EU climate policy up to 2030: reasoning around overlapping instruments and cost effectiveness of investing in green energy technologies

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1. Introduction

The current climate policy agenda recently approved by the European Union (EU) in October 2014 and briefly addressed as EU2030 (EC, 2014a, 2014b, 2014c) constitutes the last challenging long term objective for the EU in the climate change debate. The EU2030 strategy follows the previous EU climate agenda, also called as EU2020 strategy, which was considered as a great effort in improving the quality of the policy strategy in this field. However, it is still not clear to what extent these mid-term targets will allow the EU to stay on track with respect to a long-term reduction pathway to 2050.

The EU2020 framework defined three goal to achieve by 2020: a 20% reduction in greenhouse gas (GHG) emissions with respect to 1990 levels, a binding target of 20% of final energy consumption from renewable sources , increasing energy efficiency to reach a 20% reduction in primary energy consumption (EC 2009a, 2009b, 2012). The main instrument to reduce GHG emissions is the European Emission Trading System (EU ETS), which only covers the energy and industry sectors, but Member States can also define further discretionary measures to achieved the targets in other sectors (above all, transport) such as environmental and energy taxation (de Miera and Rodriguez, 2015). The renewable energy goal set binding national targets but left to each States free to choose which types of supporting framework to implement (e.g., feed-in tariff and premium, green certificates or quota system). Finally, a binding target on energy efficiency was not defined until the 2012 Directive, when national and sectoral targets were identified (especially for energy suppliers) together with several regulatory instruments and a great flexibility in deciding how to meet the targets[1].

[1] Article 7 of Directive 2012/27/EU leave open to the Member States to decide the subjects and sectors to be included, as well the measures to be implemented, such as taxation, standards, a national fund for energy efficiency, voluntary agreements, information and education programs and monitoring activities.

The main novelty of the EU2020 was the explicit combination of different policy instruments and different policy objectives in a unique coordinated strategy, and the EU2030 as well follows this approach. The newly approved agenda set the following goals: a 40% target for domestic reduction in GHG emissions by 2030 compared to 1990 level (where the EU ETS keeps playing the core role); a target of at least 27% for the share of renewable energy in 2030; an increase of at least 27% in energy efficiency in 2030.

The three objectives, reducing CO_2 emissions, enhancing energy saving and increasing the share of renewable energies in the energy mix, are strictly connected and the achievement of each goal strongly influences the others, in a not univocal way. There are some controversies in such policy strategy, which may arise at the macro and micro level. To give an example, if substantial energy efficiency improvements are achieved, energy consumption becomes cheaper, since the reduction in competing for energy demand will produce a reduction in market prices, in a well-known rebound effect mechanism (Greening *et al.*, 2000; Bentzen, 2004; Barker et al., 2007; Sorrell, 2007; Saunders, 2008; Gillingham et al., 2013). This reduction in energy prices will increase energy demand, and if it is satisfied by fossil fuels, the CO_2 emission level is more difficult to be reduced. This means that improvements in energy efficiency will reduce the costs of achieving abatement targets from one side, but a countervailing effect might arise if cheap energy will induce an increase in consumption. This second effect might produce an increase in the carbon tax level necessary to oblige the system to fulfil the abatement target, if the energy mix is unchanged. To this sense, a second example is given by the introduction of quotas for renewable energies. If from one side energy efficiency might increase carbon tax level, when introducing renewable energies, the increase in energy demand provoked by the rebound effect might be satisfied by clean energy, thus reducing the carbon tax level. Another way of reasoning regards the linkages between energy efficiency and renewables in a context of no emission reduction targets. In this case, if energy efficiency will not produce a strong rebound effect resulting in a final reduction of energy demand, the share of renewable energies of a reduced energy demand amount will result in a reduced total amount of renewable energy demanded by consumers. This effect might influence the investors' behaviour negatively, reducing the total installed capacity of renewable energies, thus increasing the final production cost of energy, with a detrimental effect for final consumers. A possible solution to this negative effect might be the introduction of dynamic quotas, changing over time in order to maintain the proper stimulus for investors. This means that the interaction across different policy tools must be investigated in a dynamic setting, since changes over time of policy objectives might adjust existing trade-offs and side effects derived from the interaction of different policy tools.

The extent to which the side effects of each policy can be smoothed or removed by the interaction with other policies is strictly dependent from the case study under scrutiny.

A further aspect to carefully account for is to what extent the newly approved 2030 agenda will allow the EU to stay on track with respect to the long-term 2050 abatement goal. In other words, the cost of achieving the CO_2 abatement targets depends not only on the amount of emissions to be reduced and the alternative ways through which the reduction can be done, but also on the timing of the reduction path.

The analysis of the EU climate strategy under the lens of potential trade-offs or complementarities among simultaneous policies in a dynamic setting is an optimal case study to be developed both at the theoretical and empirical side.

In this paper, the EU2030 climate strategy will be addressed by considering the effects of alternative mixes of policy tools on selected impacts, as cost effectiveness, economic competitiveness, welfare effects, in a dynamic Computable General Equilibrium (CGE) analytical setting to consider the differences in costs of meeting the emissions targets due to the distribution of reductions through time.

