusion

The European Union (EU) 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 affecting world energy prices, international competitiveness and the geographical allocation of carbon intensive production processes. The unilateral imposition of stringent climate policies may produce distortive effects in terms of displacement and re-allocation of carbon intensive production processes to unregulated countries where no climate policies are in force, a phenomenon also known as carbon leakage. 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 scenarios range from a global effort where all countries participate to reach the necessary emissions reductions in 2050 that are compatible with the 450ppm GHG concentration target, to a EU alone scenario, where only the EU achieves these necessary reductions. For the latter scenario, three different anti-leakage measures are modelled, two measures implementing border carbon adjustments (BCA) and one focussing on investing in energy efficiency and renewable energy through a 10% levy on carbon tax revenue.

The results show two interesting things. First, if all countries cooperate, there is obviously no carbon leakage and the economic effects for the EU are overall positive. There are small 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 planning 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, distinguishing the criteria environmental effectiveness, cost-effectiveness, and political feasibility revealed that the extra investment in energy efficiency and renewable scored relatively well on all criteria in contrast to the border carbon adjustment measures that scored not so well, especially on the political feasibility criteria.

Apart from protecting the competitiveness of 'sunset' industries, like the energy-intensive industries (in the words of Hallegatte et al. (2013)), the investment option may also enhance the international competitiveness of 'sunrise' industries such as the renewable energy technology industry. We carry out an econometric estimation of ‘first mover advantages’ of renewable energy technology manufacturers on the global market place due to the support of renewable energy deployment in Europe. We find clear evidence of first mover advantage, sustained in the wind industry and temporary (at least for four years) in the solar PV industry. These results are in line with other non-econometric studies.

Our conclusions are in line with the qualitative assessment of policy options to mitigate carbon leakage and adverse effects on competitiveness that was carried out in parallel to our research and that is reported in Deliverable 5.3a. The best policy to mitigate adverse effects on carbon leakage and competitiveness is to have an international agreement with broad cooperation. In the event of a lack of international cooperation, the second-best policy for the EU is to accelerate investments in energy efficiency and renewable energy, protecting the competitiveness of ‘sunset’ industries and enhancing the competitiveness of ‘sunrise’ industries.

