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ISSN 2279-6916 Working papers
(Dipartimento di Economia Università degli studi Roma Tre) (online)

Working Paper n° 236, 2018
I Working Papers del Dipartimento di Economia svolgono la funzione di divulgare tempestivamente, in forma definitiva o provvisoria, i risultati di ricerche scientifiche originali. La loro pubblicazione è soggetta all'approvazione del Comitato Scientifico.

Per ciascuna pubblicazione vengono soddisfatti gli obblighi previsti dall'art. 1 del D.L.L. 31.8.1945, n. 660 e successive modifiche.

Copie della presente pubblicazione possono essere richieste alla Redazione.

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REDAZIONE:
Dipartimento di Economia
Università degli Studi Roma Tre
Via Silvio D'Amico, 77 - 00145 Roma
Tel. 0039-06-57335655  fax 0039-06-5733571
E-mail: dip_eco@uniroma3.it
http://dipeco.uniroma3.it
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Some reflections on policy mix in the EU low-carbon strategy

Massimiliano Corradini, Department of Business Studies, Roma Tre University, Rome, Italy
Valeria Costantini, Department of Economics, Roma Tre University, Rome, Italy
Anil Markandya, Ikerbasque Professor, Basque Centre for Climate Change (BC3), Bilbao, Spain
Elena Paglialunga, Department of Economics, Roma Tre University, Rome, Italy
Giorgia Sforna, Department of Economics, Roma Tre University, Rome, Italy

Abstract
The EU low-carbon strategy includes different complementary policies. Potential interactions between instruments and timing of their implementation can influence the cost and likelihood of achieving the targets. We test the interactions between the three main pillars of the EU strategy through a dynamic CGE model (GDynEP) with a time horizon of 2050. Main results are: i) going for the unilateral EU carbon mitigation target without any complementary technological policy will produce large economic losses; ii) by investing in clean energy technologies (energy efficiency and renewable energy) with a carbon tax revenue recycling mechanism, these losses will substantially decrease; iii) when complementary clean energy technology policies are implemented, the optimal timing of binding targets changes; iv) the higher the contribution to clean energy technologies, the larger the economic gains in early adoption of challenging abatement targets.

JEL codes: H21; O32; Q47; Q54

Keywords: EU low-carbon strategy; dynamic CGE model; GTAP; abatement optimal timing; policy mix design; clean energy technologies

Acknowledgements
We acknowledge financial support received by the EU D.G. Research (research project “CECILIA2050 — Choosing efficient combinations of policy instruments for low-carbon development and innovation to achieve Europe's 2050 climate targets”, grant agreement no. 308680), the Italian Ministry of Education, University and Research (Scientific Research Program of National Relevance 2010 on “Climate change in the Mediterranean area: scenarios, economic impacts, mitigation policies and technological innovation”), the Regione Lazio (research project SMART ENVIRONMENTS), and the Department of Economics of Roma Tre University. We are also indebted with the research group of the National Consortium CREA-ENEA-ROMATRE for the continuous scientific support in CGE modelling.

* Corresponding author: Valeria Costantini, Department of Economics, Roma Tre University, Via Silvio D’Amico 77, 00145 Rome, Italy. Tel: +39 06 57335749. Fax: +39 06 57335771. Email: valeria.costantini@uniroma3.it.
Summary

The Climate and Energy Policy Framework approved by the European Union (EU) in October 2014 (hereafter EU2030), constitutes a very challenging objective in climate mitigation policy. The EU2030 strategy explicitly combines different policy instruments and objectives in a unique strategy with three goals to be achieved by 2030: a 40% reduction in greenhouse gas (GHG) emissions with respect to 1990 levels; an EU-wide binding target of at least 27% of final energy consumption from renewable sources (RS); and a 27% increase in energy efficiency (EE) with respect to a business as usual scenario (BAU).

Accordingly, the EU low-carbon strategy includes different complementary policies. While GHG reduction is clearly a target and deserves a policy instrument, the other two goals (RS and EE) are simultaneously targets, set to address potential negative effects deriving from excessive costs in achieving the GHG reduction target. Indeed, the European Emission Trading System (ETS) as the instrument historically chosen by the EU for respecting the reduction target (Sáenz de Miera and Muñoz Rodríguez, 2015), has been found not to be dynamically efficient and needs to be complemented with incentives for innovation in clean energy technologies (CET) to reduce negative economic impacts on regulated firms (Martin et al., 2016).

The ambitious targets of the EU long term energy transition policy raise, in our view, five open questions: the effectiveness of the ETS in achieving the abatement targets; the choice of the criteria to evaluate the policy mix performance (once acknowledged that complementary CET policies are required and affected by the double role of targets and instruments); the effects of the interaction of such complementary policies with the carbon pricing mechanism; the financing mechanisms of complementary instruments and CET policies; the potential interactions between instruments and the timing of their implementation (influence on costs and likelihood of achieving the targets).

To address the above questions and empirical analyse the interactions between the three main pillars of the EU strategy, we develop a dynamic CGE model (GDynEP) with a time horizon of 2050 that contains the standard carbon pricing mechanism, two additional policy instruments (public support to EE and RS), and a novel financial mechanism for such public policy support modelled via a carbon tax revenue (CTR) recycling mechanism. Considering the different reduction potentials of alternative technologies and the risk of technological lock-in, we also compare two emission paths that correspond to two different timing profiles with respect to short and long-term targets.

Main results are: i) going for the unilateral EU carbon mitigation target without any complementary technological policy will produce large economic losses; ii) by investing in clean energy technologies (energy efficiency and renewable energy) with a carbon tax revenue recycling mechanism, these losses will substantially decrease; iii) when complementary clean energy technology policies are implemented, the optimal timing of binding targets changes; iv) the higher the contribution to clean energy technologies, the larger the economic gains in early adoption of challenging abatement targets.
1. Introduction

The Climate and Energy Policy Framework approved by the European Union (EU) in October 2014, and submitted to the United Nations Framework Convention on Climate Change (UNFCCC) as the EU’s Intended Nationally Determined Contribution (INDC) in view of the Paris Conference of Parties (COP21) (hereafter briefly addressed as EU2030 (EC, 2014a, 2014b, 2014c, 2014d)), constitutes a very challenging objective for the EU in climate mitigation policy. The EU2030 strategy follows the previous EU climate agenda, the so-called EU2020, and explicitly combines different policy instruments and objectives in a unique strategy defining three goals to be achieved by 2030: a 40% reduction in greenhouse gas (GHG) emissions with respect to 1990 levels; an EU-wide binding target of at least 27% of final energy consumption from renewable sources (RS); and a 27% increase in energy efficiency (EE) with respect to a business as usual scenario (BAU).\(^1\)

While GHG reduction is clearly a target and deserves a policy instrument, the other two goals are simultaneously targets set to address potential negative effects deriving from excessive costs in achieving the GHG reduction target. Indeed, the European Emission Trading System (ETS) as the instrument historically chosen by the EU for respecting the reduction target (Sáenz de Miera and Muñoz Rodríguez, 2015), has been found not to be dynamically efficient and needs to be complemented with incentives for innovation in clean energy technologies (CET) in order to reduce negative economic impacts on regulated firms (Martin et al., 2016). The co-occurrence of the two as policy targets and instruments implies the need to analyse the effectiveness of the policy mix design of the EU energy strategy.

With this purpose, recent contributions emphasize the need for adopting a broad perspective in the analysis of the EU energy transition policy mix design that not only examines the interaction of instruments, but also captures other aspects related to the policy mix in terms of its coherence and consistency, and the correspondence of policy strategies with their long-term targets (Rogge et al.,

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\(^1\) This 27% renewable energy target share in 2030 would translate in a 45% share in renewable electricity, in a range from 43% to 47% according to domestic technological capabilities and energy mix of Member States (EC, 2014a; 2014c).
The present paper contributes to this debate by focussing on three specific aspects: i) the reciprocal influence of instruments and targets forming the EU2030 strategy; ii) the potential benefits deriving from the application of a revenue recycling mechanism of carbon taxation; iii) the linkages between different timing of abatement profiles and policy mix effectiveness under different evaluation criteria. Henceforth, the EU2030 strategy is analysed by considering the effects of alternative mixes of policy tools and of different distributions of reduction targets over time on selected issues, namely cost effectiveness and economic impacts. We develop a dynamic Computable General Equilibrium (CGE) model that simulates the EU2030 strategy under different combinations of the three main policy pillars and tests alternative timing profiles of decarbonisation path up to 2050.

The findings are: i) going for the unilateral EU carbon mitigation target without any complementary technological policy will produce large economic losses; ii) by investing in CET (energy efficiency and renewable energy) with a carbon tax revenue recycling mechanism, these losses will substantially decrease; iii) alternative distributions of financial support to the two CET options under investigation produce different impacts on the overall mitigation cost; iv) when CET policies are implemented, the optimal timing of binding targets changes and the higher the contribution to CET, the larger the economic gains in early adoption of stringent abatement targets.

The rest of the work is structured as follows. Section 2 reviews the literature on open issues on ex-ante evaluation of the EU energy transition strategy with respect to policy mix setting and timing; Section 3 describes the dynamic CGE model; Section 4 provides the numerical simulation results; Section 5 outlines main conclusions and policy implications.

2. Literature review

The ambitious targets of the EU long term energy transition policy raise, in our view, five open questions that deserve further empirical analysis in order to provide policy makers quantitatively grounded advices to improve effectiveness of the policy mix design while minimizing the costs for
such energy transition process.

The first concern regards the effectiveness of the EU-ETS in achieving the abatement targets, given two crucial factors that influence the carbon pricing mechanism that are uncovered by the current ETS design. First, EU Member States actually have a plethora of policies, as taxes, tradable permits, subsidies, tax exemptions, simultaneously influencing the carbon emission levels with evident contrasting effects on price mechanisms. Second, the ETS was initially designed as a compensating mechanism for those energy intensive industries that would face large economic losses from a carbon mitigation policy. This would have implied the implementation of a carbon policy for the whole economic system. In practice, however, a carbon tax at the national level, including non-ETS sectors, has been adopted only in few EU countries (e.g., Denmark, Finland, Italy, Sweden) with heterogeneous mechanisms, values and temporal application. Accordingly, the ETS sectors emerge as the only ones contributing substantially to mitigation targets through a market-based instrument at the EU level, and this implies increasing mitigation costs precisely for those sectors that need to be protected. For this reason Tol (2013) proposes that a carbon tax applied to EU Member States in a coordinated approach would be rather preferred to the current ETS in order to achieve the abatement targets at lower costs.

The second issue is the choice of the criteria to evaluate the policy mix performance, once it is acknowledged that complementary CET policies are required but are affected by the double role of targets and instruments. When designing the policy framework, it must be considered that a number of dimensions are relevant to instrument choice, such as cost effectiveness, equity in distributive effects, etc., and that no single instrument is best along all dimensions (Goulder and Parry, 2008). Accordingly, a combination of different instruments would not violate Tinbergen’s rule as long as the different policy evaluation dimensions correspond to different policy targets, or in other words if there are coexisting market failures that should be addressed (Tinbergen, 1952, 1956). As an example, while a carbon tax is justified by the existence of the negative environmental externality, additional policies to promote CET are needed to the extent that they address other market failures, such as the
free riding behaviour of agents in exploiting knowledge created by others. As another example, while CET development and diffusion for EE and RS are instruments for reducing the weight of reduction costs on the economic system, higher performance in EE and larger shares of RS on energy production are targets themselves from an energy security strategy perspective. In the case of a such complex framework, policy evaluation exercises should look at the performance of the entire policy mix bearing in mind the multiple targets under investigation (Görlach, 2014).

The third critical point in the literature refers to the effects of the interaction of such complementary policies with the carbon pricing mechanism. Several authors have analysed the EU energy and climate strategy focussing on the cost effectiveness of the policy mix and potential economic losses for the EU economy, especially in a unilateral climate policy perspective, by considering: the 2020 targets (Böhringer et al., 2009a,b; Capros et al., 2011; Tol, 2012), the long-term implications (Capros et al., 2014; Hübler and Löschel, 2013), and the potential costs of overlapping climate and energy instruments (de Vos et al., 2014; Enerdata, 2014; Flues et al., 2014; Fraunhofer ISI Report, 2014). One outcome from these investigations is the observation that, given environmental policy usually operates in a second-best setting, the existence of externalities, market failures and other economic, social, environmental and technology goals may justify additional policy instruments and the appropriate instruments mix should be designed to avoid additional costs caused by the overlapping regulation (Böhringer et al., 2009a; 2016; OECD, 2011).

Selected contributions typically analyse single interaction mechanisms. A first example is given by the mutual influence played by support measures for RS and a carbon pricing mechanism. In a cap-and-trade system where emissions are fixed, the introduction of support measures for RS could result in a reduced demand for allowances with the consequence of increasing the production of the carbon-intensive technologies and shifting of emissions to other sectors not covered by the permits scheme (Böhringer, 2014; Delarue and van der Berg, 2016; Lehmann and Gawel, 2013). The consequent reduction in carbon prices, coupled with lower incentives for innovation and investment in green technologies, may increase the overall costs of the climate strategy and harm the acceptance
of climate policy. Contrary to the aforementioned studies, Duscha et al. (2016) suggest that even if RS are not the most cost-effective option, they can help achieve a triple dividend (environmental protection, energy security and jobs creation) resulting in positive (but still uncertain and model-specific) economic gains, which could be further increased with a higher RS share from more diversified sources. Accordingly, in order to achieve the potential economic benefits fully from RS transition, energy and climate policy should be enhanced beyond the pure market mechanism and integrated with industrial and innovation policies (Ćetković and Buzogány, 2016).

A second example of policy interaction concerns the mutual influence between EE and the carbon pricing mechanism. From one side EE contributes to the emissions reduction goal and also reduces the vulnerability of consumers to high and volatile energy prices, thus enhancing the security of the energy system. From the other side, if substantial energy savings are achieved, energy becomes cheaper. Accordingly, the reduction in energy prices could further lead to an increase in energy demand due to a rebound effect mechanism (Barker et al., 2007; Bentzen, 2004; Gillingham et al., 2013). In addition, lower carbon prices would also result in lower incentives for GHG abatement and, eventually, reduce ETS revenue that governments can use to support complementary climate actions.

The third example of interaction refers to the co-existence of the three policy pillars under scrutiny. While the ETS increases the market price for fossil energy, support for RS and EE tends to mitigate price rise, partly reducing the decarbonisation trend. Moreover, the promotion of RS technologies tends to reduce the incentives for energy saving and investment in EE (reducing, ceteris paribus, the level of fossil fuel demand and, consequently, the carbon price). This in turn can have a negative effect on RS production (del Río, 2008). These interactions strongly depend on the specific instruments in place and the optimality of the policy mix depends on how each instrument and its interaction with the other could support the set of targets the policy makers have in mind (del Río, 2010). Following Popp (2016), an optimal climate policies portfolio should include both carbon pricing and support for innovation because while the latter can address knowledge-related market failures, only the former can stimulate demand for low-emission technologies and their diffusion and
adoption. Accordingly, while ETS may be addressed as the cost-effective instrument to reduce emissions, it is a short-term mechanism more driven toward a “pick winners” strategy rather than providing enough incentives for radical innovation and backstop technologies in the long-term (Gerlagh et al., 2014). At a more general level, the overall policy mix should present consistency of the instruments mix with the policy strategy in order to work in a unique direction (Rogge and Reichardt, 2016). This is particularly difficult in the case of the EU long-term energy transition strategy given that the policy targets in some cases also correspond to instruments, thus adding uncertainty elements in the complex interactions architecture.

The fourth relevant issue regarding the EU2030 strategy concerns the financing mechanisms of complementary instruments, especially regarding technology development and diffusion. Although according to the Directive 2009/29/EC (EC, 2009), the financing mechanism of CET policies has been already determined, as at least half of the ETS auctioning revenues should be used to reduce GHG emissions by promoting EE and RS (Esch, 2013; Grießhaber, 2011),\(^2\) empirical analyses on the effects associated with such revenue recycling mechanism are few, and mainly look at where revenues are allocated, as for instance to support the overall tax system (Bowen, 2015), or to finance innovation policies (Bosetti et al., 2011), without any assessment on effectiveness and performance of the overall policy mix.