The rest of the work is structure as follows. Section 2 provides the literature review on the relevance of the timing of reduction pathways, the policy mix strategies and the potential trade-offs, especially in the climate and energy economics literature. Section 3 illustrates the model description and simulation scenarios, while Section 4 and Section 5 outline, respectively, main results and conclusions.

2. Literature Review

There are several alternative policy options to mitigate climate change and the related negative externalities, in both economic and environmental terms. In particular, the EU has established the biggest market-based emission trading system (EU ETS) as the core mean to achieve the targeted GHG 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. Energy intensive sectors are more reliable on energy sources and, consequently, climate change policies may generate deeper negative impacts with respect to light industries (for example in term of production costs or competitiveness). This could also lead to variations in term of comparative advantages, especially for carbon intensive and trade exposed activities. In fact, in an interconnected global market, a unilateral policy may result in an increase of carbon intensive production in non-regulated countries, partially annulling the GHG reduction achieved in abating countries. Therefore, one of the main instruments invoked to correct for this negative mechanism, also known as carbon leakage, is the introduction of carbon tariff (as import tariff or export subsidies) based on the carbon content of the traded goods. Besides the fact that the implementation of such measures is not yet straightforward, also the potential benefits of reducing the leakage rate and restoring the competitiveness level are not necessary achieved at the same time (Antimiani *et al*., 2013b).

Even if the market-based EU ETS is addressed as the cost-effective solution to reduce CO_2 emissions, alternative mitigation measures can be implemented and, indeed, from 2005 Phase I of EU ETS, the evolution and structure of European climate policy has been more complex. This includes: sector specific goals and roadmaps, as for buildings, transport, biofuel; Strategic Energy Technologies Plans (SET Plans) for wind, solar, bioenergy, CCS, electricity grids, nuclear; the electricity market liberalisation; support to R&D in clean technologies; activities to support infrastructures, information and labelling programs (Kanellakis *et al*., 2013).

As remarked in the new EU2030, next to the main target of GHG emissions reduction, there are two more goals, binding at the EU level, to reach by 2030: energy efficiency and renewable energy. In line with the principle of cost-effectiveness, the EU ETS is the main instrument to achieve the 40% reduction target, but also the security of energy supply and economic competitiveness need to be assured. Members States are allowed to set ambitious national targets for energy efficiency and renewable energy, though, given the intermittent nature of renewable energy, they need to consider the degree of integration in the internal energy market.

Thus, together with the cost effectiveness issue, meaning that the EU aims to reach the climate policy target at the lower costs through the market based approach, also the impacts in term of distribution of economic costs and competitiveness are crucial. Indeed, possible trade off may arise and a first example is given by the rebound effect, which implies that, *ceteris paribus*, an increase in energy efficiency would reduce energy consumption but, leading to decreasing prices for energy commodities, can result in a higher energy demand (and GHG emissions). Hanley *et al.* (2009) claim that, in order to limit the risks of rebound effect, it is necessary to offset the positive impact in term of competitiveness due to the cheaper access to energy input, especially in energy-intensive firms. Thus, they conclude that "what energy efficiency stimuli do create is the potential for energy taxes to be levied without generating any of the adverse effects on economic activity that would otherwise be expected" (Hanley *et al*., 2009, p. 706).

Certainly, if the increase in energy efficiency actually leads to a reduction in energy consumption, the green quota of renewable energy is easier to achieve. As in the previous case, also support measures to renewable energy sources (RES) have been under scrutiny for their possible interaction with emission trading schemes. Lehmann and Gawel (2013) claims that the introduction of support measures for renewable electricity could result in a reduced demand for allowances (and hence in the price), shifting the emissions to other sectors covered by the EU ETS, and in welfare losses. However, they conclude that, while in a perfect competitive markets the EU ETS would be the only required measure, in real world situations with market imperfections and multiple policy objectives, RES support schemes may well complement the ETS in the energy mix.

Several examples of analysis of the economic impact of mitigation policies are available. Regarding the EU2020 policy, Böhringer *et al.* (2009a) evaluate the economic impact of the climate package and consider different policy scenarios with respect to a business-as-usual together with alternative baseline projections to 2020. They use the PACE model to investigate the potential for excessive costs in case of market segmentation and green quotas in the EU ETS. Among the alternative approaches used to analyse the climate package, Tol (2012) provides a cost-benefit analysis of the 2020 European targets; Capros *et al.* (2011) use an energy model with non-CO_2 greenhouse gas information to assess the inclusion of renewable targets and other policy options (Clean Development Mechanisms, trade of renewable permits, biofuel use in transport); Böhringer *et al* (2009b) compare three computable general equilibrium models to evaluate the costs associated to restricted trading across ETS and no ETS sectors and a renewable energy target.

Moreover, with the EU2030 recently being approved, even more effort is being directed to the definition of the optimal policy design, considering the potential costs of a complex policy mix and overlapping regulation. Few reports are already available on the EU2030, as: a Cost Benefit Analysis conducted by Enerdata (2014) on the additional costs of renewable energy and energy efficiency targets with respect to a market-based GHG reduction; a Briefing Paper by Ecofys with an assessment of ambition of the 2030 targets, also with respect to the 2050 goals (de Vos *et al*., 2014); the development and evaluation of long-term scenarios for a balanced European climate and energy policy until 2030 by E3MLab using PRIMES model (Capros *et al*., 2014); a Fraunhofer ISI Report (2014) on the estimation of the future costs of the energy system with renewable energy development[2]; an analysis on the interaction between emission trading mechanism and a minimum target for renewable energy sources, considering different electricity demand projections in a partial equilibrium model (Flues *et al.,* 2014).