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Annex 1

Table A.1 List of GDYnE countries

GTAP code	Code	Country	GTAP code	Code	Country	GTAP code	Code	Country
BRA	bra	Brazil	EU27	mlt	Malta	RAM	gtm	Guatemala
CAN	can	Canada	EU27	nld	Netherlands	RAM	hnd	Honduras
CHN	chn	China	EU27	pol	Poland	RAM	nic	Nicaragua
CHN	hkg	Hong Kong	EU27	prt	Portugal	RAM	pan	Panama
EExAf	xcf	Central Africa	EU27	rou	Romania	RAM	pry	Paraguay
EExAf	egy	Egypt	EU27	svk	Slovakia	RAM	per	Peru
EExAf	nga	Nigeria	EU27	svn	Slovenia	RAM	xca	Rest of Central America
EExAf	xnf	Rest of North Africa	EU27	esp	Spain	RAM	xna	Rest of North America
EExAf	zaf	South Africa	EU27	swe	Sweden	RAM	xsm	Rest of South America
EExAf	xac	South Central Africa	EU27	gbr	United Kingdom	RAM	ury	Uruguay
EExAm	arg	Argentina	FSU	blr	Belarus	RAS	arm	Armenia
EExAm	bol	Bolivia	FSU	rus	Russian Federation	RAS	bgd	Bangladesh
EExAm	col	Colombia	IDN	idn	Indonesia	RAS	bhr	Bharain
EExAm	ecu	Ecuador	IND	ind	India	RAS	khm	Cambodia
EExAm	ven	Venezuela	JPN	jpn	Japan	RAS	kgz	Kyrgyztan
EExAs	aze	Azerbaijan	KOR	kor	Korea	RAS	lao	Lao People's Democr. Rep.
EExAs	irn	Iran Islamic Republic	MEX	mex	Mexico	RAS	mng	Mongolia
EExAs	kaz	Kazakhstan	NOR	nor	Norway	RAS	npl	Nepal
EExAs	kwt	Kuwait	RAF	bwa	Botswana	RAS	xea	Rest of East Asia
EExAs	mys	Malaysia	RAF	cmr	Cameroon	RAS	xoc	Rest of Oceania
EExAs	omn	Oman	RAF	civ	Cote d'Ivoire	RAS	xsa	Rest of South Asia
EExAs	qat	Qatar	RAF	eth	Ethiopia	RAS	xse	Rest of Southeast Asia
EExAs	xsu	Rest of Form Sov Un.	RAF	gha	Ghana	RAS	sgp	Singapore
EExAs	xws	Rest of Western Asia	RAF	ken	Kenya	RAS	lka	Sri Lanka
EExAs	sau	Saudi Arabia	RAF	mdg	Madagascar	RAS	twn	Taiwan
EExAs	are	United Arab Emirates	RAF	mwi	Malawi	RAS	pak	Pakistan
EU27	aut	Austria	RAF	mus	Mauritius	RAS	phl	Philippines
EU27	bel	Belgium	RAF	moz	Mozambique	RAS	tha	Thailand
EU27	bgr	Bulgaria	RAF	nam	Namibia	RAS	vnm	Vietnam
EU27	cyp	Cyprus	RAF	xec	Rest of East Africa	REU	alb	Albania
EU27	cze	Czech Republic	RAF	xsc	Rest South Afr Cus	REU	hrv	Croatia
EU27	dnk	Denmark	RAF	xwf	Rest of West Africa	REU	geo	Georgia
EU27	est	Estonia	RAF	sen	Senegal	REU	xee	Rest of Eastern Europe
EU27	fin	Finland	RAF	tza	Tanzania	REU	xef	Rest of EFTA
EU27	fra	France	RAF	uga	Uganda	REU	xer	Rest of Europe
EU27	deu	Germany	RAF	zmb	Zambia	REU	xtw	Rest of the World
EU27	grc	Greece	RAF	zwe	Zimbabwe	REU	tur	Turkey
EU27	hun	Hungary	RAF	mar	Morocco	REU	ukr	Ukraine
EU27	irl	Ireland	RAF	tun	Tunisia	ROECD	aus	Australia
EU27	ita	Italy	RAM	xcb	Caribbean	ROECD	isr	Israel
EU27	lva	Latvia	RAM	chl	Chile	ROECD	nzl	New Zealand
EU27	ltu	Lithuania	RAM	cri	Costa Rica	ROECD	che	Switzerland
EU27	lux	Luxembourg	RAM	slv	El Salvador	USA	usa	United States of America

Table A.2 - List of GDYnE regions

GTAP code	Description
CAN	Canada
EU27	European Union
FSU	Former Soviet Union
JPN	Japan
KOR	Korea
NOR	Norway
USA	United States
ROECD	Rest of OECD
BRA	Brazil
CHN	China
IND	India
IDN	Indonesia
MEX	Mexico
EExAf	African Energy Exporters
EExAm	American Energy Exporters
EExAs	Asian Energy Exporters
RAF	Rest of Africa
RAM	Rest of America
RAS	Rest of Asia
REU	Rest of Europe

