A dynamic assessment of instrument interaction and timing alternatives in the EU low-carbon policy mix design

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Abstract

The European Union low-carbon strategy includes a range of complementary policies. Potential interactions between instruments and different 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 European Union strategy through a dynamic Computable General Equilibrium model (GDynEP) with a time horizon of 2050. Main results are: i) going for the unilateral European Union 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 decrease substantially; iii) when complementary clean energy technology policies are implemented, the optimal timing of binding targets changes; iv) the higher the public support to clean energy technologies, the larger the economic gains in early adoption of challenging abatement targets.

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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 referred to as the EU2030 strategy and commonly cited in the documents published by the European Commission (EC) during 2014 (EC, 2014a,b,c,d) - 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 targets are simultaneously instruments themselves designed 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.

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, consistency, and the

[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,c).

correspondence of policy strategies with their long-term targets (Rogge et al., 2017; Rosenow et al., 2017).

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. For this purpose, we have developed 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 rest of the paper 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 at least 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. The ETS was initially partly designed as a compensating mechanism for energy intensive industries that would face large economic losses from a comprehensive carbon mitigation policy. Such a policy 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 all emitting sectors, has been adopted only in 11 EU countries with varying mechanisms, tax rates and temporal application.[2] Accordingly, the ETS sectors emerge as the ones contributing substantially to mitigation targets through a market-based instrument, and this implies increasing mitigation costs precisely for those sectors that need to be protected. For this reason Tol (2013) proposed a carbon tax be applied to EU Member States in a coordinated approach in preference 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 their effectiveness is affected by the double role of targets and instruments. When designing the policy framework, it must be recognized 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 costs of the transition on the economic system, they 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 refers to the effects of the interaction of such complementary policies with

[2] The 11 European Union Member States that implemented at least for one year a carbon tax system from 1990 are: Denmark, Estonia, Finland, France, Ireland, Italy, Latvia, Poland, Portugal, Slovenia, Sweden. For a detailed description on implementation issues see World Bank (2017).

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, 2014). As a general conclusion the literature argues that the existence of externalities, market failures and other economic, social, environmental and technology goals may justify additional policy instruments but the appropriate instruments mix should be designed to avoid additional costs caused by the overlapping regulation (Böhringer et al., 2016; OECD, 2011).

Selected contributions typically analyse single interaction mechanisms. A first example is given by the mutual influence of 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 den Bergh, 2016; Lehmann and Gawel, 2013). On the contrary, 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 uncertain economic gains. Accordingly, energy and climate policy should be designed taking account of factors 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).

A 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 the 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). These interactions strongly depend on the specific instruments in place and the optimality of the policy mix depends on how the interactions of each instrument with the others could support the set of targets the policy makers have in mind (del Río González, 2008, 2010). An optimal climate policies portfolio should include both carbon pricing and support for CETs 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, thus providing enough incentives for radical innovation and backstop technologies in the long-term (Gerlagh et al., 2014; Popp, 2016). 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).

The fourth relevant issue regarding the EU2030 strategy concerns the financing mechanisms of complementary instruments, especially technology development and diffusion. Although according to 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),[3] empirical analyses on the effects associated with such revenue recycling mechanism are few, and mainly look at where revenues are

[3] 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.

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. The cost of achieving the abatement target depends not only on the amount of emissions to be reduced and the multiple forms of policy support but also on the timing of the reduction path. On the one side, the early adoption of stringent targets might face public opposition 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 have developed 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 number of behavioural parameters, input-output data at the sector and country level, and inter-sectoral and international linkages to be included, a CGE framework allows for all these factors 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 in addition to the standard carbon price instrument in GDynE, represented by public support for EE and RS, and a novel financial mechanism for such public policy support modelled via a carbon tax revenue (CTR) recycling mechanism.[4]

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_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 achieving the emission target at the minimum cost. As a general remark, by modelling EU as an aggregate and covering all sectors, the two available market-based policy options, CT and ETS, are perfectly equivalent, since the Pigouvian CT in the whole EU corresponds to the minimum cost for achieving the target, which is equivalent to the permit 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).[5] 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 involve the introduction of a percentage rate of the total CTR (γ) directed to finance the two CET options explored here. 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

[4] In order to describe how we modelled in GDynEP the three policy instruments forming the EU low carbon strategy, we have developed a simplified theoretical model available as Supplementary Material Appendices A and B. Such a 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. In addition, all details on GDynEP in terms of merging different model versions and databases together with details on sectors and regional aggregation are described in Supplementary Material, Appendix C.