In the long-run perspective to 2050, there are several examples of assessment of possible solutions to reach the defined CO_2 targets and the induced economic effects as in Hübler and Löschel (2013) or within the the CECILIA2050 Project (Meyer et al., 2014; de Koning et al., 2014). Hübler and Löschel (2013), for example, analyse the EU roadmap to 2050 in a CGE framework considering alternative unilateral and global policy scenarios, with and without the inclusion of Clean Development Mechanism (CDM) and equalization of permits price across sectors (ETS and non-ETS) and world regions. They conclude that R&D and new technology options are of crucial importance and that a unilateral European policy will have high mitigation costs, but they also remark that robust sectoral results are needed.

[2] They use the Green-X model, a specialised model on the future development and deployment of renewable energy sources, and the PowerACE model of the power sector, with the relations with conventional electricity supply and infrastructural prerequisites.

Even if a well-designed and operating ETS is able to move the system in the right direction (in term of decarbonisation of the economic system and promotion of energy efficiency and RES), nothing can ensure that it will also reach the specific targets by the identified year. Indeed, the timing of reduction path is particularly relevant when both short and long-term targets are considered, especially with respect to the different reduction potentials across technology and the risk of lock-in. The distribution of the reduction costs through time depends on technological progress, which will probably allow decreasing abatement cost through time, so that delaying the emissions reduction will be cheaper but also involve higher risks. Stavins and Olmestead (2010) claim that the Kyoto Protocol aims to reach "too little too fast" and suggest two possible solutions: "firm but moderate targets in the short term to avoid rendering large parts of the capital stock prematurely obsolete, and flexible but considerably more stringent targets for the long term to motivate (now and in the future) technological change, which in turn is needed to bring costs down over time" (Stavins and Olmestead, 2010, p.). Del Rio (2008) states that ETS is an adequate instrument ensuring the cost-effective abatement solution, but it might not guarantee long-term efficiency in term of incentives to mitigation technology and RD investment against carbon lock-in. Hence, he suggest integrating the market-based instrument with a more comprehensive technology policy. Moreover, Vogt-Schilb and Hallegatte (2014) investigate the optimal abatement pathway considering different types of marginal abatement cost (MAC) curves and abatement technologies that differ for costs and potentials. Firstly, they find that, given the influence of long-term objectives on short-term strategies, the inclusion of a 2050 target would change also the optimal strategy to 2020 or 2030. Moreover, they also suggest that implementing, in a sequential order, all those technologies with abatement cost lower than the carbon price and a unique price instruments may not be the best solutions.

Beyond the abatement timing issue, when the inherent coherence of the tools mix of the European climate policy is under scrutiny, there are several trade off to consider. In this respect, cost effectiveness apart, there is a fervent debate on the optimality of policy mix, on the interactions between different policy instruments and on possibilities for coordination.

Starting from Tinbergen (1952), from economic theory, we know that there should be at least the same number of instruments as there are targets. However, the existence of externalities, market failures and further economic, social or environmental goals may justify additional policy instruments. Accordingly, Böhringer *et al*. (2006, 2009a), Böhringer and Rosendhal (2010) and a report by OECD (2011) find that an appropriate instruments mix to climate change needs to be cautiously designed, otherwise the there could be the case for overlapping regulation that creates additional costs. Böhringer *et al*. (2006) investigate the potential losses deriving from the application of additional emission taxes in the EU emissions trading system, and conclude that the combination of the two measures can be ineffective and generate efficiency losses (in fact, firms subject to both instruments will abate more than efficiently required, while other firms within the

EU ETS will benefit from lower international emission permit prices). Böhringer *et al*. (2009a) provide and impact assessment of EU2020 climate package based on a CGE analysis. Their *first-best* conclusions suggest that the exclusion of non-energy intensive firms from EU ETS generates market segmentation and substantial excess costs with respect to uniform permit pricing. On the other hand, the introduction of green quota for electricity generation within the cap-and-trade system, leads to modest additional costs, because the increase in renewable energy production from EU ETS itself is already significant, and the effects of the additional subsides is low. Moreover, Böhringer and Rosendhal (2010) show that trading system (black quota) and renewables subsides (green quota) end up increasing the production of the most emission-intensive technologies, because in a cap-and-trade system where the emissions are fixed (by the black quota) the introduction of green quota reduces the permits prices, favoring the most emitting firms.

However, given market failures, environmental externalities and goals different from GHG emission abatement, additional measures could promote also other goals and be justified. Hence, a combination of policies to mitigate concentration of GHG emissions and, at the same time, to promote R&D activities, support technology or improve energy security may however occur (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 R&D) may allow reaching the abatement targets at lower costs than any single policy alone would imply. Furthermore, in presence of market distortions "If 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*., 2009a, p. S304).