The last issue is the influence of alternative timing profiles on policy mix effectiveness. In other words, the cost of achieving the emissions target depends not only on the amount of emissions to be reduced and the multiple choices of policy support through which the reduction can be achieved, but also on the timing of the reduction path. Bearing in mind the different reduction potentials of alternative technologies together with the risk of technological lock-in, the timing of the reduction

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\(^2\) Revenues from the auction process of emission permits in the ETS over the period 2013-2015 were allocated as follows: 80% to “green spending” (energy efficiency, renewable energy, R&D and any other effort for GHG reduction) and 20% to general government funds without spending obligations. No share of the carbon revenue, however, was recycled for reducing other tax rates on firms or individuals (Carl and Fedor, 2016). In particular, according to Vaidyula and Alberola (2016), over the same period about 29% and 28% of the ETS revenue were used for, respectively, RS and EE support on average, inherently linking the first pillar of the EU climate policy (GHG reduction via carbon pricing) with the other two.
path is particularly relevant when both short and long-term targets are considered. On one side, the early adoption of stringent targets might face opposition in general opinion given the gap between the large (and quite concrete) short term economic costs of abatement and long term potential and uncertain benefits from mitigating global warming, referred to as the climate policy dilemma (Pindyck, 2013). On the other side, efforts in fast-tracking the adoption of low-carbon transition pathways might bring first mover comparative advantages due to technological competitiveness, thus reducing welfare costs due to delaying interventions (Acemoglu et al., 2016).

3. Model settings and scenarios

To address the questions posed above we develop a dynamic CGE model based on a modified version of the GTAP (Global Trade Analysis Project) model, hereafter referred to as GDynEP. Given the ex-ante nature of such scenario analysis and the large amount of behavioural parameters, input-output data at the sector and country level, inter-sectoral and international linkages to be included, a CGE framework allows for all these issues to be examined relying on well-established and already existing databases and modelling methodologies.

GDynEP results from merging the GDynE (the energy version of the dynamic GDyn) developed by Golub (2013) and improved by Markandya et al. (2015) with the new GTAP-Power (Peters, 2016), which introduces for the first time in GTAP a detailed representation of the renewable electricity sector. GDynEP relies on the version of the GTAP-Database 9.1 updated to 2011. It is a recursive dynamic model that allows the representation of long-term policies, including assessment exercises related to different timing in implementing climate policies.

GDynEP contains two additional policy instruments with respect to the standard carbon tax instrument represented by public support to EE and RS, and a novel financial mechanism for such public policy support modelled via a carbon tax revenue (CTR) recycling mechanism.

3 The included electricity generating technologies are Coal, Gas, Oil, Hydro, Wind, Solar, Nuclear and Other Base Load Power sources, while Gas, Oil, Hydro and Solar generating technologies are further divided between Base and Peak Load. All details on GDynEP are described in Supplementary Material, Appendix C.
Regarding the standard carbon pricing as the core instrument to achieve the GHG reduction target, we consider a market-based mechanism driven by a target on CO\textsubscript{2} emissions based on a carbon tax (CT) applied to the whole EU economic system. Such a design corresponds to a full participation of all sectors to the ETS. As a general remark, by modelling EU as an aggregate, the two available market-based policy options, CT and ETS, result as perfectly equivalent, since the Pigouvian CT in the whole EU corresponds to the minimum cost for achieving the target, which is equivalent to the permits price level reached if the whole economy of all EU countries is involved into ETS. The inclusion of all sectors (industries, services, households) under the umbrella of a carbon tax policy addresses the criticism of ETS failures as claimed by Tol (2013). Accordingly, in the following we refer to CT as the market-based instrument representing the first policy pillar of the EU2030 strategy, that is equivalent to an ETS involving all sectors. As one standard procedure, the whole CTR collected by the EU central authority is transferred to consumers as a lump sum in the Equivalent Variation (EV) measure.

The other two policy instruments (support to EE and RS) financed by a CTR recycling mechanism imply the introduction of a percentage rate of the total CTR ($\gamma$) directed to finance the two CET options here explored. The implementation of such a policy is reflected in the reduction of CTR directed as a lump sum to consumers. To the best of our knowledge this is the first contribution directly assessing the effectiveness and economic impact of the whole EU2030 strategy by explicitly analysing a financial mechanism for supporting CET and thus also including the cost of public support into policy impact evaluation.

In order to quantify how public investments might be translated into clean energy innovation at an empirical level, we have computed two elasticity parameters, namely EE ($\varphi$) and RS ($\theta$), by considering data on the last ten years of investments in the EU in these fields with respect to the

\[ \text{In order to make clear how we model in GDynEP the financial mechanism of CTR for CET support policies, we have developed a simplified theoretical model available as Supplementary Material Appendices A and B. Such stylized model is also helpful in disentangling and interpreting the multiple interactions across the three policy pillars (given a specific abatement target) and the influence played by selected behavioural parameters.} \]

More specifically, in order to transform investment efforts (millions of USD) into input-augmenting technical change in energy efficiency ($\phi$) we use a standard elasticity computation method based on changes over time of total innovation efforts (here represented by R&D stock) and gains in energy efficiency expressed as energy service improvements (Griliches and Lichtenberg, 1984; Hall and Mairesse, 1995). For the sake of simplicity, we assume that EE uniformly influences productivity in all sectors and that the diffusion path of innovation is not affected by technical barriers. The elasticity parameter has been calibrated according to latest data on the sectoral efficiency gain and the public investment in energy efficiency innovation during the decade 2002-2011 given by IEA R&D statistics, as an average value for industry, residential sector and transport for the EU. The simplifying assumption here is that the reaction parameter homogeneously influences input efficiency of all energy inputs in every output. The value for ($\phi$) adopted is 1.8, and can be interpreted as follows: an increase by 1% of public R&D stock in energy efficiency produces an improvement in energy efficiency on average of the whole energy system (industries, transport, households) of 1.8\%.

With respect to financial support to RS, for the sake of simplicity we have implemented it only in the electricity sector where the target settled by the EU is a 45% share of renewables in electricity generation by 2030 (EC, 2014a). In this case, the reactivity parameter of the electricity sector to public investments is calibrated considering the public R&D investment in renewable energies given by the IEA R&D database, accounted as R&D stock as for EE, and the corresponding increase in installed capacity in renewable electricity in EU countries during the same period (1992-2011 IEA Energy Balance dataset available online), resulting as an output-augmenting technical change.

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3 R&D stock values are computed by applied the standard Perpetual Inventory Method (PIM) formulation as in OECD (2009) to R&D expenditure flows data available from IEA. Considering the GDynEP structure here developed, an increase in R&D stock for CET corresponds to the current R&D expenditure flow in the period under investigation, that is exactly how the CTR mechanism works in GDynEP, as explained in mathematical terms in Appendix A.

6 We have decided to exclude renewable energy sources for the transport sector since they necessitate additional modelling efforts on the raw material side, which will complicate the analysis considerably.

7 It is worth noting that, by working in a dynamic setting, this corresponds to a conservative assumption of constant returns to scale over time. In order to better shape this dynamic pattern, in addition to the consequences of barriers to diffusion and adoption that are here ignored, 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 together with a sensitivity
According to Andor and Voss (2016), promoting renewable energies by capacity investments (rather than by generation subsidies) must be chosen under uncertainty about demand conditions and capacity availability. The value for (\( \theta \)) here adopted is 4.5, and is to be interpreted as follows: an increase by 1% of public R&D stock in renewable energies produces an 4.5% increase in the installed capacity of electricity produced by RS.

It is worth mentioning that in this simulation exercise we are not able to define the exact way the policy support is designed in practical terms (e.g., a tax exemption, a fiscal subsidy, etc.). Rather we only consider broad financial support to CET development, assuming that the coefficients (\( \varphi \)) and (\( \theta \)) include all aspects of technology development, deployment, diffusion and adoption. In addition, we model the two CET options as completely independent from each other, in order to better represent the financing mechanism with a budget constraint. We recognize this is a conservative assumption that excludes the possibility of synergies between technologies in EE and RS (as for instance the development of more efficient storage systems) as emphasized in IRENA (2017).

Summing up, the three policy targets here considered are: emissions reduction, increase in EE, increase in the share of RS on energy consumption. The three instruments designed for achieving the targets are: carbon pricing, financial support to EE, financial support to RS. By considering CTR as the practical fiscal mechanism to finance both CET options, we jointly include in the modelling design the existence of a budget constraint and the mutual interaction between the carbon pricing mechanism and the achievement of the EE and RS policy targets. Given a fixed abatement target, support for CET will reduce the carbon price level (represented by the Pigouvian carbon tax) and

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3 The introduction of RS in the electricity sector deriving from merging GDynE with GTAP-Power requires the introduction of an additional nest into the production function tree and also to add an elasticity of substitution parameter between electricity from fossil fuels and electricity from renewable sources. While standard elasticity parameters in the energy nests are based on Antimiani et al. (2015), the elasticity parameter in the electricity sector has been calibrated by the ENEA research team combining results of MARKAL/TIMES model for the EU and GDynEP. Bearing in mind that such behavioural parameters must account for all aspects (not only technical ones) that influence the choice in the input demand decision by the production (and consumption) system, although the substitutability of the two forms of electricity is almost complete at the technical level, the final value adopted is 0.6 allowing to consider all infrastructural and technical barriers in the electricity system from the supply side that impede electricity from RS to completely replace electricity from fossil fuels in the demand system. We are aware that further work for empirical estimation of elasticity of substitution parameters based on historical data is required and it will be part of future research.
consequently the total amount of carbon tax revenue will decrease. A smaller amount of investments will be then available for supporting CET development with a mutual interaction that brings to requiring additional evaluation criteria for the optimality of the policy mix that is not a priori predictable.

With regard to scenario building, projections for macro variables as GDP, population and labour force are based on a combination of sources. In particular, GDP projections are the simple average values of four 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) while projections for the labour force (modelled as skilled and unskilled separately) 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 separated).

As for the calibration of CO₂ emissions, the baseline case corresponds to a BAU scenario with a regional distribution of emissions assigned according to projections provided by the International Energy Agency (IEA, 2015). Such a distribution embodies the effects of only those government policies and measures that had been adopted by mid-2013.

The CO₂ emissions profile for the policy options here considered are based on two emission paths that correspond to two different timing profiles, labelled EU2030 and EU450. The former is based on the EU2030 abatement target until 2030 and it is complemented by the target of the 450PPM scenario developed by IEA (2015) up to 2050. Accordingly, two targets need to be achieved: a reduction of CO₂ emissions by 40% by 2030 with respect to 1990 levels (EU2030), and an 80% reduction by 2050 (450PPM), in line with the global target to limit the concentration of GHG in the atmosphere to around 450 parts per million of CO₂-equivalent. The EU450 is based only on the 450PPM IEA scenario and implies the same long-term target by 2050 as before, but it has a different temporal profile in the abatement path with respect to EU2030. Accordingly (Figure 1) the EU2030 target of 40% by 2030 is lower than the 450PPM case, whose corresponding target implies a 52% reduction.
by 2030, while the 80% reduction by 2050 is the same for the two timing profiles.

Therefore, while in the EU2030 timing profile in order to achieve both the 2030 and the 2050 targets, the EU abatement rate should increase after 2030, in the 450PPM profile we assume a constant rate of emissions reduction along the time horizon, implying that emission reduction is more challenging in the early periods with respect to EU2030. In Figure 1 we also report a “EU2030 trend” path that is calculated assuming a CO₂ abatement trend that enables EU to reach the 40% reduction target (w.r.t. 1990) in 2030 and that remains unchanged until 2050. This allows visualizing the gap in 2050 with the EU abatement target necessary to respect the Paris Agreement purpose.

**Figure 1 – CO₂ emission paths for EU28 (Mton)**

Finally, turning to the issue of optimal timing of a climate strategy, we have reproduced the same policy scenarios considering two alternative emission pathways, EU2030 and EU450. The scenarios are:

1. Business As Usual (BAU);
2. CT: only the EU reduces emissions with a market-based instrument implemented as a homogeneous carbon tax;
3. CT-Policy Mix: only the EU reduces emissions with a CT and a percentage of the CTR is
invested in CET.\textsuperscript{9}

Scenarios (2) and (3) are evaluated considering the two different emission paths: EU2030 (40% emission reduction by 2030 with respect to 1990 level and the achievement of the 450PPM target by 2050, which is about 80% with respect to 1990) and EU450 (450PPM target by 2050).

For both emission paths we evaluate the CT-Policy Mix Scenario considering alternative values for the share of CTR directed to CET ($\gamma$) and for the distribution of financial support ($\delta$) to EE and RS (with a total of 223 scenarios investigated):

i) Ten different shares of the CTR ($\gamma$) to be invested in CET (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%);

ii) For each value assumed by ($\gamma$), eleven alternative allocations of the resources received for mitigation purpose ($\delta$) (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1), going from financing entirely RS ($\delta = 0$) to financing entirely EE ($\delta = 1$).

As for the country and sector coverage, we consider 19 regions and 22 sectors. With regard to the former, following the Kyoto Protocol scheme, we differentiate between Annex I (European Union, United States, Russian Federation, Rest of Europe, Rest of OECD East and Rest of OECD West) and non-Annex I countries (Brazil, China, India, Asian Energy Exporters, Continental Asia, Rest of South Asia, South East Asia, African Energy Exporters, Western Africa, East and South Africa, American Energy Exporters, South America and Central America and Caribbean).

For the sectoral aggregation, we distinguish 22 industries: Agriculture; Food, beverages and tobacco; Textile; Wood; Pulp and paper; Chemical and petrochemical; Non-metallic Minerals; Basic metals 1; Basic metals 2; Machinery equipment; Transport equipment; Other manufacturing industries; Transport; Water Transport; Air transport and Services, while energy commodities have

\textsuperscript{9} In both cases we assume that only EU will act and no other region will make any further abatement policy except for those already included in BAU as current policies. Although it might seem an extreme view, this is due to the fact that the main objective of this work is to analyse the potential interactions between policy instruments in a unilateral climate policy case. Obviously, the unilateral abatement policy implies greater costs compared to the case in which also other countries implement mitigation actions (Antimiani et al., 2016). Additional work on how the EU policy mix could interact with alternative global scenarios will be part of future research.
been disaggregated in Coal, Oil, Gas, Oil products, electricity from fossil and nuclear sources and electricity from RS. Finally, in terms of the temporal dimension ($t$), we consider a time horizon to 2050, in steps of five years.

A robustness check for model calibration has been carried by comparing results in GDynEP with those described in Fragkos et al. (2017) obtained by performing the GEM3 model. The comparison has been performed on GDP percentage losses between the BAU and the EU2030 strategy scenarios (with the three targets fully respected). GDP losses in GDynEP are -0.3% and -1.9% in 2030 and 2050, respectively, while in Fragkos et al. (2017) GEM3 provides for the same temporal dimensions GDP losses of -0.4% and -1.0% respectively, but the cost for policy support to CET is not included.

4. Discussion on numerical results

4.1 Carbon pricing and CET policy support: instruments and targets interactions

Given the large number of scenarios and the multiple relationships we are interested in, we first comment on the interactions between the three policy instruments considering the EU2030 emission path, and then we look at how different timing profiles in emission reduction (EU2030 and EU450) change the effectiveness of the EU energy transition strategy according to alternative policy mix designs and different evaluation criteria.

In Figure 2 we report the carbon price trend with respect to the share of carbon tax revenue invested in CET ($\gamma$) and its redistribution between EE and RS ($\delta$) in the EU2030 Scenario.\(^\text{10}\) Results for numerical simulations are reported for the range ($\gamma \in [10 - 50]$) for graphical reasons. The reported relationships also hold for higher values of $\gamma$ and results are available upon request.