Table A.3 - List of GDYnE commodities and sectors

Sector	Code	Products	Sector	Code	Products
agri	pdr	paddy rice	wood	lum	wood products
agri	wht	wheat	paper	ppp	paper products, publishing
agri	gro	cereal grains nec	oil_pcts	p_c	petroleum, coal products
agri	v_f	vegetables, fruit, nuts	chem	crp	chemical, rubber, plastic products
agri	osd	oil seeds	nometal	nmm	mineral products nec
agri	c_b	sugar cane, sugar beet	basicmet	i_s	ferrous metals
agri	pfb	plant-based fibers	basicmet	nfm	metals nec
agri	ocr	crops nec	basicmet	fmp	metal products
agri	ctl	bovine cattle, sheep and goats, horses	transeqp	mvh	motor vehicles and parts
agri	oap	animal products nec	transeqp	otn	transport equipment nec
agri	rmk	raw milk	macheqp	ele	electronic equipment
agri	wol	wool, silk-worm cocoons	macheqp	ome	machinery and equipment nec
agri	frs	forestry	oth_man_ind	omf	manufactures nec
agri	fsh	fishing	electricity	ely	electricity
Coal	coa	coal	gas	gdt	gas manufacture, distribution
Oil	oil	oil	services	wtr	water
Gas	gas	gas	services	cns	construction
nometal	omn	minerals nec	services	trd	trade
food	cmt	bovine cattle, sheep and goat meat products	transport	otp	transport nec
food	omt	meat products	wat_transp	wtp	water transport
food	vol	vegetable oils and fats	air_transp	atp	air transport
food	mil	dairy products	services	cmn	communication
food	pcr	processed rice	services	ofi	financial Oth_Ind_serices nec
food	sgr	sugar	services	isr	insurance
oth_man_ind	ofd	Oth_Ind_ser products nec	services	obs	business and other services nec
food	b_t	beverages and tobacco products	services	ros	recreational and other services
textile	tex	textiles	services	osg	public admin. and defence, education, health
textile	wap	wearing apparel	services	dwe	ownership of dwellings
textile	lea	leather products			

Table A.4 - List of GDYnE sectors

Sector	Full description
agri	Agriculture
food	Food
coal	Coal
oil	Oil
gas	Gas
oil_pcts	Petroleum, coal products
electricity	Electricity
text	Textile
nometal	Non-metallic mineral products
wood	Wood
paper	Pulp and paper
chem	Chemical and petrochemical
basicmet	Basic metal
transeqp	Transport equipment
macheqp	Machinery and equipment
oth_man_ind	Other manufacturing industries
transport	Transport
wat_transp	Water Transport
air_transp	Air Transport
services	Services

Table A.5 - Baseline GDP projections to 2050 (Bln USD)

	2010	2015	2020	2025	2030	2035	2040	2045	2050	Growth p.a.
CAN	1,424	1,668	1,893	2,092	2,286	2,493	2,707	2,924	3,145	2.1%
EU27	16,489	18,302	20,051	21,451	22,627	23,714	24,823	25,943	27,080	1.3%
FSU	1,344	1,589	1,858	2,105	2,346	2,580	2,782	2,937	3,065	2.2%
JPN	4,186	4,575	4,895	5,173	5,379	5,500	5,546	5,592	5,641	0.8%
KOR	1,100	1,316	1,474	1,595	1,686	1,759	1,817	1,863	1,896	1.4%
NOR	393	427	472	522	572	621	672	728	786	1.8%
USA	13,947	15,868	17,779	19,633	21,548	23,565	25,656	27,799	29,986	2.0%
ROECD	1,646	1,861	2,071	2,267	2,459	2,660	2,872	3,099	3,330	1.8%
BRA	1,474	1,753	2,077	2,421	2,775	3,137	3,500	3,863	4,223	2.8%
CHN	4,687	7,157	10,602	15,128	20,630	26,893	33,517	40,130	46,321	6.8%
IND	1,482	2,091	2,925	4,068	5,591	7,558	9,996	12,872	16,119	7.0%
IDN	498	648	848	1,104	1,421	1,802	2,250	2,769	3,361	5.4%
MEX	995	1,233	1,478	1,733	1,985	2,219	2,432	2,636	2,830	2.8%
EExAf	889	1,117	1,408	1,785	2,273	2,902	3,702	4,722	6,039	5.4%
EExAm	801	942	1,126	1,326	1,542	1,772	2,014	2,266	2,525	3.1%
EExAs	1,723	2,092	2,529	3,026	3,559	4,125	4,708	5,297	5,898	3.3%
RAF	571	733	953	1239	1627	2102	2692	3400	4271	5.7%
RAM	753	912	1,087	1,278	1,489	1,750	2,049	2,380	2,746	3.5%
RAS	1528	1932	2457	3112	3924	4927	6151	7631	9394	5.1%
REU	962	1,152	1,379	1,612	1,842	2,063	2,269	2,459	2,638	2.7%
World	56,893	67,366	79,362	92,669	107,560	124,142	142,154	161,311	181,294	3.1%
Developing	16,364	21,760	28,869	37,832	48,658	61,250	75,279	90,427	106,366	5.3%
Developed	40,529	45,606	50,493	54,836	58,902	62,892	66,875	70,884	74,928	1.6%