In fact, an efficient ETS market would promote the achievement of the three goals in the right directions but, giving the existing imperfections, the energy efficiency and renewable energy instruments, other than being objectives in themselves, are meant to improve the ETS design and reduce market and technology failures, driving economic change toward sustainability. These three measure tend to reduce the consumption of fossil fuels, however while the ETS should increase the market price for energy sources, renewable and energy efficiency support tends to mitigate the increase in carbon prices. Moreover, the promotion of renewable energy technologies tends to reduce the incentives for energy saving promotion, while investment in energy efficiency (reducing, ceteris paribus, the level of fossil fuel demand and, consequently, the carbon price) can have antagonistic effect on the renewable production (Lecuyer and Bibas, 2012). In case of green quota, energy efficiency measure can facilitate to reach the desired level of renewable energy, especially in case of stringent target (Del Rio, 2010). Hence, the introduction of energy efficiency and renewable energy supports to an existing emission trading system can improve, respectively, the static and dynamic efficiency of the EU ETS, where the latter represents the ability to promote the diffusion and the locking-out of low carbon technologies (Sorrel, 2003; Del Rio, 2008).

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 of 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. In the context of the CECILIA2050 Project, for example, 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 Emission Trading System. According to Helm (2014), for example, the lack of adequate physical interconnections (as electricity grids and gas pipeline system) and competitiveness in the energy market have limited the benefits of a unified internal energy market. However, a critic is also directed to mistakes in policy design, as the fact that the introduction of renewables within the overall cap allowed for increasing consumption of coal.

Finally, further questions concern the optimality of 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).

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 as fossil fuels. There are numerous examples of simulation 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 it is the approach chosen, and depending on the issue under investigation, a particular aspect to take account for is the role of the behavioural parameters that regulate the responsiveness of economic agents and the effects of the modelled policy scenarios.

In particular, applied general equilibrium (AGE) or computable general equilibrium (CGE) models are analytical representation of the interconnected exchanges taking place among all the economic agents 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 and economic trade-off in a multi-region and intertemporal perspective.

Assessment of the potential impacts of climate change policy and mitigation measures are an essential input to policy decisions about what constitutes risky interference with the climate system (Burton *et al*., 2002). In the perspective of providing a comprehensive analysis of alternative policies, numerous global models combining economic and social data with climate and technology information have been developed. Great efforts have also been directed to link bottom-up technology models and LCA into partial or general equilibrium model to provide a better representation of the key energy system in more details (Guinée *et al*. 2010; Plevin *et al*. 2014; Creutzig *et al.* 2012; Masanet *et al*. 2013; Bento and Klotz 2014; Rajagopal 2014). In general, these models try to deal with the high level of uncertainty in the costs of mitigation policies, generally in 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.

3. Model

The dynamic version (GDynE) of the GTAP (Global Trade Analysis Project) model, as described in Golub (2013), is an upgrading of the static energy version GTAP-E (Burniaux and Truong, 2002; McDougall and Golub, 2007) in combination with the dynamic GDyn (Lanchovichina and McDougall, 2000).

In the static GTAP-E, energy enters in the production structure as a good within the energy-capital composite in the value added nest, with labour and land. The nesting structure presents the following levels: energy-capital composite, (within energy) electricity and non-electricity nest, (within non-electricity) coal and non-coal, (within non-coal) natural gas, oil, oil products. Energy demand is explicitly specified and there is substitution in both the factors and fuels mix. Data on CO_2 emissions are introduced through social account matrices (SAM) and are region and sector specific and it includes the modelling of market-based instruments, as carbon taxes and emission trading.

The dynamic version GTAP-Dyn 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, thus regional capital stock include capital stock physically located within the region as well as financial assets from abroad, and there is a Global Trust acting as the single intermediary for all the international investment. Physical capital is property of firms and households hold financial assets directly in local firms and, through the Global Trust, on equity of foreign firms. On the other hand, households own land and natural resources, which lease to firms, while the Global Trust hold equity in firms in all regions.

Time is an explicit variable in the model equations and dynamic representation of specific dynamics in global economy can be represented. In particular, in each period the financial intermediary distributes the global funds between regions according to investors' expectation. Hence, capital progressively moves to regions with high (expected) rates of return where the gap between expected and actual rates of return fall 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 production function in industrial sectors as a 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 GTAP-Dyn with the detailed representation of 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 path for both CO_2 emissions and 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 whole assessment of the economic impacts of standard 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 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 along with the arrays in standard GTAP-Database 8.1.

3.1 Model improvements

The GDynE model adopted for this assessment exercise contains two policy options modelled for the evaluation of the EU climate policy mix, a carbon tax and the investments in RD for energy efficiency and renewable energy.

The main novelty is that, together with the standard climate policy options represented by a carbon tax and emission trading system, we introduce a mechanism to finance directly RD in energy efficiency and renewable sources in the electricity sector, according to Antimiani *et al.* (2014). In this case, we suppose a different use of the revenue from environmental taxation, which directly finance RD activities, in terms of energy efficiency gains and the increase in the share of renewables. In this paper we assume that a portion of the total carbon tax revenue (CTR) is directed to financing RD activities in energy efficiency, in a input-augmenting technical change approach, and investments to increase the installed capacity of renewable energy. In this second case, investment efforts must be interpreted as an output augmenting technical change. In other 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 equivalent variation (EV). Indeed, an *Environmental Tax Reform* (ETR), shifting the tax burden to energy and polluting resource (lowering those on capital and labour[3]), could provide the potential for a *double dividend*, where the increase in environmental

[3] Examples are improvements in the labour market, cut on non-wage labour, as social security contributions paid by employers or on personal income taxes.

quality is coupled to economic benefits (see Bosquet, 2000; Goulder, 1995; Patuelli et al., 2002; Fernández et al., 2011).