Starting with the relation between carbon price and the share of CTR allocated to CET ($\gamma$) we note first that when $\gamma$ increases the carbon price decreases. Second, when $\gamma$ increases, the reaction of carbon price with respect to $\delta$ increases too. In other words, the higher is the share of the CTR

\(^{10}\) We show the results associated to the EU2030 emission path because this is the path coherent with the current European climate strategy. However, the direction of the interactions also holds in the EU450 case.
allocated to support CET the greater is the carbon price reduction, and such reduction increases with a relatively higher share of public support directed to EE w.r.t. RS.\footnote{The numerical simulations help finding an inverse relationship between carbon price and $\gamma$ according to a combination of behavioural parameters that are mathematically synthesized by the conditions $\alpha_1 > 0$ and $\alpha_2 < 0$ in eq. (41) in Supplementary Material, Appendix A.}

**Figure 2 – Influence of $\gamma$ and $\delta$ on carbon price (CT) in 2050 (USD per ton of CO2) - EU2030**

Let us now look at the relation between carbon price and $\delta$. If resources are entirely allocated to finance renewables ($\delta = 0$), the carbon price remains very high, although slightly decreasing when $\gamma$ increases. Although decreasing, the level of CT remains close to the level observed in the absence of a revenue recycling mechanism, namely in the CT Scenario (537 USD per ton of $\text{CO}_2$). This is in line with other studies according to which investments in renewables do not contribute to lowering emission prices (Boeters and Koornneef, 2011; Böhringer, 2014; Fan et al., 2017).

On the other hand, increasing investments in EE strongly decreases the CT. Indeed, the investments directed to improve EE provide new and more efficient technologies that contribute to generating a lower carbon equilibrium price. Thus, while financing only renewable energy has an almost neutral effect on the emission price, the greatest reductions are observed when only EE is financed. For example, with a 10% of carbon tax revenue allocated to EE, the price drops from 536
USD to 392 USD per ton of CO₂; in case of a 50% share of the recycling mechanism, the difference between the two policy options dramatically increases (from 528 USD to 176 USD). This is due to the fact that EE has a leading role in lowering the emission price required to achieve the desirable abatement target, and the more it is financed, the greatest is the reduction in CT level. Obviously, the absolute values in carbon tax gaps between scenarios must be taken as only informative, given the simplifying assumptions of constant returns to scale for investments in CET and no diffusion and adoption barriers.

From these results we can conclude that the numerical simulations find an inverse relationship between CT and δ. Furthermore the combined action of the two parameters (γδ) that result in the lowest emission prices is associated with a scenario in which the recycled CTR is maximum (γ = 50%) and it is entirely invested to finance EE (δ = 1).

An additional point refers to the impacts of the share of revenues generally allocated to CET and the relative allocation to EE (γ and δ respectively) on the use of RS. Figure 3 illustrates this relation.

**Figure 3 – Influence of γ and δ on renewable electricity consumption in 2050 (Mtoe) - EU2030**

Not surprisingly, higher levels of renewable electricity consumption occur with lower values of δ.
that is when all or most of resources are invested for increasing the RS installed capacity. Accordingly, it emerges that while the best solution in terms of cost-effectiveness (minimum carbon price) is associated with a 100% investment of recycled carbon tax revenues in EE (Figure 2), the highest level of renewable electricity consumption, which is a target itself in the EU2030 strategy (Figure 3), occurs when resources are entirely allocated towards RS (in particular in the scenario with γ = 50% and δ = 0). Moreover, there is a threshold value of δ (around 40% in this set of numerical simulations) above which an increased share of CTR invested in CET (γ) produces a reduction in renewable consumption that brings the share of renewables on total electricity consumption below the value obtained with carbon price as the only policy instrument inforce. If the share of renewables in electricity consumption is a target itself rather than a complementary instrument to reduce private mitigation costs, there are selected combinations of investment distribution between the two CET options that turn to be harmful for the RS-related target.

Finally, consider the achievement of the EE objective (Figure 4). Quite intuitively, unlike the previous case, the best outcomes occur when both γ and δ are high, that is when a large amount of money is invested in EE. The opposite holds when a high percentage of CTR is used to finance renewables (δ = 0). Indeed, in this case the policy mix might generate a contrasting effect due to an increase in the overall energy availability that might turn into an increase of energy consumption, thus raising energy intensity.

Last, if the three pillars are all included in the policy mix, it might seem desirable to invest in renewables but not the entire amount of resources (e.g. a scenario with γ = 50% and δ = 40%). In this way, there might be an increase in RS consumption without compromising the achievement of the EE target and, at the same time, a reduction in emission prices with respect to a simple CT mechanism.

However, as already emphasized in aforementioned contributions, there are several additional issues and interactions that might influence the choice of the best policy mix and, consequently, the success of the entire EU low-carbon strategy. First, the optimal policy mix strictly depends on the evaluation criteria adopted that in turn follow the externalities determining market failures. Second,
optimality conditions might substantially change when different timing in abatement profiles is of interest. Accordingly, the next step is to analyze policy options in a general equilibrium framework applied to the EU climate strategy. The purpose is twofold: i) to investigate the effects of alternative combinations of $\gamma$ and $\delta$, in light of the three pillars of the EU climate strategy; ii) to examine the issue of timing, through the comparison of two emission paths (EU2030 and EU450).

**Figure 4 – Energy efficiency in 2050 as GDP to energy consumption ratio (Mln USD/toe)**

![Energy efficiency in 2050 as GDP to energy consumption ratio (Mln USD/toe)](image)

**4.2 General equilibrium economic impacts and timing options**

We consider as a first evaluation criterion the abatement cost minimization. Figure 5 compares the marginal abatement cost (MAC) curves for alternative policy mixes applied to the two alternative emission paths. The four policies depicted in Figure 5 combine the extreme values of both $\gamma$ and $\delta$ used for graphical representation of results. Accordingly, for each mitigation path, we show the following combinations: i) 10% of CTR entirely directed towards renewables ($\gamma = 10\%_{RS}$); ii) 10% of CTR entirely directed towards EE investments ($\gamma = 10\%_{EE}$); iii) 50% of CTR entirely directed towards renewables ($\gamma = 50\%_{RS}$); iv) 50% of CTR entirely directed towards EE investments ($\gamma = 50\%_{EE}$); v) 50% of CTR entirely directed towards EE investments ($\gamma = 50\%_{EE}$); vi) 10% of CTR entirely directed towards renewables ($\gamma = 10\%_{RS}$); vii) 50% of CTR entirely directed towards EE investments ($\gamma = 50\%_{EE}$); viii) 50% of CTR entirely directed towards EE investments ($\gamma = 50\%_{EE}$); ix) 10% of CTR entirely directed towards renewables ($\gamma = 10\%_{RS}$); x) 50% of CTR entirely directed towards EE investments ($\gamma = 50\%_{EE}$); xi) 50% of CTR entirely directed towards EE investments ($\gamma = 50\%_{EE}$).
50%_EE). We select these scenarios in order to represent the situations in which mitigation cost reaches its minimum (scenario iv) and maximum (scenario iii) values, as reported in Figure 2. By fixing the abatement target to be reached in 2050 (about 80% reduction in CO₂) as the same for all scenarios, Figure 5 might be interpreted as the trends in MACs over the period 2015-2050 where alternative emission paths entail a different temporal allocation of abatement efforts.

Figure 5 - Marginal Abatement Cost (MAC) curves (USD per ton of CO₂)

As already mentioned, the options with higher costs are those in which all resources are invested in renewables, whatever the share of CTR gathered. On the contrary, when investments are directed toward energy efficiency, private mitigation costs are much lower. Furthermore, in this case also the parameter γ plays a role, since the distance between the RS and EE related MAC curves increases with a higher amount of invested resources.

With respect to the choice of the best emission path, Figure 5 shows EU2030 to be superior in the short-term, since it entails a smaller abatement effort in the earlier years before 2030 (see Figure 1, corresponding to an amount of Gton abated up to 600 units in Figure 5). However, in the long-term the EU450 solution is preferable given the lower MAC associated with the 2050 emission target. This result is valid only if cost effectiveness in carbon price terms is the unique policy evaluation criterion.
adopted. When multiple objectives are under scrutiny, the lowest CT level does not ensure that the corresponding policy set is necessarily the best.

Let us consider now a second evaluation criterion namely the EE target (the second pillar of the EU climate strategy). As already mentioned, the objective is a target of at least 27% energy savings in 2030 compared with a BAU scenario. Accordingly, Table 1 shows the state of compliance with respect to the EE objective in the alternative scenarios. Starting from a BAU scenario in which the level of EE (as the inverse of energy intensity) in 2030 is 14.15, an increase of 27% means that the EU is compliant with the EE target whenever values reported in Table 1 exceed 17.97.

Table 1 - Energy efficiency depending on $\gamma$, $\delta$ and CO2 abatement path

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<tr>
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<tr>
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<td></td>
</tr>
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<tr>
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<td>100% EE</td>
<td>16.97</td>
<td>61.76</td>
<td>20.72</td>
<td>62.61</td>
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</table>

Note: compliance with EE target in EU2030 climate strategy in grey.

From Table 1, it is clear that with the current emission path (EU2030) EU never reaches this target by 2030 and is able to be compliant only from 2035 on. However, the EU could reach and overtake the target by taking more challenging actions in the short-term – that is by undertaking the EU450 emission path. Indeed, in this case the target is always reached in 2030 in almost every scenario (CT included); the only scenarios in which the target is not reached is when recycled CTR is completely used to increase installed capacity in electricity production from RS, especially with high values of $\gamma$.

Conversely, the largest benefits occur when all resources are invested in EE.

It is also worth noting the interactions between these policies. Therefore, while so far the
investment of 50% of CTR in EE seems to be the best solution both in terms of cost effectiveness and in terms of the EE target itself, this strategy can also have negative consequences. Indeed, it might lower the price of electricity produced by fossil fuels, leading to a rebound effect that might compromise the success of the overall energy policy or, at least, the fulfillment of the last pillar.

Finally, we consider what happens in terms of compliance with respect to the third policy pillar (a target of at least a 27% share of renewable energy consumption in 2030). Given that the model only takes into account renewable sources in electricity production, this target corresponds to at least 45% share of renewable electricity consumption (EC, 2014a). Table 2 compares the alternative scenarios for the two emission paths. The first thing to note is that, unlike the EE case, the target is never reached in 2030, whatever emission path is considered. We first reach the objective in 2035, but only in the EU450 case and under some conditions: at least 30% of CTR mostly invested in renewables ($\delta=0; \delta=10\%$), although with a 20% carbon revenues entirely directed towards renewables the EU gets very close to the expected share. Furthermore, the share of resources to renewables ($\delta$) needed to reach the target decreases when the total amount of available investments increases, that is for higher values of $\gamma$. In particular, with $\gamma$ equal to 40% and 50% it is sufficient to direct 80% of CTR resources to renewables ($\delta = 20\%$).

As for scenario EU2030, the EU gets very close to the target in 2035 only if 50% of CTR is entirely invested in renewables. However, the objective is not completely reached up to 2040, when huge investments in renewables might contribute to fully achieving the target.

To sum up, while in terms of both cost effectiveness and energy efficiency it might be desirable to invest in energy efficiency, Table 2 shows that this might compromise the success of the third pillar, reached only through impressive efforts in renewables financing.

The trade-offs are thus becoming clear: if we go for such a high investment in renewables this might increase the overall energy consumption, thus affecting the energy efficiency pillar. The combination of results therefore highlights the deep interactions that exist between the three objectives and the need for policy makers to take them into account when discussing and
This interaction is also evident when the amount of resources available to finance CET are compared in alternative emission paths. Figure 6 highlights the multiple interactions between the
three pillars. If the emission price is high, the amount of resources for CTR recycling increases, but when such resources are invested in CET the total available revenues for CET will be reduced due to a reduction in CT. This could easily constitute a fourth evaluation criterion of the optimality of the policy mix, if the maximization of financial resources for developing CET is the policy target, independently from the achievement of the specific pillar under scrutiny.

Figure 6 – CTR recycled for investments in CET (Mln USD)

This last reflection brings to consider additional optimality criteria that address different policy feasibility dimensions. In this regard, the impacts that alternative policy mixes have on the whole economy might add further elements of uncertainties in choosing the optimal policy mix.

Table 3 shows the GDP percentage changes with respect to BAU considering data on the cumulated GDP from 2015 to 2050. Data are expressed in terms of Net Present Value (NPV) with a 4% social discount rate, which is the one recommended by the European Commission.12

Finally, Table 3 compares the EU2030 Scenario with the EU450 one, in order to investigate the

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12 It corresponds to the intermediate level between the highest (6%) and lowest (2%) discount rates resulting, respectively, from the ethical and descriptive approach and representing lower or higher social preference for the future (IPCC, 1996, SAR Chapter 4). See http://ec.europa.eu/smart-regulation/guidelines/tool_54_en.htm.
current preference towards a mitigation path rather than the other.

In the CT case, there is a GDP loss with respect to BAU due to the implementation of the mitigation policy that results higher for the EU450 scenario. Accordingly, the current choice of the EU to adopt the mitigation path described by the EU2030 scenario (that is less stringent abatement targets in the short-term) seems to be preferable on these grounds.

If, however, we take into account the additional issues related to the three pillars of the energy strategy by introducing a mechanism to finance CET, the situation changes. GDP losses decrease and in some cases turn into gains, especially for high values of $\gamma$ and $\delta$ (as before the turning point is associated to lower values for $\delta$ when $\gamma$ increases). Moreover, the preference for one mitigation path over another strictly depends on the combination of the three policy pillars. In this regard, the first result is that the preference for the EU450 emission path increases when $\delta$ is high. In fact, Table 3 shows that the more the investments in energy efficiency, the more the incentive to mitigate in the short-term, because of lower emission prices associated to these scenarios.

<table>
<thead>
<tr>
<th>Table 3 – GDP % change w.r.t. BAU 2015-2050 (cumulated NPV, 4% discount rate)</th>
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<tbody>
<tr>
<td><strong>CT</strong> 10% CTR</td>
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<tr>
<td>100%RS</td>
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<td>10%EE</td>
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<tr>
<td>90%EE</td>
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<td>100%EE</td>
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Note: preference for a mitigation path in light grey. Indifference in preference in dark grey.

Furthermore, when $\gamma$ increases, the shift in convenience from the EU2030 to the EU450 emission path occurs for lower $\delta$. In other words, if a higher amount of money is invested, it is sufficient to use

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13 Even if the loss of GDP might seem small considering that the rest of the world is free riding, these results can be explained due to: i) the adoption of the new version of the GTAP database that includes renewables; ii) a lower distance between the emissions in BAU and in CT given the CO$_2$ reduction already obtained by current climate policies. Moreover, values reported in Table 3 refer to a NPV for the whole period 2015-2050. However, the GDP loss by 2050 comparing CT with BAU is 6.9% for the EU, in line with results obtained in Antimiani et al. (2016).
a minor part of it to finance EE in order to reach a preference for immediate more stringent actions (e.g. when $\gamma = 10\%$, EU prefers the EU2030 path up to $\delta = 80\%$; when $\gamma = 40\%$ and $50\%$, EU prefers the EU2030 path just up to $\delta = 20\%$).\textsuperscript{14}

It is worth mentioning that this long term perspective in policy evaluation should be combined with the short term social acceptability of policies. As an example, by comparing the abatement cost in 2030 in terms of GDP changes w.r.t. BAU, the abatement target in EU2030 would bring to a -0.96\% GDP reduction, while in the EU450 the GDP loss would be rather larger (-2.43\%). This reveals a trade off for policy makers in choosing the optimal policy mix. From one side the likelihood of a broad acceptance of abatement policies increases with a less ambitious mitigation target, at least in the medium term. From the other side more ambitious targets help gaining in resource efficiency with first mover advantages that will more than compensate short term costs in the long term.