Table A.6 - Baseline CO2 projections to 2050 (Gt CO2)

	2010	2015	2020	2025	2030	2035	2040	2045	2050	% Change 2010-2050
CAN	0.53	0.58	0.65	0.66	0.66	0.66	0.67	0.68	0.70	30.2%
EU27	3.67	3.52	3.31	3.20	3.12	3.01	2.95	2.86	2.83	-22.7%
FSU	1.62	1.70	1.75	1.84	1.89	1.96	2.05	2.06	2.09	28.9%
JPN	1.11	1.11	1.10	1.09	1.08	1.05	1.04	1.02	1.01	-8.7%
KOR	0.48	0.51	0.56	0.57	0.56	0.53	0.51	0.50	0.50	4.1%
NOR	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.07	0.07	8.4%
USA	5.36	5.33	5.31	5.29	5.29	5.27	5.27	5.22	5.19	-3.3%
ROECD	0.51	0.54	0.62	0.61	0.59	0.57	0.55	0.53	0.53	2.9%
BRA	0.35	0.39	0.47	0.52	0.56	0.61	0.65	0.71	0.81	130.9%
CHN	7.19	9.42	11.58	12.80	13.76	14.33	14.42	14.51	14.78	105.6%
IND	1.59	1.93	2.37	3.03	3.62	4.21	4.77	5.28	5.75	261.7%
IDN	0.41	0.48	0.54	0.60	0.69	0.75	0.79	0.86	0.95	133.4%
MEX	0.41	0.41	0.45	0.45	0.45	0.46	0.46	0.47	0.47	15.9%
EExAf	0.70	0.84	1.04	1.18	1.27	1.39	1.50	1.61	1.76	151.0%
EExAm	0.41	0.49	0.59	0.67	0.75	0.82	0.88	0.93	0.99	139.9%
EExAs	2.06	2.49	3.07	3.49	3.82	4.13	4.43	4.82	5.28	156.5%
RAF	0.19	0.20	0.25	0.30	0.36	0.41	0.49	0.58	0.75	300.3%
RAM	0.29	0.31	0.38	0.44	0.50	0.50	0.48	0.49	0.52	80.8%
RAS	1.14	1.45	1.92	2.23	2.49	2.72	3.06	3.44	3.88	240.1%
REU	0.63	0.70	0.82	0.87	0.89	0.92	0.96	1.01	1.09	74.0%
World	28.71	32.48	36.84	39.90	42.39	44.38	46.00	47.67	49.95	74.0%
Developing	15.36	19.13	23.47	26.56	29.14	31.24	32.90	34.72	37.04	141.1%
Developed	13.35	13.35	13.37	13.34	13.25	13.14	13.10	12.95	12.91	-3.3%

Table A.7: List of countries

Country	Code	Wind	PV	Country	Code	Wind	PV
Argentina	ARG	Yes		Italy	ITA	Yes	Yes
Australia	AUS	Yes	Yes	Japan	JPN	Yes	Yes
Austria	AUT	Yes	Yes	South Korea	KOR	Yes	Yes
Belgium	BEL	Yes	Yes	Lithuania	LTN	Yes	Yes
Bulgaria	BGR	Yes	Yes	Luxembourg	LUX		Yes
Brazil	BRA	Yes		Morocco	MAR	Yes	
Canada	CAN	Yes	Yes	Mexico	MEX	Yes	Yes
Switzerland	CHE	Yes	Yes	Malta	MLT		Yes
Chile	CHL	Yes		Malaysia	MYS		Yes
China	CHN	Yes	Yes	Nicaragua	NIC	Yes	
Costa Rica	CRI	Yes		Netherlands	NLD	Yes	Yes
Cyprus	CYP	Yes	Yes	Norway	NOR	Yes	Yes
Czech Republic	CZE	Yes	Yes	New Zealand	NZL	Yes	
Germany	DEU	Yes	Yes	Pakistan	PAK	Yes	
Denmark	DNK	Yes	Yes	Philippines	PHL		Yes
Egypt	EGY	Yes		Poland	POL	Yes	
Spain	ESP	Yes	Yes	Portugal	PRT	Yes	Yes
Estonia	EST	Yes		Romania	ROM	Yes	Yes
Ethiopia	ETH	Yes		Singapore	SGP	Yes	Yes
Finland	FIN	Yes	Yes	Slovakia	SVK		Yes
France	FRA	Yes	Yes	Slovenia	SVN		Yes
United	GBR	Yes	Yes	Sweden	SWE	Yes	Yes
Greece	GRC	Yes	Yes	Thailand	THA	Yes	Yes
Croatia	HRV	Yes		Tunisia	TUN	Yes	
Hungary	HUN	Yes	Yes	Turkey	TUR	Yes	
India	IND	Yes	Yes	Taiwan	TWN	Yes	Yes
Ireland	IRL	Yes		Ukraine	UKR	Yes	Yes
Israel	ISR		Yes	United States	USA	Yes	Yes