The choice of the percentage to be taken from the CTR, collected through a carbon tax or an emissions trading scheme, and 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 EU, while in all the other regions the total amount of the CTR still contributes to the EV.

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, the formation of the CTRD is built as follows.

We have modelled the contribution to CTRD as a share of the total CTR[4]. In formulas, total revenue from CO_2 abatement is computed as:

$$CTR = CO2 \cdot CTAX \tag{1}$$

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, *CO2* is the amount of taxable emissions in EU.

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

$$CTRD = \alpha \cdot CTR \tag{2}$$

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:

$$EVnew = EV - CTRD \tag{3}$$

Having introduced the RD financing mechanism only in the EU, the value of the EV will be unvaried in all other countries except 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 EU and to zero for all the countries of the rest of the wold.

[4] In the GDYnE carbon taxation is modelled as a standard lump sum in welfare computation.

The total amount of CTRD can be used for improving technical change in energy efficiency (CTRDEE) and for improving output augmenting technical change in renewable energies (CTRDRW). The choice of the share of total CTRD to be directed to 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) 55% is directed towards energy efficiency (40% in firms and 15% in households) and 45% to renewable energies. Accordingly:

$$CTRDEE = \beta \cdot CTRD \tag{4}$$

$$CTRDRW = \gamma \cdot CTRD \tag{5}$$

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

The relationship between technical change in energy efficiency and CTRDEE is modelled in a very simple way. An elasticity parameter, $R_{EE}(i,j)$, is taken in order to transform RD efforts (millions of US dollars) into technical progress in energy efficiency by using an average (*and rather low*) elasticity value based on the literature on this topic (Adams and Jaffe, 1996; Griffith et al., 2006; Griliches and Lichtenberg, 1984; Hall and Mairesse, 1995; Lichtenberg and Siegel, 1991).

In this case, we adopted a differentiated value for R_{EE} for energy inputs (i) that influences produced commodities (j) in 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

$$t_{EE}(i,j) \; = \; R_{EE}(i,j) \; \cdot \; CTRD_{EE} \tag{6}$$

where $t_{EE}(i,j)$ is the technical energy efficiency gain in input *i* as a result of funds allocated to R&D in energy efficiency that uniformly influence productivity in all sectors. In this paper we have assumed that all R&D efforts from the fund 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:

$$R_{EE}(j,r) = EE\ gains / RD_{EE,t-1} \tag{7}$$

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 use and technologies. In order to better shape such dynamic pattern, it will be necessary to link the macro CGE model with bottom-up energy models, which is out of the scope of the current work but it will constitute the next research agenda.

The second technology option is to use CTRD to finance the increasing production of renewable energies. In this case, a share of $CTRD$ devoted to technology options is directed toward financing the production of renewable energies. Here, from a pure modelling approach, what it is affected is not an input augmenting technical change parameter as $t_{EE}(i)$ in energy efficiency, but an improving technical change measure in the electricity sector, given by $el_{RW}(j)$ (we ignore biofuels and other non-electricity renewable sources):

$$el_{RW}(j,r) = [R_{RW}(j,r)] \cdot CTRD_{RW} \tag{8}$$

where $R_{RW}(j)$ represents the reactivity of the electricity sector to R&D investments. In this specific case, the reactivity parameter is calibrated with regard to the last ten years of investment in R&D activities in renewable energies (RD_{RW}) and the corresponding increase in installed capacity in renewable electricity in OECD countries, at the numerator in the following formula (IEA energy Balance dataset available online):

$$R_{RW}(j,r) = \frac{(C_t - C_{t-1})}{C_{t-1}} / RD_{RW\ t-1} \tag{9}$$

3.2 Baseline and policy scenarios

The model will be used to conduct an analysis on EU2030 policy but, coherently with CECILIA2050 Project, the GDynE in use extends the time horizon to 2050 in order to perform long-term analysis of climate change policies in a world-integrated framework.

GDynE here developed presents the EU at aggregate level, and the projections for macro variables 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 (which result as aggregate) with those provided by the GTAP Macro projections (where skilled and unskilled labour force 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 as GCAM in a "Do-nothing"[5] scenario for EU countries are also compared with GDynE output.

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 is 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 policy options (emission trading, carbon tax, RD efforts in energy efficiency and renewable energies in electricity production), these are based on the 450PPM scenario developed by IEA (and RCP 2.6 by IPCC) and the EU2030 scenario. Indeed, the 450PPM Scenario establishes the goal of limiting the concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO2 equivalent (ppm CO2-eq). In the latter, the 2030 target recently adopted by the European Parliament is considered, consisting in a reduction of CO_2 emissions of 40% by 2030 with respect to 1990 levels, while the 2050 target is the same as in the 450PPm Scenario. In particular, the reduction requirement at year 2030 is more stringent in the 450PPM case.