The final perspective we consider is the welfare maximization. Accordingly, Table 4 shows the impacts in terms of welfare, here given by changes in the EV, following the same configuration of Table 3.\textsuperscript{15}

| Table 4 – EV % change w.r.t. BAU 2015-2050 (cumulated NPV, 4\% discount rate) |
|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
|                              | EU2030                        | 450PPM                        |                              |                              |                              |                              |                              |
| CT                            | 10\%CTR                       | 20\%CTR                       | 30\%CTR                       | 40\%CTR                       | 50\%CTR                       | 10\%CTR                       | 20\%CTR                       | 30\%CTR                       | 40\%CTR                       | 50\%CTR                       |
| 20\%EE                        | -7.79                         | -4.85                         | -2.45                         | -0.49                         | 1.13                          | -9.54                         | -5.98                         | -3.04                         | -0.61                         | 1.41                          |
| 30\%EE                        | -6.15                         | -2.18                         | 0.82                          | 3.14                          | 4.98                          | -7.57                         | -2.72                         | 0.99                          | 3.88                          | 6.16                          |
| 40\%EE                        | -4.63                         | 0.09                          | 3.45                          | 5.93                          | 7.83                          | -5.73                         | 0.08                          | 4.24                          | 7.32                          | 9.66                          |
| 50\%EE                        | -3.24                         | 2.05                          | 5.60                          | 8.14                          | 10.04                         | -4.02                         | 2.50                          | 6.90                          | 10.03                         | 12.36                         |
| 60\%EE                        | -1.94                         | 3.75                          | 7.40                          | 9.94                          | 11.82                         | -2.44                         | 4.59                          | 9.11                          | 12.23                         | 14.51                         |
| 70\%EE                        | -0.75                         | 5.23                          | 8.92                          | 11.44                         | 13.29                         | -0.98                         | 6.42                          | 10.97                         | 14.05                         | 16.28                         |
| 80\%EE                        | 0.35                          | 6.53                          | 10.23                         | 12.72                         | 14.53                         | 0.38                          | 8.03                          | 12.57                         | 15.59                         | 17.76                         |
| 90\%EE                        | 1.37                          | 7.69                          | 11.37                         | 13.82                         | 15.59                         | 1.64                          | 9.46                          | 13.96                         | 16.92                         | 19.03                         |
| 100\%EE                       | 2.32                          | 8.73                          | 12.38                         | 14.79                         | 16.52                         | 2.81                          | 10.73                         | 15.18                         | 18.07                         | 20.13                         |

Note: preference for a mitigation path in light grey.

First, considering the two CT policy scenarios, and in accordance with GDP results, the EU2030

\textsuperscript{14} These results hold also in case of a discount rate equal to 2\% and 6\%.

\textsuperscript{15} The EV in GTAP reproduces the income that must be given to an agent, at some fixed set of prices, to make them as well-off as they would be under some policy change. Accordingly, it represents a monetary measure of the welfare effects of different policies, for it constitutes a quantitative evaluation of how much better or worse off the households are.
strategy seems preferable in terms of welfare impact. This is consistent with van der Ploeg (2016) according to which in a second-best perspective (and opposed to the first-best case) a postponed increase in mitigation reduction (and consequently in carbon prices), as in our EU2030 scenario with respect to the 450PPM, is likely to reduce the negative welfare effects.

If we compare Tables 3 and 4, the preference for one emission path over another is quite similar, in terms of both GDP and EV changes, when investments in clean energy technologies are taken into account. The EU450 path is preferable when most resources are directed towards energy efficiency. However, especially when not so many resources are available (e.g. $\gamma = 10\%$), in the EV case the turning point happens for lower levels of $\delta$, compared to the GDP case.

Nevertheless, some differences also occur. First, while from Table 3 it is clear that the introduction of a CTR recycling system always entails an improvement in terms of GDP change compared to CT, consequences in terms of welfare depend on $\delta$, that is the allocation of resources between different clean energy technologies. Indeed, Table 4 shows that if all resources were allocated towards renewables, the EU would face a larger welfare loss than the one associated to the CT scenario, whatever the emission path considered.

Moreover, in this specific case (i.e. resources entirely invested in renewables) an increase in $\gamma$ would worsen the situation, while in all the other scenarios higher availability of resources entails an improvement in terms of both GDP and welfare. Nevertheless, if a part of the money is invested towards energy efficiency purposes, even a small part (from $\delta = 10\%$ onwards), the opposite holds: there is a welfare improvement with respect to CT and benefits increase when both $\gamma$ and $\delta$ increase, perfectly in line with what happens in terms of GDP (Table 3).

This result can be easily explained by considering differences in how investments in CET influence the energy system in GDynEP. Resources directed to EE increase input-augmenting technical change for all sectors including households. This brings to a reduction in carbon tax level that positively influences EV levels. On the contrary, resources directed to RS help augmenting the quantity of electricity available at the national level. For a fixed emission target, the system reacts using energy
input as much as possible, given a fixed amount of fossil fuels consistent with the emission target. This in turn helps reducing production costs for firms, but it does not reduce the burden of carbon tax on households budget. Hence the small reduction in EV for the case of full employment of CTR in RS with respect to the CT policy case is entirely explained by losses welfare for households.

5. Conclusions and policy implications

This work has analyzed the interactions among the different policy targets and instruments within the EU low-carbon strategy and their impacts in terms of different evaluation criteria. We compare policy mix scenarios sharing the same timing in abatement targets, with a market-based mechanism (carbon price) including or not investments in clean energy technologies through a revenue recycling mechanism. The increasing abatement targets over time require an increase in the carbon tax level, which ensures a growth in the amount of resources to be invested in CET, given a fixed levy on carbon tax revenue. Therefore, by investing in CET through the introduction of a higher levy on the carbon tax revenue, the economic losses of GDP (which are general small anyway) with respect to the baseline case can be compensated by efficiency gains in the energy sector up to a point where efficiency gains are higher than losses due to the abatement costs. Additionally, the introduction of measures to foster energy efficiency and renewable energies have also positive effect in reducing the electricity price and the energy intensiveness of economic activities. Nonetheless, when the three pillars are combined, not all the policy mix designs ensure the achievement of the multiple targets forming the EU low-carbon strategy, revealing severe concerns in term of overlapping regulation effects and potential trade-offs across policy instruments and targets.

When considering the comparison among policy scenarios with different timing in abatement targets, a first observation is that the choice on preferring or not to delay more stringent targets in the future also depends on the selected mitigation options. Indeed, when only the carbon price is in place, postponing the achievement of more stringent CO₂ reduction seems preferable. On the contrary, when introducing energy efficiency and renewable energy support, the relative suitability of anticipating
more challenging abatement targets seems to increase. Therefore, the time path of these emission reductions influences the effectiveness of the investment in CET. Certainly, this is also due to the specific modelling strategy we used, where the greater the emissions reduction are, the higher will be the carbon tax level, together with the carbon tax revenue and the flow of public investment in CET. However, considering a policy maker perspective, this seems reasonable in term of the actual feasibility to propose strategies to finance additional investments in clean energy technologies.

As a general remark, our results show that the selection of the best policy mix design is strongly influenced by the evaluation criterion adopted. Consequently, the choice of the optimal mix of the three pillars needs to be considered in accordance with negotiated criteria, which all have to be politically feasible.

From a methodological perspective, several improvements can be pursued. In order to introduce a better representation of specific alternative technologies, which would better ensure the achievement of mitigation and technology innovation targets, model developments would involve linking up with technology-specific models that distinguish between innovation and diffusion phases. Additionally, different assumptions about the returns to scale effect associated to technological innovation in the energy system, as well as assumptions on adoption and diffusion paths are also relevant.


Golub, A., 2013. Analysis of Climate Policies with GDyn-E, GTAP Technical Papers No. 32. Center for Global Trade Analysis, Department of Agricultural Economics, Purdue.


Appendix A – Theoretical model for instruments interactions

We consider three simplified policy instruments in order to analyse the potential interactions between the three pillars forming the EU2030 low-carbon strategy. First, we have a standard market-based instrument shaped as a carbon tax; then we consider two additional instruments in the form of public support to technological innovation in RS and EE. We introduce a mechanism to recycle the revenue coming from carbon taxation to directly invest in RS and EE. We assume additional technical change in RS and EE as driven exclusively by direct investments, ignoring spillover effects, barriers to technology adoption and diffusion, sector (and firm) specific characteristics and further external factors affecting innovation. This corresponds to a direct adoption of EE technological change, and a direct improvement in output productivity of RS due to investments, without any barrier in the transformation process of invention and innovation into technical improvement in the production function. We describe the potential interactions among the three pillars by adopting an equilibrium-displacement model linearly transformed according to Gardner (1987), as the simplest representation of a static comparison of two equilibrium solutions with and without the policy under scrutiny.

In algebraic terms, eq. (1) presents the production function as follows:

\[ Y = f(K, F, R) \]  

(1)

Where \( Y \) is the produced good (the output), \( K \) is the capital stock, \( F \) stands for the amount of fossil-fuel energy and \( R \) the renewable energy used as inputs. The global amount of energy consumption \( E \) is thus divided into two primary sources, where \( F \) is the polluting one (associated with \( \text{CO}_2 \) emissions) while \( R \) is the carbon free energy source.

Accordingly, the total energy input in the production function is defined as:

\[ E = F + R \]  

(2)

This modeling approach allows considering the energy input as non-homogeneous with respect to climate policy, where \( F \) is subject to a carbon taxation (or whatever emission target tool) while \( R \) is free from carbon abating burden. This assumption can be easily formulated as:
Where $\beta$ is a fixed coefficient representing the carbon content of the fossil-fuel energy input adopted. In this model there is a unique fossil fuel input in order to have a single $\beta$ coefficient, while in the CGE numerical simulations each fossil fuel source has a specific carbon intensity parameter.

The model includes equations representing the value of marginal product (or factor price) as:

$$f_K P_Y = P_K \quad (4)$$

$$f_F P_Y = P_F \quad (5)$$

$$f_R P_Y = P_R \quad (6)$$

The factor supply equations are given as follows:

$$K = g(P_K) \quad (7)$$

$$F = h(P_F) \quad (8)$$

$$R = l(P_R) \quad (9)$$

Finally, the product demand equation is given by:

$$Y = D(P_Y) \quad (10)$$

We assume a simplified one-region model with a unilateral climate policy. In the numerical simulations this assumption is removed since the impact on foreign regions not implementing climate target is also taken into account in the CGE structure. The emission abatement target is exogenously assigned, independently of the economic impacts produced by the climate policy adopted.

By assuming that the production function is linear and homogeneous of degree one implies that the output elasticities with respect to inputs are equal to factor shares. In the following, we express all equations in log linear form to better represent changes in the production function due to changes in selected parameters and policy shocks. This implies that eq. (1) can be written as:
\[ y = \alpha_k k + \alpha_f f + \alpha_r r \]  

Where \( \alpha_k, \alpha_f, \alpha_r \) represent factor shares and \( \alpha_k + \alpha_f + \alpha_r = 1 \).

We also adopt the following technical assumptions. With respect to substitution elasticity between inputs in the production function we assume symmetric Allen elasticities. More specifically, the two energy sources have the common elasticity value:

\[ \sigma_{FR} = \sigma_{RF} = \sigma_{EE} \cong 1 \]  

The two energy sources are also equivalent substitutes with respect to capital:

\[ \sigma_{KF} = \sigma_{KR} = \sigma_{KE} \]  

Finally, symmetric Allen elasticity between capital and energy gives:

\[ \sigma_{KE} = \sigma_{EK} \]  

By assuming that the capital market is perfectly elastic, equations for inputs demanded to produce good \( Y \) are:

\[ p_K = -\frac{\alpha_F}{\sigma_{KE}} k - \frac{\alpha_R}{\sigma_{KE}} k + \frac{\alpha_F}{\sigma_{EE}} f + \frac{\alpha_R}{\sigma_{EE}} r + p_Y = 0 \]  

\[ p_F = -\frac{\alpha_K}{\sigma_{KE}} f - \frac{\alpha_R}{\sigma_{EE}} f + \frac{\alpha_R}{\sigma_{EE}} r + \frac{\alpha_K}{\sigma_{KE}} k + p_Y \]  

\[ p_R = -\frac{\alpha_K}{\sigma_{KE}} r - \frac{\alpha_F}{\sigma_{EE}} r + \frac{\alpha_F}{\sigma_{EE}} f + \frac{\alpha_K}{\sigma_{KE}} k + p_Y \]

The supply functions for the energy inputs demanded for producing output \( Y \) are given by:

\[ p_F = \frac{1}{\psi_F} f \]  

\[ p_R = \frac{1}{\psi_R} r \]  

Where \( \psi_F \) and \( \psi_R \) represent supply elasticity for fossil fuels and renewables, respectively.

The log linear representation of the demand equation for output \( Y \) becomes:
\[ y = \eta p_Y \]  

(20)

Where \( \eta \) represents the demand elasticity with respect to market price changes.

Let us introduce the climate policy here modelled as the carbon tax \( \tau \) ensuring the compliance with the emission abatement target. Since the carbon tax acts on the energy input responsible for CO\(_2\) emissions, this implies that only the fossil fuel demand equation will include it as:

\[
p_F = -\frac{\alpha_K}{\sigma_{KE}} f - \frac{\alpha_R}{\sigma_{EE}} f + \frac{\alpha_R}{\sigma_{EE}} r + \frac{\alpha_K}{\sigma_{KE}} k + p_Y - \tau
\]

(21)

According to Antimiani et al. (2013), the initial level value for \( \tau \) is modelled as the ad valorem equivalent influencing the price of fossil fuel as an input in the production process \( p_F \), that is a function of the specific carbon tax \( C_{TAX} \), the carbon content of the production function (given by the ratio between the CO\(_2\) emissions and the output \( Y \)), and the initial price of fossil fuels as follows:

\[
\tau = \frac{C_{TAX}}{P_F} \frac{CO2}{Y} = \frac{C_{TAX}}{P_F} \frac{\beta F}{P_F}
\]

(22)

Let us assume that a portion of the total carbon tax revenue (CTR) is directed to finance activities in EE in the form of an input-augmenting technical change, and to finance increases in the installed capacity of RS in the form of an output-augmenting technical change. This modelling choice is coherent with an Environmental Tax Reform (ETR) approach, where the tax burden on energy and polluting resource could provide the potential for a double dividend, where the increase in environmental quality is coupled to economic benefits (Alexeev et al., 2016; Bennear and Stavins, 2007; Fernández et al., 2011; Goulder, 1995; Patuelli et al., 2002; Pezzey and Jotzo, 2012). In the case of a carbon emissions reduction policy, such recycling mechanism is highly recommended since, according to Galinato and Yoder (2010), by taxing highly-pollutant energy sources and subsidizing clean sources it is possible to change the relative price of clean and dirty energy sources and

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\(^{16}\) In this simplified formulation we assume carbon content to be exogenously given and fixed, excluding the effects associated to potential carbon capture and storage technical change. Moreover, by recalling that it is a comparative static exercise, the introduction of a carbon tax is a new policy and the value of \( \tau \) added in eq. (21) corresponds to the ad valorem equivalent expressed in eq. (22), since it is the difference between zero (the initial value) and the ad valorem effect depending on the CO\(_2\) abatement target.
simultaneously reducing the net energy price increase.

The choice of the percentage to be taken from the CTR collected through a carbon tax and directed towards green energy technologies is exogenously given, meaning that it is independent from the total amount of CTR gathered. While the percentage is exogenous, the total amount of CTR directed to finance clean energy technologies (CET) is endogenously determined by the emission abatement target and the nominal carbon tax level. This means that when CET resources are transformed into efficiency gains or into an increase in production of renewable energies, the final effects on the economic system will influence the carbon tax level (for a given abatement target) and consequently the total CET amount.

In equations, total revenue from CO₂ abatement is expressed as:

\[ CTR = C_{TAX} CO₂ = C_{TAX} \beta F \]  

(23)

The amount of CTR directed to investment activities in clean energy technologies is defined as:

\[ CET = \gamma CTR \]  

(24)

Where \( \gamma \) is the exogenous percentage rate defined by policy makers.