Table A.8: HS 2007 codes used for the wind industry

HS 2007 Code	Product
730820*	Towers and lattice masts, of Iron or Steel
841290*	Parts of Other Engines and Motors
848210	Ball Bearings
848220	Tapered Roller Bearings, Including Cone and Tapered Roller Assemblies
848230	Spherical Roller Bearings
848240	Needle Roller Bearings
848250	Other Cylindrical Roller Bearings
848280	Other Bearings, Including Combined Ball or Roller Bearings
848340	Gears and Gearing; Ball Screws; Gear Boxes and Other Speed Changers
850161	Ac Generators of an Output Not Exceeding 75kva
850162	Ac Generators of an Output Exceeding 75kva But Not Exceeding 375kva
850163	Ac Generators of an Output Exceeding 375kva But Not Exceeding 750kva
850164*	Ac Generators of an Output Exceeding 750kva
850230	Other Generating Sets
850231*	Wind-powered electric generating sets
850300*	Parts, of Motors, of Generators, of Generating Sets, of Rotary Converters
850421	Liquid Dielectric Transformers, Not Exceeding 650kva
850422	Liquid Dielectric Transformers, Power Handling Capacity 650-10,000kva
850423	Liquid Dielectric Transformers, Exceeding 10, 000kva
850431	Other Transformers, Power Handling Capacity Not Exceeding 1kva
850432	Other Transformers, Exceeding 1kva But Not Exceeding 16kva
850433	Other Transformers, Exceeding 16kva But Not Exceeding 500kva
850434	Other Transformers, Power Handling Capacity Exceeding 500kva
854459	Other Electric Conductors, Exceeding 80v But Not Exceeding 1, 000v
854460	Other Electric Conductors, for a Voltage Exceeding 1, 000v
890790	Other floating structures
902830	Electricity meters
903020	Cathode-ray oscilloscopes and cathode-ray oscillographs
903031	Multimeters
903081	With a recording device(Volt Meters, Am Meters, Circuit Testers)

Table A.9: HS 2007 codes used for the solar industry

HS 2007 Code	Product
700991	Unframed Glass mirrors
700992	Framed Glass mirrors
711590	Other articles of precious metal or of metal clad with precious metal
732290	Solar Collector, Air Heater, Hot Air Distributor, and Parts Thereof
830630	Photograph, picture or similar frames; mirrors; and parts thereof , of Base Metal
841280	Other Engines and Motors
841919	Other Instantaneous or Storage Water Heaters, Non-electric
841950	Heat Exchange Units
841989	Other Apparatus for Treatment of Materials By Temperature
841990	Parts of Apparatus for Treatment of Materials By Temperature
850230	Other Generating Sets
850440*	Static Converters
854140*	Photosensitive Semiconductor Devices; Light Emitting Diodes
900190	Other: prisms, mirrors and other optical elements, of any material, unmounted, other than such elements of glass not optically worked
900290	Other Optical Elements, of Any Material, Mounted
900580	Other instruments: Monoculars, Other Optical Telescopes; Other Astronomical Instruments