The abatement target to 2030 can be achieved by implementing different policy options, which are at the basis of the EU2030 strategy, which is the focus of this paper.

The first policy option refers to market-based instruments for emission abatement purpose, as a domestic carbon tax, where every country or region reduces its own emissions internally, and an international emission trading system, which allows all countries to trade emissions until an equilibrium price is reached. In order to simplify the analysis, by modelling EU as an aggregate, the two market-based policy options, carbon taxation and emission trading, result as perfectly equivalent, since the Pigouvian carbon tax in the whole EU corresponds to the minimum cost for achieving the target, which is equivalent to the permits price level if EU countries are singled out and the whole economy is involved into emission trading system.

The second policy option is the increase in energy efficiency, with a target declared by the EU2030 strategy which refers to an improvement in energy efficiency by 27% in 2030 with respect to a current policy scenario.

The third policy option here tested refers to the share of renewable energies in the energy mix. Considering the specific GDynE model features, we have modelled only a part of the EU2030 strategy, namely the share of

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

45% of electricity produced by renewable sources by 2030 (EC, 2014a), without considering other renewables used in other sectors.

In terms of the temporal dimension, we consider a temporal horizon from 2010 to 2050. However, given the extent of the EU2030 policy, after 2030 there are no additional exogenous shocks to the model, and results are only affected by the cumulative path and dynamics deriving from previous periods. As a standard modelling choice, periods here are shaped as a 5-year temporal structure.

As far as the country and sector coverage is concerned, we consider 20 regions and 20 sectors. With respect to the former, we distinguishing 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). The former includes countries in Annex I in the Kyoto Protocol or rich ones with less relevance with respect to efforts to emissions abatements. Among the developing aggregate, we consider single countries (the main emerging economies with strong bargaining positions in the negotiations and eligible to emission cut commitment) as well as aggregates. Finally, considering a geographically based rule (Africa, America and Asia) we distinguish both energy exporter countries group and all remaining ones (rest of) into three groups each. In fact, it is relevant to analyse the impact of abatement policies on economies rich in natural resources but it is also crucial to compare it with the effect on countries in the same area with less or none resource availability, and across macro regions.

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.

What we are most interested in, is performing a sensitivity analysis looking to different behavioural parameters sets and analysing what happen to the model's results when we change the values of elasticities of substitution in the energy nests.

4. Results

The different policy options here considered are:

450PPM: only EU reduces emissions with a domestic market price policy (carbon tax), respecting the 450PPM scenario by 2050 developed by IEA;

450PPM-10: The same as before but we also apply a 10% to the total carbon tax revenue to be detracted from the lump sum and directed to RD activities in energy efficiency and the production of electricity with renewable sources.

450PPM-20: The same as before but we apply a 20% levy on the total carbon tax revenue.

EU2030: only EU reduces emissions with a domestic market price policy (carbon tax), respecting the 40% reduction by 2030 and the 450PPM scenario by 2050 developed by IEA.

EU2030-10: The same as before, but we also apply a 10% to the total carbon tax revenue to be detracted from the lump sum and directed to RD activities in energy efficiency and the production of electricity with renewable sources.

Table 1 - Carbon Tax level for EU27 (US Dollars per ton)

	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
GCTAX	13	26	103	206	269	340	457	582
EUCTAX	10	17	71	140	173	209	266	310
EU2030-10	12	23	68	126	152	180	224	252
EU2030-20	12	22	66	117	138	160	195	216
EU2030-30	12	22	63	109	126	145	175	193

Table 2 - EU Carbon Tax Revenue for EU27 (Million US Dollars)

	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
GCTAX	47,693	86,446	294,660	489,313	529,765	546,462	608,885	626,520
EUCTAX	34,961	58,484	201,463	331,171	342,343	346,852	362,743	347,354
EU2030-10	44,737	76,569	194,718	298,034	302,138	298,711	303,927	281,208
EU2030-20	44,689	75,468	187,709	278,077	273,277	264,093	263,434	240,486

EU2030-30	44,626	74,298	180,686	259,896	249,592	238,273	235,713	214,375

The outcome in terms of an aggregate amount of budget to be invested in RD in the two technological domains (energy efficiency and renewable) could constitute an overall value to be reproduced in more details by models controlling for more specific technological patterns. As an example, in Table 3, it is worth noting that the increasing abatement targets over time produce an increase in carbon tax level, which ensures an increasing value of RD investments up to 2045, where the trend is inverted.

Table 3 – Annual flows of public investment in RD activities for EU (Mln$)

	Year	*2010*	2015	2020	2025	2030	2035	2040	2045	2050
EU2030-10	Energy Efficiency	*1,936*	2,684	4,594	11,683	17,882	18,128	17,923	18,235	16,872
	Renewable Energy	*1,589*	1,789	3,063	7,789	11,921	12,085	11,948	12,157	11,248
EU2030-20	Energy Efficiency	*1,936*	5,363	9,056	22,525	33,369	32,793	31,691	31,612	28,858
	Renewable Energy	*1,589*	3,575	6,037	15,017	22,246	21,862	21,127	21,075	19,239
EU2030-30	Energy Efficiency	*1,936*	8,033	13,374	32,523	46,781	44,926	42,889	42,428	38,587
	Renewable Energy	*1,589*	5,355	8,916	21,682	31,187	29,951	28,592	28,285	25,725

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 with respect to 2010 registered value, thus revealing a feasible policy mix strategy.