For the sake of simplicity, the total amount of CET can be used for improving technical change in energy efficiency (\( CET_{EE} \)) and for improving output-augmenting technical change in renewable energies (\( CET_R \)). It is further assumed that CET is entirely used in each time period without a banking option. The choice of the share of total CET to be directed to energy efficiency or renewable energies is exogenously given, as part of the policy options for the climate strategy.

Accordingly:

\[ CET_{EE} = \delta CET \]  

(25)

\[ CET_R = (1 - \delta) CET \]  

(26)

Where \( \delta \) represents the share of CET directed toward input-augmenting technical change in energy efficiency.

Investments in CET are transformed into final technical change outcomes according to a simple
formulation:

\[ tc_{EE} = \varphi \, CET_{EE} \]  \hspace{1cm} (27)  

\[ tc_{R} = \theta \, CET_{R} \]  \hspace{1cm} (28)  

Where \( \varphi \) and \( \theta \) represent elasticities of technical change with respect to investments in energy efficiency and renewables, respectively. In this stylized model we consider innovation in clean energy technologies as a pure public good, completely funded by public investments with no barriers to adoption and with constant returns to scale. This treats investments in clean energy technologies as a choice independent from private profit maximization criteria adopted by the private sector producing clean technologies. Moreover, we consider input-augmenting technical change in EE and output-augmenting technical change in R as the final result of all innovation-related investments (including all technology-push policy efforts in the specific domain).

As a consequence, according to Klein et al. (1980) and Carraro and De Cian (2013), factor-augmenting technical change is also included in the modeling framework. Hence, eqs. (21), (17) and (19) become respectively:

\[ p_F = - \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_R}{\sigma_{EE}} \right) f \, tc_{EE} + \frac{\alpha_R}{\sigma_{EE}} \, r \, tc_{EE} + \frac{\alpha_K}{\sigma_{KE}} \, k + p_Y - \tau \]  \hspace{1cm} (29)  

\[ p_R = - \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right) r \, tc_{EE} + \frac{\alpha_F}{\sigma_{EE}} \, f \, tc_{EE} + \frac{\alpha_K}{\sigma_{KE}} \, k + p_Y \]  \hspace{1cm} (30)  

\[ p_R = (r + tc_{R}) \frac{1}{\psi_R} \]  \hspace{1cm} (31)  

In order to analyse the interactions in the economy-energy system determined by the combination of multiple policies, we proceed with a simple comparative static exercise. In particular, what we are interested in is the behaviour of the carbon tax and the price of renewable electricity with respect to policy choice expressed in term of \( \gamma \) and \( \delta \).

By combining eqs. (11) and (20) in eq. (15), we can write:\footnote{See Appendix B Section B.1 for derivation of eq.(32) corresponding to EQ.1 in Appendix B.}
\[ af + br = cy \]  

Where \( a, b, c \) are combination of \( \alpha_F, \alpha_R, \alpha_K, \sigma_{KE}, \eta \).

Furthermore, combining eqs. (11) and (20) with eqs. (18), (22)-(25), (27), (29), we can write:

\[ d\delta\gamma f\tau - e\delta \gamma r\tau + gf + hr + \tau = iy \]  

Where \( d, e, g, h, i \) are combination of \( \alpha_F, \alpha_R, \alpha_K, \sigma_{KE}, \varphi, P_F, y, \sigma_{EE}, \psi_F \).

Finally, combining eqs. (11) and (20) with eqs. (22)-(28), (30), (31), we can write:

\[ -l\delta\gamma f\tau + m\delta \gamma r\tau + nf + pr + q(1-\delta)\gamma \tau = iy \]  

Where \( l, m, n, p, q \) are combination of \( \alpha_F, \alpha_R, \alpha_K, \sigma_{KE}, \varphi, P_F, y, \sigma_{EE}, \psi_R, \theta \).

Eqs. (32)-(34), resulting from the original equation for \( k, p_y, tc_{EE} \) and \( tc_R \), constitute a non-linear system in three unknown variables \( f, r, \tau \), which depend on both \( \gamma \) and \( \delta \). Even by obtaining an explicit expression for \( f \) (or \( r \)) from eq. (32) and combining it with equations (33) and (34), with a resulting system reduced to two equations in two unknown variables, it would be still a non-linear solution.

Given this complexity, from a theoretical point of view we can only provide few general observations.

From eq. (32) it follows that:

\[ -af_f + br_f = 0 \quad \Rightarrow \quad f_f = -\frac{b}{a} r_f \quad \text{with} \quad \frac{b}{a} > 0 \]  

(35)

\[ -af_\delta + br_\delta = 0 \quad \Rightarrow \quad f_\delta = -\frac{b}{a} r_\delta \quad \text{with} \quad \frac{b}{a} > 0 \]  

(36)

We then calculate \( \tau \) and, starting from the previous eqs. and after some algebra, an equivalent system with respect to eqs. (32)-(34) is given by:

\[ A(\delta,\gamma)\tau^2 + B(\delta,\gamma)\tau + Cy = 0 \quad \Rightarrow \quad \tau = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \]  

(37)

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18 See Appendix B Section B.2 for detailed description of parameters.
19 See Appendix B Section B.1 for derivation of eq.(33) corresponding to EQ.2 in Appendix B.
20 See Appendix B Section B.1 for derivation of eq.(34) corresponding to EQ.3 in Appendix B.
\( f = \frac{\alpha_2}{\alpha_1} y - \frac{\beta_1 + (\beta_3 - \beta_2) y \delta \gamma + \beta_4 (1 - \delta)}{\alpha_1} \tau \rightarrow f \)  
(38)

\( r = \frac{c}{b} y - \frac{a}{b} f \rightarrow r \)  
(39)

Where\(^{21}\)

\[ A_{(\delta, \gamma)} = [\beta_1 \beta_5 + \beta_5 (\beta_3 - \beta_2) y \delta \gamma + \beta_4 \beta_5 (1 - \delta) \gamma] \delta \gamma > 0 \]

\[ B_{(\delta, \gamma)} = (\alpha_3 - \alpha_1) \beta_1 + [\alpha_3 (\beta_3 - \beta_2) + \alpha_1 \beta_2 - \alpha_2 \beta_5] y \delta \gamma + \alpha_3 \beta_4 (1 - \delta) \gamma \]

\[ C = (\alpha_1 \alpha_4 - \alpha_2 \alpha_3) \]

Accordingly, \( \tau \) can be calculated, which allows obtaining \( f \) and, from \( f \), \( r \).

We can proceed to study the behaviour of \( \tau \) with respect to \( \gamma \), which is \( \tau_{\gamma} \). Considering the expression:

\[ A \tau^2 + B \tau + C = 0 \]  
(40)

It follows that:

\[ A_{\gamma} \tau^2 + 2A \tau \tau_{\gamma} + B_{\gamma} \tau + B_{\gamma} = 0 \Rightarrow (2A \tau + B) \tau_{\gamma} + A_{\gamma} \tau^2 + B_{\gamma} \tau = 0 \Rightarrow \tau_{\gamma} = -\frac{A_{\gamma} \tau^2 + B_{\gamma} \tau}{2A \tau + B} \]  
(41)

Where

\[ A_{\gamma} = [\beta_5 (\beta_3 - \beta_2) y \delta + \beta_4 \beta_5 (1 - \delta)] \delta \gamma + \frac{A}{\gamma} > 0 \]

\[ B_{\gamma} = [\alpha_3 (\beta_3 - \beta_2) + \alpha_1 \beta_2 - \alpha_2 \beta_5] y \delta + \alpha_3 \beta_4 (1 - \delta) \geq 0 \]

If \( \alpha_1 > 0 \iff \psi_R - \psi_F > 0 \) and if \( \alpha_2 < 0 \iff \psi_R \) or \( \eta \) are sufficiently small,\(^{22}\) it follows that \( B > 0 \) and \( B_{\gamma} > 0 \), which lead to \( \tau_{\gamma} < 0 \).

For \( \delta = 0 \), the condition \( \tau_{\gamma} < 0 \) is always satisfied given that:

\[ A = 0; \]

\[ A_{\gamma} = 0; \]

\[ B_{\gamma} = \alpha_3 \beta_4 > 0 \]

\(^{21}\) See Appendix B Section B.2 for full description of parameters \( a, b, \alpha_i, \beta_i \).

\(^{22}\) The conditions ensuring that \( \alpha_2 < 0 \) are: i) \( |\eta| < \frac{c_4 \psi_R + c_4}{c_1 \psi_R - c_3} \) if \( \psi_R > \frac{c_1}{c_3} \) (where \( c_i \) are combinations of \( \alpha_K, \alpha_F, \alpha_R, \sigma_{EE}, \sigma_{KE} \)) or ii) \( \psi_R < \frac{c_4}{c_3} \), \( \forall \eta \).
\[ B = (\alpha_3 - \alpha_1)\beta_1 + \alpha_3\beta_4\gamma > 0. \]

The result for \( \delta = 0 \) is also valid for \( \delta \) sufficiently small since \( \tau_\gamma \) is a continuous function of \( \delta \). As \( \delta \) increases, if the conditions \( \alpha_1 > 0 \) and \( \alpha_2 < 0 \) are not satisfied, \( \tau_\gamma \) could also become positive.

Conversely, having \( \gamma \) sufficiently small does not ensure \( \tau_\gamma < 0 \).

This brings to conclude that a revenue recycling mechanism of carbon tax for subsidizing clean energies does not necessarily implies a reduction in the carbon tax level, since the final effect is influenced by several additional conditions.

We can proceed to study the behaviour of the \( \tau \) with respect to \( \delta \), which is \( \tau_\delta \). Considering the expression:

\[ \tau_\delta = -\frac{A_\delta \tau^2 + B_\delta \tau}{2A\tau + B} \]  

(42)

Where

\[ A_\delta = [\beta_5 (\beta_3 - \beta_2)\gamma - \beta_4\beta_5\gamma] \delta \gamma + \frac{A}{\delta} \geq 0 \]

\[ B_\delta = [\alpha_3 (\beta_3 - \beta_2) + \alpha_1\beta_2 - \alpha_2\beta_5] \gamma \gamma - \alpha_3\beta_4\gamma \geq 0 \]

We can affirm that, given that \( A_\delta \) e \( B_\delta \) can either be positive or negative depending on the value assigned to each parameter, the sign of \( \tau_\delta \) can not be \textit{a priori} established. This means that the carbon tax level might be reduced by financing energy efficiency, but the final effect is subject to several other variables.
Appendix B – Mathematical details on Appendix A

Section B.1 – System definition

From eq. (11):

$$k = \frac{y}{\alpha_K} - \frac{\alpha_F}{\alpha_K} f - \frac{\alpha_R}{\alpha_K} r \quad (B1)$$

From eq. (20):

$$p_Y = \frac{y}{\eta} \quad (B2)$$

From eq. (15):

$$0 = -(\alpha_F + \alpha_R)k + \alpha_F f + \alpha_R r + \sigma_{KE} p_Y \quad (B3)$$

Combining eqs. (A1) and (A2) in eq. (A3), we can write:

$$0 = -(\alpha_F + \alpha_R) \left[ \frac{y}{\alpha_K} - \frac{\alpha_F}{\alpha_K} f - \frac{\alpha_R}{\alpha_K} r \right] + \alpha_F f + \alpha_R r + \frac{\sigma_{KE}}{\eta} y \Rightarrow$$

$$\Rightarrow - \frac{(\alpha_F + \alpha_R)}{\alpha_K} y + (\alpha_F + \alpha_R) \frac{\alpha_F}{\alpha_K} f + (\alpha_F + \alpha_R) \frac{\alpha_R}{\alpha_K} r + \alpha_F f + \alpha_R r + \frac{\sigma_{KE}}{\eta} y = 0 \Rightarrow$$

$$\Rightarrow \left[ (\alpha_F + \alpha_R) \frac{\alpha_F}{\alpha_K} + \alpha_F \right] f + \left[ (\alpha_F + \alpha_R) \frac{\alpha_R}{\alpha_K} + \alpha_R \right] r + \left[ - \frac{(\alpha_F + \alpha_R)}{\alpha_K} + \frac{\sigma_{KE}}{\eta} \right] y = 0 \quad (B4)$$

Assuming:

$$a = (\alpha_F + \alpha_R) \frac{\alpha_F}{\alpha_K} + \alpha_F = \frac{\alpha_F}{\alpha_K} > 0$$

$$b = (\alpha_F + \alpha_R) \frac{\alpha_R}{\alpha_K} + \alpha_R = \frac{\alpha_R}{\alpha_K} > 0$$

$$c = \frac{(\alpha_F + \alpha_R)}{\alpha_K} - \frac{\sigma_{KE}}{\eta} > 0 \quad (\text{since } \eta < 0)$$

Eq. (A4) can be re-written as:

$$af + br = cy \quad \text{(EQ.1)}$$

From eqs. (18) and (29) we have:

$$- \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_R}{\sigma_{EE}} \right) f tc_{EE} + \frac{\alpha_R}{\sigma_{EE}} r tc_{EE} + \frac{\alpha_K}{\sigma_{KE}} k + p_Y - \tau = \frac{1}{\psi_F} f \quad (B5)$$
From eqs. (22)–(25) and (27) we can write:

\[ t_{cEE} = \varphi C_{ET_{EE}} = \varphi \delta CTR = \varphi \delta y C_{TAX} \beta F = \varphi \delta y y F F \tau \Rightarrow \]

\[ \Rightarrow t_{cEE} = \varphi y F F \delta y \tau \]  \hspace{1cm} (B6)

Combining eqs. (B1), (B2) and (B6) in eq. (B5), we have:

\[ -\left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_R}{\sigma_{EE}} \right) f \varphi y P_F \delta y \tau + \frac{\alpha_R}{\sigma_{EE}} r \varphi y P_F \delta y \tau + \frac{\alpha_K}{\sigma_{KE}} \left( \frac{y}{\alpha_K} - \frac{\alpha_F}{\alpha_K} f - \frac{\alpha_R}{\alpha_K} r \right) + \frac{y}{\eta} - \tau - \frac{1}{\psi_F} f = 0 \Rightarrow \]

\[ \Rightarrow \left[ -\left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_R}{\sigma_{EE}} \right) \varphi y P_F \right] \delta y f \tau + \left[ \frac{\alpha_R}{\sigma_{EE}} \varphi y P_F \right] \delta y r \tau - \frac{\alpha_F}{\sigma_{KE}} f - \frac{\alpha_R}{\sigma_{KE}} r \tau - \frac{1}{\psi_F} f = 0 \Rightarrow \]

\[ \Rightarrow \left[ -\left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_R}{\sigma_{EE}} \right) \varphi y P_F \right] \delta y f \tau + \left[ \frac{\alpha_R}{\sigma_{EE}} \varphi y P_F \right] \delta y r \tau - \left[ \frac{\alpha_F}{\sigma_{KE}} + \frac{1}{\psi_F} \right] f - \frac{\alpha_R}{\sigma_{KE}} r - \frac{1}{\psi_F} f = 0 \Rightarrow \]

\[ + \left( \frac{1}{\sigma_{KE}} + \frac{1}{\eta} \right) y = 0 \]  \hspace{1cm} (B7)

Assuming:

\[ d = \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_R}{\sigma_{EE}} \right) \varphi y P_F > 0 \]

\[ e = \frac{\alpha_R}{\sigma_{EE}} \varphi y P_F > 0 \]

\[ g = \frac{\alpha_F}{\sigma_{KE}} + \frac{1}{\psi_F} > 0 \]

\[ h = \frac{\alpha_R}{\sigma_{KE}} > 0 \]

\[ i = \left( \frac{1}{\sigma_{KE}} + \frac{1}{\eta} \right) \]

Eq. (7) can be re-written as:

\[ d \delta y f \tau - e \delta y r \tau + g f + h r + \tau = i y \]  \hspace{1cm} (EQ.2)

Finally, from eqs. (30)–(31):

\[ -\left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right) r t_{cEE} + \frac{\alpha_F}{\sigma_{EE}} f t_{cEE} + \frac{\alpha_K}{\sigma_{KE}} k + p_F = (r + t_{cR}) \frac{1}{\psi_R} \]  \hspace{1cm} (B8)

From eqs. (22)–(24), (26), (28), we can write:
\[
tc_R = \theta \ CET_R = \theta (1 - \delta) \ CET = \theta (1 - \delta) \gamma \ CTR = \theta (1 - \delta) \gamma \ C_{TAX} \ \beta \ F = \theta (1 - \delta) \gamma yP_F \tau \Rightarrow \\
\Rightarrow tc_R = \theta yP_F (1 - \delta) \gamma \tau 
\]

Combining equations (B1), (B2), (B6) and (B9) in eq. (B8), we have:

\[
- \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right) r \ \psi_P \delta \gamma \tau + \frac{\alpha_F}{\sigma_{EE}} f \ \psi_P \delta \gamma \tau + \frac{1}{\sigma_{KE}} (y - \alpha_F f - \alpha_R r) + \frac{y}{\eta} = \\
= \frac{1}{\psi_R} r + \frac{1}{\psi_R} \theta yP_F (1 - \delta) \gamma \tau \\
\Rightarrow \frac{\alpha_F}{\sigma_{EE}} \psi_P \delta \gamma f \tau - \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right) \psi_P \delta \gamma r \tau - \frac{\alpha_F}{\sigma_{KE}} f - \left( \frac{\alpha_R}{\sigma_{KE}} + \frac{1}{\psi_R} \right) r \\
- \frac{1}{\psi_R} \theta yP_F (1 - \delta) \gamma \tau = - \left( \frac{1}{\sigma_{KE}} + \frac{1}{\eta} \right) y
\]

Assuming:

\[
l = \frac{\alpha_F}{\sigma_{EE}} \psi_P \delta f \tau > 0
\]

\[
m = \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right) \psi_P \delta f \tau > 0
\]

\[
n = \frac{\alpha_F}{\sigma_{KE}} > 0
\]

\[
p = \frac{\alpha_R}{\sigma_{KE}} + \frac{1}{\psi_R} > 0
\]

\[
q = \frac{1}{\psi_R} \theta yP_F > 0
\]

Eq. (B10) can be re-written as:

\[
-l \delta \gamma f \tau + m \delta \gamma r \tau + nf + pr + q (1 - \delta) \gamma \tau = iy
\]

(EQ.3)

Thus EQ.1, EQ.2, and EQ.3, resulting from the original eqs. for \( k, p_y, tc_{EE} \) and \( tc_R \), constitute a non-linear system in three unknown variables \( f, r, \tau \). Each variable is, in general, dependent on both \( \gamma \) and \( \delta \). Even if we obtain an explicit expression for \( f \) (or \( r \)) from EQ.1 and combine it with EQ.2 and EQ.3, the system can be reduced to two equations in two unknown variables but it would be still non-linear.
In fact, starting from equation EQ.1, we can write:

\[ r = \frac{c}{b} y - \frac{a}{b} f \]  

(B11)

and combining eq. (B11) in EQ.2, we have:

\[
d\delta y f \tau - e\delta y \tau \left( \frac{c}{b} y - \frac{a}{b} f \right) + gf + h \left( \frac{c}{b} y - \frac{a}{b} f \right) + \tau = iy \Rightarrow
\]

\[
\Rightarrow d\delta y f \tau - e\delta y \tau \frac{c}{b} y + e\delta y \tau \frac{a}{b} f + gf + \frac{c}{b} hy - \frac{a}{b} f + \tau = iy \Rightarrow
\]

\[
\Rightarrow \left( d + \frac{ea}{b} \right) \delta y f \tau + \left( g - \frac{ha}{b} \right) f + \left( 1 - y \frac{ec}{b} \delta y \right) \tau = iy - \frac{ch}{b} y \Rightarrow
\]

\[
\Rightarrow (bd + ae)\delta y f \tau + (bg + ah)f + (b - cey\delta y)\tau = (ib - ch)y \quad \text{(B12)}
\]

Combining equation (B11) in EQ.3 we also have:

\[
-l\delta y f \tau + m \left( \frac{c}{b} y - \frac{a}{b} f \right) \delta y \tau + nf + p \left( \frac{c}{b} y - \frac{a}{b} f \right) + q(1 - \delta)\gamma \tau = iy \Rightarrow
\]

\[
\Rightarrow -l\delta y f \tau + \left( \frac{mc}{b} - \frac{ma}{b} \right) \delta y f \tau + nf + \frac{pc}{b} y - \frac{pa}{b} f + q(1 - \delta)\gamma \tau = iy \Rightarrow
\]

\[
\Rightarrow -\left( l + m \frac{a}{b} \right) \delta y f \tau + \left( n - p \frac{a}{b} \right) f + \left[ m \frac{c}{b} y \delta y + q(1 - \delta)\gamma \right] \tau = iy - p \frac{c}{b} y \Rightarrow
\]

\[
\Rightarrow -(bl + am)\delta y f \tau + (bn - ap)f + [cmy\delta + bq(1 - \delta)]\gamma \tau = (bi - cp)y \quad \text{(B13)}
\]

By multiplying eq. (A12) times \((bl + am)\) and eq. (A13) times \((bd + ae)\), we have:

\[
(bl + am)(bd + ae)\delta y f \tau + (bl + am)(bg + ah)f + (bl + am)(b - cey\delta y)\tau = (bl + am)(bi - ch)y
\]

\[
= (bl + am)(bi - ch)y \quad \text{(B14)}
\]

\[
-(bd + ae)(bl + am)\delta y f \tau + (bd + ae)(bn - ap)f + (bd + ae)[cmy\delta + bq(1 - \delta)]\gamma \tau = (bd + ae)(bi - cp)y
\]

\[
= (bd + ae)(bi - cp)y \quad \text{(B15)}
\]

Adding each side of eqs. (B14) and (B15):

\[
[(bl + am)(bg - ah) + (bd + ae)(bn - ap)]f + [(bl + am)(b - cey\delta y) + (bd + ae)(cmy\delta + bq(1 - \delta)\gamma)]\gamma \tau = [(bl + am)(bi - ch) + (bd + ae)(bi - cp)]y
\]

\[
\text{(B16)}
\]

Assuming \((\alpha_i)\) have an a priori undetermined sign while \((\beta_i)\) are positive):
\[ \alpha_1 = (bl + am)(bg - ah) + (bd + ae)(bn - ap) \]

\[ \beta_1 = b(bl + am) \]

\[ \beta_2 = ce(bl + am) \]

\[ \beta_3 = cm(bd + ae) \]

\[ \beta_4 = bq(bd + ae) \]

\[ \alpha_2 = (bl + am)(bi - ch) + (bd + ae)(bi - cp) \]

Eq. (A16) becomes:

\[ \alpha_1 f + \left[ \beta_1 - \beta_2 y\delta\gamma + \beta_3 y\delta\gamma + \beta_4(1 - \delta)\gamma \right] \tau = \alpha_2 y \quad \text{(B17)} \]

From eq. (B17) it follows that for \( f_\gamma \) and \( \tau_\gamma \) (as well as \( f_\delta \) and \( \tau_\delta \)) there is no a defined sign relationship, which depends on the parameters values. Given from EQ.1 that \( f_\gamma = -\frac{b}{a} r_\gamma \) and \( f_\delta = -\frac{b}{a} r_\delta \) (with \( \frac{b}{a} > 0 \)), the same holds for \( \tau_\gamma \) and \( r_\gamma \) (as well as for \( \tau_\delta \) and \( r_\delta \)).

From eq. (B17) we can write \( f \) as a function of \( \tau \):

\[ f = \frac{\alpha_2}{\alpha_1} y - \frac{\left[ \beta_1 + (\beta_3 - \beta_2) y\delta\gamma + \beta_4(1 - \delta)\gamma \right]}{\alpha_1} \tau \quad \text{(B18)} \]

Assuming (\( \alpha_i \) have an a priori undetermined sign while \( \beta_i \) are positive):

\[ \beta_5 = (bl + am)(bd + ae) \]

\[ \alpha_3 = (bl + am)(bg - ah) \]

\[ \alpha_4 = (bl + am)(bi - ch) \]

Eq. (A14) becomes:

\[ \beta_5 \delta\gamma f \tau + \alpha_3 f + (\beta_1 - \beta_2 y\delta\gamma) \tau = \alpha_4 y \quad \text{(B19)} \]

Combining eqs. (B18) and (B19):

\[ \beta_5 \frac{\alpha_2}{\alpha_1} y\delta\gamma \tau - \frac{\beta_5}{\alpha_1} \left[ \beta_1 + (\beta_3 - \beta_2) y\delta\gamma + \beta_4(1 - \delta)\gamma \right] \delta\gamma \tau^2 + \frac{\alpha_2 \alpha_3}{\alpha_1} y \]

\[ - \frac{\alpha_3}{\alpha_1} \left[ \beta_1 + (\beta_3 - \beta_2) y\delta\gamma + \beta_4(1 - \delta)\gamma \right] \tau + (\beta_1 - \beta_2 y\delta\gamma) \tau = \alpha_4 y \Rightarrow \]
\[
\Rightarrow \frac{\beta_5}{\alpha_1} [\beta_1 + (\beta_3 - \beta_2)y\gamma + \beta_4(1 - \gamma)\gamma] \delta\gamma \tau^2
\]
\[
+ \left[ - \frac{\beta_5}{\alpha_1} \alpha_2 y\gamma + \frac{\alpha_3}{\alpha_1} [\beta_1 + (\beta_3 - \beta_2)y\gamma + \beta_4(1 - \gamma)\gamma] - \beta_1 + \beta_2 y\gamma \right] \tau
\]
\[
- \frac{\alpha_2 \alpha_3}{\alpha_1} y = -\alpha_4 y \Rightarrow
\]
\[
\Rightarrow \frac{\beta_5}{\alpha_1} [\beta_1 + (\beta_3 - \beta_2)y\gamma + \beta_4(1 - \gamma)\gamma] \delta\gamma \tau^2
\]
\[
+ \left[ \frac{\alpha_3}{\alpha_1} \beta_1 - \beta_1 - \frac{\beta_5}{\alpha_1} \alpha_2 y\gamma + \frac{\alpha_3}{\alpha_1} (\beta_3 - \beta_2)y\gamma + \beta_2 y\gamma + \frac{\alpha_3}{\alpha_1} \beta_4(1 - \gamma)\gamma \right] \tau + \alpha_4 y
\]
\[
- \frac{\alpha_2 \alpha_3}{\alpha_1} y = 0 \Rightarrow
\]
\[
\Rightarrow [\beta_1 \beta_5 + \beta_5(\beta_3 - \beta_2)y\gamma + \beta_4 \beta_5(1 - \gamma)\gamma] \delta\gamma \tau^2
\]
\[
+ [(\alpha_3 - \alpha_1)\beta_1 + (\alpha_3(\beta_3 - \beta_2) - \beta_5 \alpha_2 + \alpha_1 \beta_2)y\gamma + \alpha_3 \beta_4(1 - \gamma)\gamma] \tau + (\alpha_1 \alpha_4 - \alpha_2 \alpha_3)y = 0
\]

Assuming:

\[ A_{(\delta,\gamma)} = [\beta_1 \beta_5 + \beta_5(\beta_3 - \beta_2)y\gamma + \beta_4 \beta_5(1 - \gamma)\gamma] > 0 \]

\[ B_{(\delta,\gamma)} = (\alpha_3 - \alpha_1)\beta_1 + [\alpha_3(\beta_3 - \beta_2) + \alpha_1 \beta_2 - \alpha_2 \beta_5] y\gamma + \alpha_3 \beta_4(1 - \gamma)\gamma \]

\[ C = \alpha_1 \alpha_4 - \alpha_2 \alpha_3 \]

Equation (B19) can be written as:

\[ A_{(\delta,\gamma)} \tau^2 + B_{(\delta,\gamma)} \tau + Cy = 0 \]  \hspace{1cm} (B20)

From which it follows that \[ \tau = \frac{-B_{(\delta,\gamma)} \pm \sqrt{B_{(\delta,\gamma)}^2 - 4AC}}{2A_{(\delta,\gamma)}}. \]

Summing up, the system given by equation EQ.1, EQ.2 and EQ.3 is equivalent to the eqs. (11), (18), (20), and the solution is given by equation (B21), according to which first \( \tau \) can be calculated, which allows obtaining \( f \) and, from \( f \), \( r \).

\[ A_{(\delta,\gamma)} \tau^2 + B_{(\delta,\gamma)} \tau + Cy = 0 \quad \rightarrow \quad \tau = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \]
\[ f = \frac{\alpha_2}{\alpha_1} y - \frac{\beta_1 + (\beta_3 - \beta_2) y \delta y + \beta_4 (1 - \delta)}{\alpha_1} \tau \quad \rightarrow \quad f \]  
\[ r = c \frac{y - a}{b} f \quad \rightarrow \quad r \]

Where the parameters \( \alpha_i \) and \( \beta_i \) are given by:

\[ \alpha_1 = (bl + am)(bg - ah) + (bd + ae)(bn - ap) \]

\[ = \varphi y \varphi_F \frac{\alpha_F \alpha_R}{\alpha_R^2 \varphi_F \varphi_R} \left( \frac{\alpha_R}{\sigma_{EE}} + \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right) (\psi_R - \psi_F) \]

Accordingly, the sign of \( \alpha_1 \) depends on the sign of \((\psi_R - \psi_F)\).\(^{21}\)

\[ \alpha_2 = (bl + am)(i_0 b - ch) + (bd + ae)(bi_0 - cp) = \left[ \frac{\alpha_F (2\alpha_R + \alpha_F)}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F \alpha_K + \alpha_R (1 - \alpha_F)}{\alpha_K \sigma_{KE}^2} \right] + \frac{1 + \alpha_K}{\alpha_K \eta} \left[ \frac{\alpha_K \alpha_F + \alpha_R (1 - \alpha_F)}{\alpha_K \sigma_{KE}} + \frac{\alpha_F (\alpha_F + 2\alpha_R)}{\alpha_K \sigma_{KE}} \right] \]

\[ + \frac{\alpha_K - 1}{\alpha_K^2 \varphi_R} \left[ \frac{1 - \alpha_F}{\sigma_{EE}} + \frac{\alpha_F}{\sigma_{EE}} \right] + \frac{1}{\alpha_K \eta \varphi_R} \left[ 1 - \alpha_F + \frac{\alpha_F \sigma_{KE}}{\sigma_{EE}} \right] \]

\[ \alpha_3 = (bl + am)(bg - ah) = \frac{\varphi y \varphi_F \alpha_F \alpha_R}{\psi_F} \frac{\alpha_K^2}{\sigma_{KE}} \left( \frac{\alpha_F}{\sigma_{KE}} + \frac{\alpha_K + \alpha_R}{\sigma_{EE}} \right) > 0 \]

\[ \alpha_3 - \alpha_1 = \frac{\psi_F}{\psi_R} \alpha_3 > 0 \]

\[ \alpha_4 = (bl + am)(bi - ch) = \varphi y \varphi_F \alpha_F \alpha_R \left[ \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{1}{\sigma_{EE}} + \frac{1 + \alpha_K}{\alpha_K \eta} \left( \frac{1}{\sigma_{KE}} + \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{KE}} \right) \right] \]

\[ \beta_1 = b(bl + am) = \varphi y \varphi_F \frac{\alpha_F \alpha_R}{\alpha_K^2} \left( \frac{\alpha_F + \alpha_R}{\sigma_{EE}} + \frac{\alpha_K}{\sigma_{KE}} \right) > 0 \]

\[ \beta_2 = ce(bl + am) = (\varphi y \varphi_F)^2 \alpha_F \alpha_R \left[ \left( \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{EE}} \right)^2 + \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{EE} \sigma_{KE}} - \frac{\sigma_{KE}}{\sigma_{EE} \eta} \left( \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{EE}} + \frac{1}{\sigma_{KE}} \right) \right] > 0 \]

\[ \beta_3 = cm(bd + ae) \]

\[ \beta_3 - \beta_2 = (\varphi y \varphi_F)^2 \frac{\alpha_R}{\sigma_{KE}} \left( \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{EE}} + \frac{\alpha_K}{\sigma_{KE}} \right) \left( \frac{\alpha_F + \alpha_R}{\alpha_K} - \frac{\sigma_{KE}}{\eta} \right) > 0 \]

\[ \beta_4 = bq(bd + ae) = \frac{\theta \varphi (y \varphi_F)^2}{\psi_R} \left( \frac{\alpha_R}{\alpha_K} \right)^2 \left( \frac{\alpha_F + \alpha_R}{\sigma_{EE}} + \frac{\alpha_K}{\sigma_{KE}} \right) > 0 \]