Table 4 - Energy Intensity for EU27 (Toe/Million US Dollars)

	2010	2015	2020	2025	2030	2035	2040	2045	2050
BAU	146.68	124.48	104.88	91.81	*82.41*	74.01	66.98	60.67	56.19
GCTAX	146.68	121.43	98.62	77.81	60.44	47.43	37.59	29.76	24.17
EUCTAX	146.68	121.15	98.64	78.58	62.29	50.10	40.70	33.31	28.18
EU2030-10	146.68	120.90	98.01	77.41	*60.68*	48.26	38.73	31.38	26.23
EU2030-20	146.68	120.66	97.47	76.39	*59.34*	46.86	37.34	30.12	25.03
EU2030-30	146.68	120.42	96.94	75.47	*58.23*	45.76	36.31	29.22	24.20

These results can be taken as the starting point for a deeper investigation at the technology specific level. Efforts in clean technologies could produce different impacts in terms of GDP, where investments in the energy sector seem to be the most promising in terms of GDP gains.

Additionally, with respect to the gains obtained by fostering clean technologies in the energy sector, by looking at GDynE results it is possible to detect which are the economic sectors benefiting the most from this technology improvement. From Table 5 it is clear that by introducing an increasing levy on carbon tax revenue the losses in GDP with respect to BAU reduce up to the 30% levy where efficiency gains are higher than the abatement cost losses.

Table 5 – GDP losses with respect to BAU for EU (%)

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
EUCTAX	-0.09	-0.27	-0.80	-1.78	-2.86	-3.86	-4.73	-5.45
EU2030-10	0.00	-0.02	-0.14	-0.42	-0.75	-1.04	-1.32	-1.54
EU2030-20	0.14	0.30	0.58	0.83	1.01	1.14	1.17	1.18
EU2030-30	0.26	0.62	1.25	1.92	2.46	2.86	3.08	3.21

Table 6 - EV losses with respect to BAU for EU (%)

Scenarios	2015	2020	2025	2030	2035	2040	2045	2050
GCTAX	-0.01	0.45	0.54	1.16	2.59	4.56	6.28	8.48
EUCTAX	-0.08	-0.26	-0.72	-1.59	-2.26	-2.54	-2.54	-2.47
EU2030-10	0.00	-0.08	-0.28	-0.61	-0.71	-0.59	-0.36	-0.13
EU2030-20	0.09	0.13	0.18	0.21	0.43	0.73	1.03	1.29
EU2030-30	0.17	0.33	0.60	0.91	1.32	1.71	2.02	2.26

Table 7 - Differences in Allocative Efficiency w.r.t. EUCTAX for EU27 (Million US Dollars)

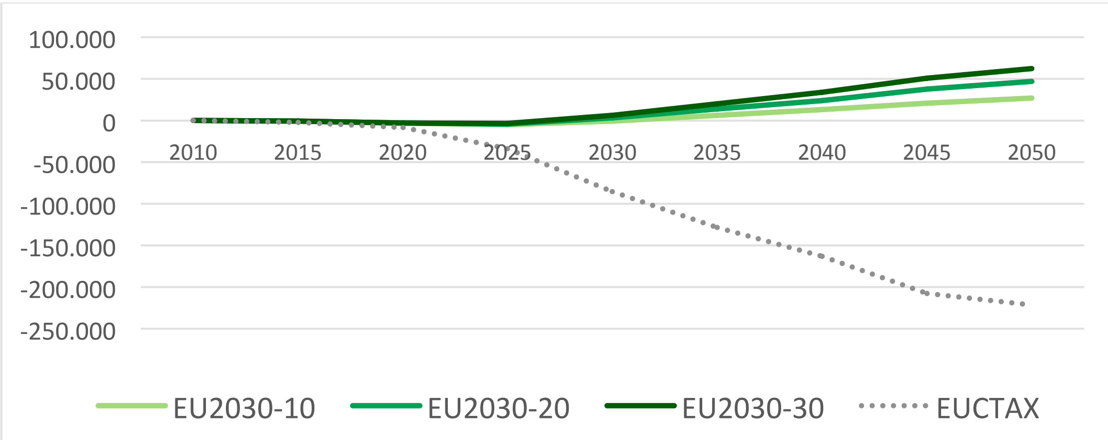
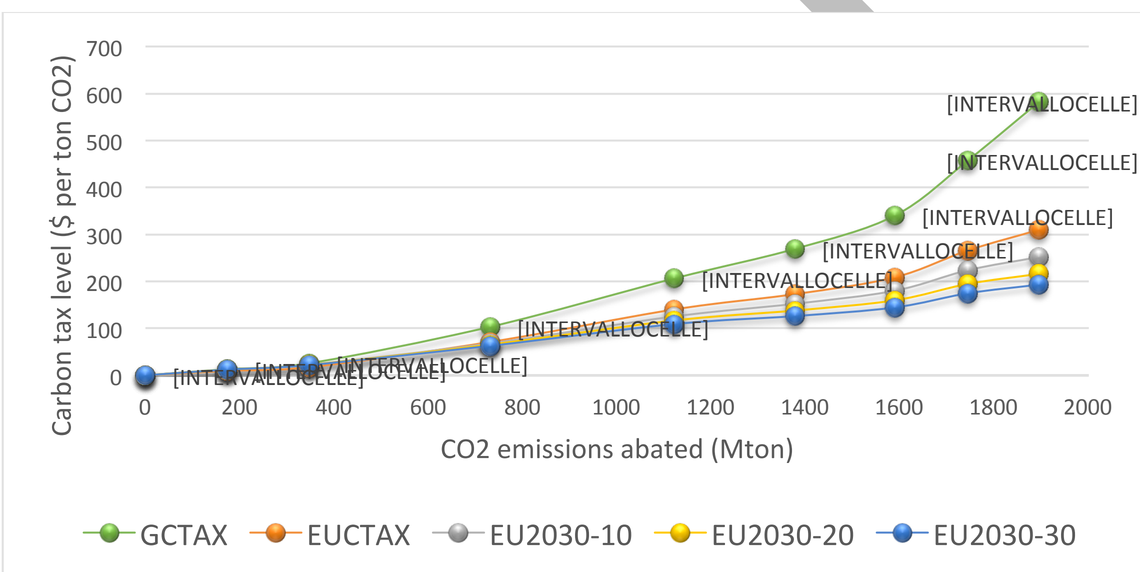