\(^{21}\) For further details on parameters, see Section B.2.
\[
\beta_5 = (bl + am)(bd + ae) \\
= (\varphi y_p)^2 \frac{\alpha_F}{\alpha_k} \left[ \frac{\alpha_K (\alpha_R + \alpha_K)}{\sigma_{KE}^2} + \frac{\alpha_F (\alpha_R + \alpha_F)}{\sigma_{EE}^2} + \frac{(\alpha_K + \alpha_R)(\alpha_F + \alpha_R) + \alpha_K \alpha_F}{\sigma_{EE} \sigma_{KE}} \right]
\]

**Analysis of \( \tau_\gamma \)**

In order to analyse \( \tau_\gamma \) we consider the expression:

\[
A \tau^2 + B \tau + C = 0
\]

It follows that:

\[
A_\gamma \tau^2 + 2A \tau \tau + B_\gamma \tau + B \tau_\gamma = 0 \quad \Rightarrow \quad (2A \tau + B) \tau_\gamma + A_\gamma \tau^2 + B \tau_\gamma = 0
\]

\[
\Rightarrow \quad \tau_\gamma = -\frac{A_\gamma \tau^2 + B \tau_\gamma}{2A \tau + B}
\]

Where:

\[
A_\gamma = [\beta_5 (\beta_3 - \beta_2) y_\delta + \beta_4 \beta_5 (1 - \delta)] \delta_\gamma + \frac{A}{\gamma} > 0
\]

\[
B_\gamma = [\alpha_3 (\beta_3 - \beta_2) + \alpha_1 \beta_2 - \alpha_2 \beta_5] y_\delta + \alpha_3 \beta_4 (1 - \delta)
\]

If \( \alpha_1 > 0 \iff \psi_R - \psi_F > 0 \) and if \( \alpha_2 < 0 \iff \psi_R < \eta \) sufficiently small, it follows that \( B > 0 \) and \( B_\gamma > 0 \), which lead to \( \tau_\gamma < 0 \). The conditions ensuring that \( \alpha_2 < 0 \) are: i) \( |\eta| < \frac{c_3 \psi_R + c_4}{c_1 \psi_R - c_3} \) if \( \psi_R > \frac{c_3}{c_1} \) (where \( c_i \) are combinations of \( \alpha_K, \alpha_F, \alpha_R, \sigma_{EE}, \sigma_{KE} \)) or ii) \( \psi_R < \frac{c_3}{c_1} \forall \eta \).

**Remark 1**

For \( \delta = 0 \), the condition \( \tau_\gamma < 0 \) is always satisfied given that:

\[ A = 0 \]

\[ A_\gamma = 0 \]

\[ B_\gamma = \alpha_3 \beta_4 > 0 \]

\[ B = (\alpha_3 - \alpha_1) \beta_4 + \alpha_3 \beta_4 \gamma > 0 \]

The results for \( \delta = 0 \) is also valid for \( \delta \) sufficiently small since \( \tau_\gamma \) is a continuous function of \( \delta \); as \( \delta \) increases, if the conditions \( \alpha_1 > 0 \) and \( \alpha_2 < 0 \) are not satisfied, \( \tau_\gamma \) could also become positive.
Analysis of $\tau_{\delta}$

We have:

$$\tau_{\delta} = -\frac{A_{\delta}\tau^{2} + B_{\delta}\tau}{2A_{\tau} + B_{\delta}} \quad (B23)$$

Where

$$A_{\delta} = [\beta_{5}(\beta_{3} - \beta_{2})y\gamma - \beta_{4}\beta_{5}\gamma]\delta\gamma + \frac{A}{\delta}$$

$$B_{\delta} = [\alpha_{3}(\beta_{3} - \beta_{2}) + \alpha_{1}\beta_{2} - \alpha_{2}\beta_{5}]y\gamma - \alpha_{3}\beta_{4}\gamma$$

**Remark 2**

Given that $A_{\delta} \leq B_{\delta}$ can either be positive or negative depending on the value assigned to each parameter, the sign of $\tau_{\delta}$ cannot be a priori established.

**Section B.2 – Parameters for mathematical details in Section B.1**

Given that:

$$\alpha_{1} = (bl + am)(bg - ah) + (bd + ae)(bn - ap)$$

Where

$$bl + am = \left[\frac{\alpha_{F} + \alpha_{R}}{\alpha_{K}} + 1 \right] \alpha_{R} \frac{\alpha_{F}}{\sigma_{EE}} \varphi y_{p_{F}} + \left[\frac{\alpha_{F} + \alpha_{R}}{\alpha_{K}} + 1 \right] \alpha_{F} \left( \frac{\alpha_{K}}{\sigma_{KE}} + \frac{\alpha_{F}}{\sigma_{EE}} \right) \varphi y_{p_{F}}$$

$$bg - ah = \left[\frac{\alpha_{F} + \alpha_{R}}{\alpha_{K}} \alpha_{K} + \alpha_{R} \right] \frac{\alpha_{F}}{\sigma_{KE}} + \frac{1}{\psi_{F}} - \left[\frac{\alpha_{F} + \alpha_{R}}{\alpha_{K}} \alpha_{F} \right] \frac{\alpha_{R}}{\sigma_{KE}}$$

$$= \left[\frac{\alpha_{F} + \alpha_{R}}{\alpha_{K}} + 1 \right] \alpha_{R} \left( \frac{\alpha_{F}}{\sigma_{KE}} + \frac{1}{\psi_{F}} \right) - \alpha_{F} \frac{\alpha_{R}}{\sigma_{KE}} > 0$$

$$bd + ae = \left[\frac{\alpha_{F} + \alpha_{R}}{\alpha_{K}} + 1 \right] \alpha_{R} \left( \frac{\alpha_{K}}{\sigma_{KE}} + \frac{\alpha_{F}}{\sigma_{EE}} \right) \varphi y_{p_{F}} + \left[\frac{\alpha_{F} + \alpha_{R}}{\alpha_{K}} + 1 \right] \alpha_{F} \left( \frac{\alpha_{R}}{\sigma_{EE}} \varphi y_{p_{F}} \right)$$

$$bn - ap = \left[\frac{\alpha_{F} + \alpha_{R}}{\alpha_{K}} + 1 \right] \alpha_{R} \frac{\alpha_{F}}{\sigma_{KE}} - \left[\frac{\alpha_{F} + \alpha_{R}}{\alpha_{K}} + 1 \right] \alpha_{F} \left( \frac{\alpha_{R}}{\sigma_{KE}} + \frac{1}{\psi_{R}} \right)$$

$$= \left[\frac{\alpha_{F} + \alpha_{R}}{\alpha_{K}} + 1 \right] \frac{\alpha_{F}\alpha_{R}}{\sigma_{KE}} - \frac{\alpha_{F}\alpha_{R}}{\sigma_{KE}} \frac{\alpha_{F}}{\psi_{R}} = \left[\frac{\alpha_{F} + \alpha_{R}}{\alpha_{K}} + 1 \right] \frac{\alpha_{F}}{\psi_{R}} $$
We obtain:

\[ \alpha_1 = \left\{ \left[ \frac{(\alpha_F + \alpha_R)}{\alpha_K} + 1 \right] \varphi y p_F \left( \frac{\alpha_R}{\sigma_{EE}^2} + \frac{\alpha_K}{\sigma_{KE}^2} + \frac{\alpha_F}{\sigma_{EE}} \right) \right\} \cdot \left\{ \left( \frac{(\alpha_F + \alpha_R)}{\alpha_K} + 1 \right) \frac{\alpha_R}{\psi_F} \right\} \]

\[ + \left\{ \left[ \frac{(\alpha_F + \alpha_R)}{\alpha_K} + 1 \right] \varphi y p_F \alpha_R \left( \frac{\alpha_F}{\sigma_{EE}^2} + \frac{\alpha_K}{\sigma_{KE}^2} + \frac{\alpha_R}{\sigma_{EE}} \right) \right\} \cdot \left\{ \left( \frac{(\alpha_F + \alpha_R)}{\alpha_K} + 1 \right) \left[ -\frac{\alpha_F}{\psi_R} \right] \right\} \]

\[ = \left[ \frac{(\alpha_F + \alpha_R)}{\alpha_K} + 1 \right]^2 \varphi y p_F \frac{\alpha_F \alpha_R}{\psi_F} \left( \frac{\alpha_R}{\sigma_{EE}^2} + \frac{\alpha_K}{\sigma_{KE}^2} + \frac{\alpha_F}{\sigma_{EE}} \right) \]

\[ - \left[ \frac{(\alpha_F + \alpha_R)}{\alpha_K} + 1 \right]^2 \varphi y p_F \frac{\alpha_F \alpha_R}{\psi_R} \left( \frac{\alpha_R}{\sigma_{EE}^2} + \frac{\alpha_K}{\sigma_{KE}^2} + \frac{\alpha_F}{\sigma_{EE}} \right) \left( \frac{1}{\psi_F} - \frac{1}{\psi_R} \right) = \]

\[ = \varphi y p_F \frac{\alpha_F \alpha_R}{\psi_F \psi_R} \left( \frac{\alpha_R}{\sigma_{EE}^2} + \frac{\alpha_K}{\sigma_{KE}^2} + \frac{\alpha_F}{\sigma_{EE}} \right) \left( \psi_R - \psi_F \right) \]

Accordingly, the sign of \( \alpha_1 \) depends on \( (\psi_R - \psi_F) \) since:

\[ \beta_3 - \beta_2 = bcdm + aecm - bcel - acem = bcdm - bcel = bc(dm - el) \]

With

\[ dm - el = \left( \frac{\alpha_K}{\sigma_{KE}^2} + \frac{\alpha_R}{\sigma_{EE}^2} \right) \varphi y p_F \left( \frac{\alpha_K}{\sigma_{KE}^2} + \frac{\alpha_F}{\sigma_{EE}} \right) \varphi y p_F - \frac{\alpha_R}{\sigma_{EE}^2} \varphi y p_F \frac{\alpha_F}{\sigma_{EE}} \varphi y p_F \]

\[ = (\varphi y p_F)^2 \left[ \frac{\alpha_F^2}{\sigma_{EE}^2} + \frac{\alpha_K \alpha_F}{\sigma_{KE}^2 \sigma_{EE}} + \frac{\alpha_K \alpha_R}{\sigma_{KE}^2 \sigma_{EE}} + \frac{\alpha_R \alpha_F}{\sigma_{EE}^2} - \frac{\alpha_R \alpha_F}{\sigma_{EE}^2} \right] \]

\[ = (\varphi y p_F)^2 \frac{\alpha_K}{\sigma_{KE}^2} \left( \frac{\alpha_R}{\sigma_{EE}^2} + \frac{\alpha_K}{\sigma_{KE}^2} + \frac{\alpha_F}{\sigma_{EE}} \right) \]

And

\[ bc = \frac{\alpha_R}{\alpha_K} \left( \frac{\alpha_F + \alpha_R}{\alpha_K} - \sigma_{KE} \right) \]

Rearranging we obtain:

\[ \beta_3 - \beta_2 = (\varphi y p_F)^2 \frac{\alpha_R}{\sigma_{KE}^2} \left( \frac{\alpha_R}{\sigma_{EE}^2} + \frac{\alpha_K}{\sigma_{KE}^2} + \frac{\alpha_F}{\sigma_{EE}} \right) \left( \frac{\alpha_F + \alpha_R}{\alpha_K} - \sigma_{KE} \right) > 0 \]
Remark 3

Considering eq. (B18) and deriving with respect to \( \gamma \) we have:

\[
f_\gamma = -\frac{[(\beta_3 - \beta_2)y\delta + \beta_4(1 - \delta)]}{\alpha_1} \tau - \frac{\beta_1 + (\beta_3 - \beta_2)y\delta \gamma + \beta_4(1 - \delta)\gamma}{\alpha_1} \tau_\gamma
\]

Given that \((\beta_3 - \beta_2) > 0\), and that the sign of \(\alpha_1\) depends on \((\psi_R - \psi_F)\), we can discuss the sign of \(f_\gamma\) as a function of the sign of \(\tau_\gamma\). In particular we have two cases:

**Case 1)**

\(\alpha_1 > 0\):

\[
f_\gamma > 0 \iff -[\beta_1 + (\beta_3 - \beta_2)y\delta \gamma + \beta_4(1 - \delta)\gamma] \tau_\gamma > [(\beta_3 - \beta_2)y\delta + \beta_4(1 - \delta)] \tau \iff f_\gamma > 0 \iff \frac{\tau_\gamma}{\tau} > -\frac{[(\beta_3 - \beta_2)y\delta + \beta_4(1 - \delta)]}{\beta_1 + (\beta_3 - \beta_2)y\delta \gamma + \beta_4(1 - \delta)\gamma}
\]

Assuming:

\[
t = \frac{[(\beta_3 - \beta_2)y\delta + \beta_4(1 - \delta)]}{\beta_1 + (\beta_3 - \beta_2)y\delta \gamma + \beta_4(1 - \delta)\gamma} > 0
\]

\[
f_\gamma > 0 \iff \frac{\tau_\gamma}{\tau} < -t
\]

It derives that, even if the elasticity of renewable supply is larger than the fossil elasticity of supply \((\alpha_1 > 0 \iff \psi_R > \psi_F)\), then \(f_\gamma > 0\) if \(\tau\) decreases too much as \(\gamma\) increases.

**Case 2)**

\(\alpha_1 < 0\):

\[
f_\gamma > 0 \iff -[\beta_1 + (\beta_3 - \beta_2)y\delta \gamma + \beta_4(1 - \delta)\gamma] \tau_\gamma < [\beta_1 + [(\beta_3 - \beta_2)y\delta + \beta_4(1 - \delta)] \tau \iff f_\gamma > 0
\iff \frac{\tau_\gamma}{\tau} > -t
\]

It derives that, if the elasticity of renewable supply is lower than the fossil elasticity of supply \((\alpha_1 < 0 \iff \psi_R < \psi_F)\), then \(f_\gamma > 0\) if \(\tau\) decreases too slowly as \(\gamma\) increases.

The same properties do not hold between \(f_\delta\) and \(\tau_\delta\) since:

\[
\alpha_3 - \alpha_1 = (bl + am)(bg - ah) - (bl + am)(bg - ah) - (bd + ae)(bn - ap)
\]

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\[-(bd + ae)(bn - ap) = - \left[ \frac{\alpha_R}{\alpha_K} \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_R}{\sigma_{EE}} \right) \varphi y p_F + \frac{\alpha_F}{\alpha_K} \frac{\alpha_R}{\sigma_{KE}} \frac{\alpha_F}{\sigma_{EE}} \varphi y p_F \right] \left( - \frac{\alpha_F}{\alpha_K} \frac{1}{\psi_R} \right) \]

And consequently it derives that:

\[ \alpha_3 - \alpha_1 = \frac{\alpha_R}{\alpha_K} \frac{\alpha_F}{\sigma_{EE}} \varphi y p_F + \frac{\alpha_F}{\alpha_K} \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_R}{\sigma_{EE}} \right) \varphi y p_F = \frac{\alpha_F}{\alpha_K} \frac{1}{\psi_R} \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_R}{\sigma_{EE}} \right) > 0 \]

Given that:

\[ \alpha_3 = (bl + am)(bg - ah) = \frac{\alpha_R}{\alpha_K} \frac{\alpha_F}{\sigma_{EE}} \varphi y p_F + \frac{\alpha_F}{\alpha_K} \frac{\alpha_R}{\sigma_{KE}} \frac{\alpha_F}{\sigma_{EE}} \varphi y p_F \frac{\alpha_R}{\alpha_K} \frac{1}{\psi_R} \]

We obtain:

\[ \alpha_3 = \left( \alpha_3 - \alpha_1 \right) \frac{\psi_R}{\psi_F} \]

Given that:

\[ \alpha_2 = (bl + am)(i_0b - ch) + (bd + ae)(bi_0 - cp) \]

\[ = \left[ \frac{\alpha_R}{\alpha_K} \frac{\alpha_F}{\sigma_{EE}} \varphi y p_F + \frac{\alpha_F}{\alpha_K} \frac{\alpha_R}{\sigma_{KE}} \frac{\alpha_F}{\sigma_{EE}} \varphi y p_F \right] \left[ \frac{\alpha_R}{\alpha_K} \frac{1}{\psi_R} + \frac{\alpha_F}{\alpha_K} \frac{\alpha_R}{\sigma_{KE}} \frac{\alpha_F}{\sigma_{EE}} \varphi y p_F \right] \left[ \frac{\alpha_R}{\alpha_K} \frac{1}{\psi_R} - \alpha_R \right] \]

\[ = \varphi y p_F \left[ \frac{\alpha_R}{\alpha_K} \frac{\alpha_F}{\sigma_{EE}} + \frac{\alpha_F}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right] \left[ \frac{\alpha_R}{\alpha_K} \frac{1}{\sigma_{KE}} + \frac{\alpha_R}{\alpha_K} \frac{1}{\psi_R} \right] \]

\[ + \varphi y p_F \left[ \frac{\alpha_R}{\alpha_K} \frac{\alpha_F}{\sigma_{EE}} + \frac{\alpha_F}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right] \left[ \frac{\alpha_R}{\alpha_K} \frac{1}{\sigma_{KE}} + \frac{\alpha_R}{\alpha_K} \frac{1}{\psi_R} \right] \]

\[ \left[ \frac{\alpha_R}{\alpha_K} \frac{1}{\sigma_{KE}} + \frac{\alpha_R}{\alpha_K} \frac{1}{\psi_R} \right] \left[ \frac{\alpha_R}{\alpha_K} \frac{1}{\sigma_{KE}} + \frac{\alpha_R}{\alpha_K} \frac{1}{\psi_R} \right] \]

\[ = \varphi y p_F \left[ \frac{\alpha_R}{\alpha_K} \frac{1}{\sigma_{EE}} + \frac{\alpha_F}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right] \frac{\alpha_R}{\alpha_K} \frac{1}{\sigma_{KE}} + \frac{\alpha_R}{\alpha_K} \frac{1}{\psi_R} \left[ \frac{\alpha_R}{\alpha_K} \frac{1}{\sigma_{KE}} + \frac{\alpha_R}{\alpha_K} \frac{1}{\psi_R} \right] \]

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\[ + \varphi y p_F \alpha_R \left[ \frac{1}{\sigma_{KE}} + \frac{\alpha_R}{\alpha_K \sigma_{EE}} + \frac{\alpha_F}{\sigma_{KE}} \right] \frac{\alpha_R}{\alpha_K \sigma_{KE}} (1 - \alpha_R - \alpha_F) + \frac{\alpha_F}{\alpha_K \psi_R} - \frac{\alpha_R}{\alpha_K \psi_R} + \frac{\alpha_R}{\eta} + \frac{\sigma_{KE}}{\eta} \psi_R \]

\[ = \varphi y p_F \alpha_R \left\{ \frac{\alpha_F}{\alpha_K \sigma_{KE}} \left[ \frac{\alpha_F}{\sigma_{KE}} + \frac{1}{\alpha_K \sigma_{KE}} \right] \frac{1 - \alpha_R - \alpha_F}{\alpha_K \sigma_{KE}} + \frac{1}{\alpha_K \eta} + \frac{1}{\eta} \right\} \]

\[ + \left[ \frac{1}{\sigma_{KE}} + \frac{\alpha_R}{\alpha_K \sigma_{KE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE}} \right] \left[ \frac{\alpha_R}{\alpha_K \sigma_{KE}} + \frac{\alpha_R}{\alpha_K \sigma_{KE}} - \frac{\alpha_F}{\alpha_K \psi_R} + \frac{\alpha_R}{\alpha_K \psi_R} + \frac{\alpha_R}{\eta} + \frac{\sigma_{KE}}{\eta} \psi_R \right] \}

\[ = \varphi y p_F \alpha_F \left\{ \frac{\alpha_F}{\alpha_K \sigma_{KE}} + \frac{1}{\sigma_{KE}} + \frac{\alpha_R}{\alpha_K \sigma_{KE}} \left[ \frac{1}{\alpha_K \sigma_{KE}} + \frac{1 + \alpha_K}{\alpha_K \sigma_{KE}} \right] \right\} \]

\[ + \left[ \frac{1}{\sigma_{KE}} + \frac{\alpha_R}{\alpha_K \sigma_{KE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE}} \right] \left[ \frac{\alpha_R}{\alpha_K \sigma_{KE}} + \frac{1}{\alpha_K \sigma_{KE}} + \frac{1 + \alpha_K}{\alpha_K \sigma_{KE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE}} \right] \]

\[ = \varphi y p_F \alpha_F \left[ \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_R (1 + \alpha_K)}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{1}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{1 + \alpha_K}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F (1 + \alpha_K)}{\alpha_K \sigma_{KE} \sigma_{EE}} \right] \]

\[ + \left[ \frac{1 - \alpha_F}{\alpha_K \sigma_{KE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE}} \right] \left[ \frac{\alpha_R}{\alpha_K \sigma_{EE} \sigma_{KE}} + \frac{1}{\alpha_K \sigma_{EE} \sigma_{KE}} + \frac{(\alpha_K - 1)}{\alpha_K \psi_R} + \frac{\sigma_{KE}}{\alpha_K \sigma_{EE} \sigma_{KE}} \right] \]

\[ = \varphi y p_F \alpha_R \left[ \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_R}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} \right] \]

\[ + \left[ \frac{\alpha_R (1 - \alpha_F)}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_R (1 + \alpha_K)}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{(1 - \alpha_F)(\alpha_K - 1)}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\sigma_{KE}(1 - \alpha_F)}{\alpha_K \sigma_{KE} \sigma_{EE}} \right] \]

\[ + \left[ \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F}{\alpha_K \sigma_{EE} \sigma_{KE}} + \frac{\alpha_F}{\alpha_K \sigma_{EE} \sigma_{KE}} \right] \]

\[ = \varphi y p_F \alpha_F \left[ \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} \right] \]

\[ + \left[ \frac{\alpha_R (1 + \alpha_K)}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_R (1 - \alpha_F)}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{(1 - \alpha_F)(\alpha_K - 1)}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\sigma_{KE}(1 - \alpha_F)}{\alpha_K \sigma_{KE} \sigma_{EE}} \right] \]

\[ + \left[ \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} \right] \]

\[ = \varphi y p_F \alpha_R \left[ \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} \right] \]

\[ + \left[ \frac{\alpha_R (1 + \alpha_K)}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_R (1 - \alpha_F)}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{(1 - \alpha_F)(\alpha_K - 1)}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\sigma_{KE}(1 - \alpha_F)}{\alpha_K \sigma_{KE} \sigma_{EE}} \right] \]

\[ + \left[ \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F}{\alpha_K \sigma_{KE} \sigma_{EE}} \right] \]

\[ + \frac{1}{\alpha_K \eta} \left( 1 - \alpha_F + \frac{\alpha_F \sigma_{KE}}{\sigma_{EE}} \right) \]
We obtain:

$$\begin{align*}
\alpha_2 &= \left\{ \frac{\alpha_F (\alpha_F + 2\alpha_R)}{\alpha_K \sigma_{KE} \sigma_{EE}} + \frac{\alpha_F \alpha_K + \alpha_R (1 - \alpha_F)}{\alpha_K \sigma_{KE}^2} + \frac{(1 + \alpha_K)}{\alpha_K \eta} \left[ \frac{\alpha_F \alpha_K + \alpha_R (1 - \alpha_F)}{\alpha_K \sigma_{KE}} + \frac{\alpha_F (\alpha_F + 2\alpha_R)}{\alpha_K \sigma_{KE}} \right] \right. \\
&\quad + \left. \frac{(\alpha_K - 1)}{\alpha_K^2 \sigma_R} \left( \frac{1 - \alpha_F}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right) + \frac{1}{\alpha_K \eta} \psi_R \left( \frac{1 - \alpha_F}{\sigma_{KE}} + \frac{\alpha_F \sigma_{KE}}{\sigma_{EE}} \right) \right\} \psi y_F \alpha_R
\end{align*}$$

Given that:

$$\alpha_4 = (bl + am)(bi - ch)$$

$$\begin{align*}
\alpha_4 &= \psi y_F \alpha_R \alpha_F \left[ \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{EE} \sigma_{KE}^2} + \frac{1}{\alpha_K \sigma_{KE}^2} + \frac{1 + \alpha_K}{\alpha_K \eta} \right] \left( \frac{1}{\sigma_{KE}} + \frac{1 + \alpha_K}{\alpha_K \sigma_{EE}} \right) \\
&= \psi y_F \alpha_R \alpha_F \left[ \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{EE} \sigma_{KE}^2} + \frac{1}{\alpha_K \sigma_{KE}^2} + \frac{1 + \alpha_K}{\alpha_K \eta} \right] \left( \frac{1}{\alpha_K \sigma_{KE}} + \frac{1 + \alpha_K}{\alpha_K \sigma_{EE}} \right)
\end{align*}$$

We obtain:

$$\begin{align*}
\alpha_4 &= \psi y_F \alpha_R \alpha_F \left[ \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{EE} \sigma_{KE}^2} + \frac{1}{\alpha_K \sigma_{KE}^2} + \frac{1 + \alpha_K}{\alpha_K \eta} \right] \left( \frac{1}{\alpha_K \sigma_{KE}} + \frac{1 + \alpha_K}{\alpha_K \sigma_{EE}} \right)
\end{align*}$$

Given that:

$$\beta_2 = ce(bl + am) = \left[ \frac{(\alpha_F + \alpha_R)}{\alpha_K} - \frac{\sigma_{KE}}{\eta} \right] \frac{\alpha_R}{\alpha_K \sigma_{EE}} \psi y_F \left[ \frac{\alpha_R}{\alpha_K \sigma_{EE}} \psi y_F \left[ \frac{\alpha_R}{\alpha_K \sigma_{EE}} \psi y_F + \frac{\alpha_R}{\alpha_K \sigma_{EE}} \psi y_F \right] \right]$$

$$\begin{align*}
&= (\psi y_F)^2 \alpha_F \alpha_R \left[ \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{EE} \sigma_{KE}} - \frac{\sigma_{KE}}{\eta} \right] \frac{\alpha_R}{\alpha_K \sigma_{EE} \sigma_{KE}} \left[ \frac{\alpha_R}{\alpha_K \sigma_{EE}} + \frac{1}{\alpha_K \sigma_{KE}} \right] \\
&= (\psi y_F)^2 \alpha_F \alpha_R \left[ \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{EE} \sigma_{KE}} - \frac{\sigma_{KE}}{\eta} \right] \left[ \frac{\alpha_R}{\alpha_K \sigma_{EE}} + \frac{1}{\alpha_K \sigma_{KE}} \right]
\end{align*}$$
We obtain:

\[
\beta_2 = (\varphi y p_F)^2 \alpha_F \alpha_R \left[ \left( \alpha_F + \alpha_R \right)^2 + \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{EE} \sigma_{KE}} - \frac{\sigma_{KE}}{\sigma_{EE} \eta} \left( \frac{\alpha_F + \alpha_R}{\alpha_K \sigma_{EE}} + \frac{1}{\sigma_{KE}} \right) \right]
\]

Given that:

\[
\beta_1 = b(b l + a m) = \frac{\alpha_R}{\alpha_K} \left[ \frac{\alpha_F}{\alpha_K \sigma_{EE}} \varphi y p_F + \frac{\alpha_F}{\alpha_K} \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right) \varphi y p_F \right]
\]

We obtain:

\[
\beta_1 = b \varphi y p_F \frac{\alpha_F \alpha_R}{\alpha_K^2} \left( \frac{\alpha_R}{\sigma_{EE}} + \frac{\alpha_R}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right) = \varphi y p_F \frac{\alpha_F \alpha_R}{\alpha_K^2} \left( \frac{\alpha_F + \alpha_R + \alpha_K}{\sigma_{EE}} \right)
\]

Given that:

\[
\beta_4 = b q (b d + a e) = \frac{\alpha_R}{\alpha_K \psi_R} \theta y p_F \left[ \frac{\alpha_R}{\sigma_{KE}} \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_R}{\sigma_{EE}} \right) \varphi y p_F + \frac{\alpha_F \alpha_R}{\alpha_K \sigma_{EE}} \varphi y p_F \right]
\]

We obtain:

\[
\beta_4 = \frac{\theta \varphi (y p_F)^2}{\psi_R} \left( \frac{\alpha_K}{\alpha_R} \right)^2 \left( \frac{\alpha_R}{\sigma_{KE}} + \frac{\alpha_R}{\sigma_{EE}} + \frac{\alpha_F}{\sigma_{EE}} \right) = \frac{\varphi (y p_F)^2}{\psi_R} \left( \frac{\alpha_R}{\sigma_{KE}} \right)^2 \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_K + \alpha_F}{\sigma_{EE}} \right)
\]

Given that:

\[
\beta_5 = (b l + a m) (b d + a e)
\]

\[
\alpha_R \left( \frac{\alpha_K}{\sigma_{KE}} \right) \varphi y p_F + \frac{\alpha_F}{\alpha_K \sigma_{EE}} \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_R}{\sigma_{EE}} \right) \varphi y p_F + \frac{\alpha_F \alpha_R}{\alpha_K \sigma_{EE}} \varphi y p_F \right]
\]

\[
\left( \varphi y p_F \right)^2 \frac{\alpha_F \alpha_R}{\alpha_K^2} \left[ \frac{\alpha_R + \alpha_K}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \left( \frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_R + \alpha_F}{\sigma_{EE}} \right) \right]
\]

\[
\left( \varphi y p_F \right)^2 \frac{\alpha_F \alpha_R}{\alpha_K^2} \left[ \frac{\alpha_R + \alpha_K}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \left( \frac{\alpha_K + \alpha_R}{\sigma_{KE}} + \frac{\alpha_F}{\sigma_{EE}} \right) \right]
\]

\[
\left( \varphi y p_F \right)^2 \frac{\alpha_F \alpha_R}{\alpha_K^2} \left[ \frac{(\alpha_R + \alpha_K)(\alpha_R + \alpha_F)}{\sigma_{KE} \sigma_{EE}^2} + \frac{\alpha_K(\alpha_R + \alpha_K)^2}{\sigma_{KE}^2} + \frac{\alpha_F(\alpha_R + \alpha_F)^2}{\sigma_{EE}^2} \right]
\]

We obtain:

\[
\beta_5 = \left( \varphi y p_F \right)^2 \frac{\alpha_F \alpha_R}{\alpha_K^2} \left[ \frac{\alpha_R(\alpha_R + \alpha_K)}{\sigma_{KE}^2} + \frac{\alpha_F(\alpha_R + \alpha_F)^2}{\sigma_{EE}^2} \right]
\]
### Table C.1 - List of GDynEP Regions

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### Table C.2 - List of GDynEP aggregates

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<td>gas Gas</td>
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<td>4</td>
<td>oil_pcts Petroleum, coal products</td>
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<tr>
<td>5</td>
<td>ely_f Electricity from fossil and nuclear energy sources</td>
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<tr>
<td>6</td>
<td>ely_rw Electricity from renewable energy sources</td>
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### Table C.3 - List of GDynEP countries

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Appendix D – Additional numerical results

Figure D.1 - Energy intensity (Toe/ Mln US Dollars) – EU2030

Figure D.2 – Fossil fuel electricity price (US Dollars/Kwh) – EU2030
Figure D.3 – Fossil fuel consumption (Mtoe) – EU2030