Table 8 - Marginal abatement cost curves for EU27



When the specific manufacturing sectors are scrutinised, it is worth mentioning that energy-intensive sectors are negatively influenced by emissions reduction if a proper policy mix with RD in clean energy technologies is not implemented (EUCTAX scenario). Losses in output with respect to BAU are consistently reduced if energy efficiency and renewables are fostered by RD activities.

Table 9 – Differences in Output value from BAU for EU (%)

Scenarios/Sectors	2015	2020	2025	2030	2035	2040	2045	2050
EUCTAX								

Non-metallic minerals	0.04	-0.01	-0.06	-0.19	-0.52	-0.99	-1.50	-1.97
Chemicals	0.03	-0.12	-0.36	-0.94	-1.98	-3.44	-5.15	-6.64
Basic metals	0.02	-0.24	-0.78	-2.41	-5.28	-8.60	-11.75	-14.10
Transport eq.	0.02	-0.09	-0.25	-0.66	-1.35	-2.21	-3.05	-3.66
Machinery eq.	0.03	-0.01	-0.14	-0.27	-0.77	-2.04	-3.45	-4.28
EU2030-10								
Non-metallic minerals	0.05	0.03	0.05	0.01	-0.07	-0.17	-0.27	-0.34
Chemicals	0.05	0.01	-0.06	-0.30	-0.65	-1.08	-1.52	-1.85
Basic metals	0.03	-0.24	-0.71	-1.99	-3.81	-5.44	-6.61	-7.12
Transport eq.	0.02	-0.05	-0.16	-0.40	-0.74	-1.05	-1.27	-1.29
Machinery eq.	0.06	-0.05	-0.25	-0.67	-1.26	-1.92	-2.38	-2.32

Table 10 - Differences in Export value from BAU for EU (%)

Scenarios/Sectors	2015	2020	2025	2030	2035	2040	2045	2050
EUCTAX								
Non-metallic minerals	-0.20	-0.55	-1.60	-3.26	-5.07	-6.89	-8.35	-9.57
Chemicals	-0.16	-0.48	-1.25	-2.62	-4.59	-6.92	-8.92	-10.74
Basic metals	-0.48	-1.38	-4.19	-8.84	-13.79	-18.44	-21.73	-24.34
Transport eq.	-0.01	-0.12	-0.25	-0.55	-1.35	-2.35	-3.13	-3.59
Machinery eq.	0.16	0.16	0.65	0.92	-0.31	-2.21	-3.48	-4.06
EU2030-10								
Non-metallic minerals	-0.19	-0.52	-1.40	-2.59	-3.65	-4.54	-5.10	-5.47
Chemicals	0.02	-0.07	-0.38	-0.86	-1.48	-2.15	-2.67	-3.03
Basic metals	-0.45	-1.19	-3.20	-6.05	-8.52	-10.39	-11.21	-11.54
Transport eq.	-0.01	-0.15	-0.47	-0.89	-1.39	-1.83	-1.94	-1.78
Machinery eq.	0.05	-0.18	-0.70	-1.51	-2.65	-3.69	-3.91	-3.55

For those sectors largely influenced by alternative policy strategies (for instance, Chemicals or Basic Metals), simulations with technology-specific models might be implemented in order to detect which kind of specific technologies should be adopted and diffused in order to maximize the positive outcome of the policy mix.

5. Conclusions

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Appendix

Table A.1 - List of GDYnE countries

GTAP code	Cod e	Country	GTAP code	Cod e	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 Former Soviet Union	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 Eastern Africa	REU	alb	Albania
EU27	cze	Czech Republic	RAF	xsc	Rest of South African Custom	REU	hrv	Croatia
EU27	dnk	Denmark	RAF	xwf	Rest of Western 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 aggregates

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 aggregates

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 (Billion constant 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 CO_2 Projections to 2050 (Gt CO_2)

	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%