[5] We acknowledge that this carbon pricing design is far from the real functioning of the EU-ETS. By differentiating economic sectors into ETS and non-ETS, the interactions across the three policy instruments become extremely complicated and unpredictable, given that the carbon pricing in that case operates only on ETS sectors, while the other two policy instruments related to CETs support interact with the whole economy. Further modelling efforts on this side will be part of future research activities.

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 the policy impact evaluation.

In order to quantify how public investments might be translated into clean energy innovation at an empirical level, two elasticity parameters are required, namely (φ) for EE and (θ) for RS. Their computation is based on considering data on the last ten years of investments in the EU in these fields with respect to the starting date of GDynEP (2011).

More specifically, in order to transform investment efforts (millions of USD) into input-augmenting technical change in energy efficiency (φ) 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 across all sectors and that the diffusion path of innovation is not affected by technical barriers. The elasticity 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 (φ) adopted is 1.8, and can be interpreted as follows: an increase by 1% of public R&D stock in EE produces an improvement in energy efficiency on average of the whole energy system (industries, transport, households) of 1.8%.[6]

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

[6] R&D stock values are computed by applying 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. The effect of R&D investment in CET in terms of increased energy efficiency starts in the first period after the CTR is collected and reinvested, given the temporal lag between the decision to invest in innovation and the effective deployment of new technologies at the commercial level.

generation by 2030 (EC, 2014a).[7] 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.[8] 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.[9] The value for (θ) 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.

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 (φ) and (θ) include all aspects of technology development, deployment, diffusion and adoption. In addition, we model the two CET options as completely independent from each other. We recognize this is a conservative assumption that excludes the possibility of synergies between technologies in EE and RS (as for instance the

[7] 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.

[8] 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 analysis of alternative calibration procedures for parameters to φ and θ.

[9] The introduction of RS in the electricity sector derives from merging GDynE with GTAP-Power and requires the introduction of an additional nest into the production function tree and also 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. This allows for 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. Also in the case of RS, the effect of R&D investment in CET in terms of increased installed capacity in RS starts in the first period after the CTR is collected and reinvested, given the temporal lag between the decision to invest in RS production and the effective entry into service of new power plants.

development of more efficient storage systems) as emphasized in IRENA (2017).[10]

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 include in the modelling design 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 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 raises the need for 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

[10] In the case of GDynEP we consider exogenous CO_2 emissions in BAU in order to calibrate them with IEA projections that are derived from a bottom-up energy-technology approach. Given that CO_2 emissions in GDynEP are directly linked to fossil fuels demand, by fixing emissions we also determine fossil fuels demand. Accordingly, in the BAU case energy prices are endogenous, since they have to adjust to market demand. In order to obtain an energy demand that is compatible with the emission path, energy intensity adjusts for each sector due to an homogenous technical change. This assumption corresponds to an unchanged energy mix over time in terms of relative share of each fossil fuel in the energy composite. As a robustness check we have compared changes in oil prices endogenously obtained in BAU with GDynEP with IEA projections. In GDynEP BAU case oil price increases by an average 1.4% per year over the period 2025-2050, while in IEA Current Policies scenario (that corresponds to our BAU) oil price increases by an average 2.6% per year over the period 2025-2040. By considering oil price as exogenous we should consider energy demand (and also CO_2 emissions) as endogenous with a reduced accuracy in BAU calibration. By looking at the theoretical model developed in Appendix A in the Supplementary Material, if oil prices are considered as exogenous, we can expect that for higher values of oil prices the carbon tax in ad valorem term would be lower. At the same time, the convenience to shift from fossil fuels to renewable sources to produce electricity will increase. The final effect could be a reduction in the cost of achieving the abatement target. The opposite will occur for lower oil prices. Nonetheless, the interactions across the three policy pillars would not change in sign but only in magnitude.

by the GTAP Macro projections (where skilled and unskilled labour force are separated).[11]

As for the calibration of CO_2 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 CO_2 emissions profiles for the policy options 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 as expressed in the EU2030 strategy (EC, 2014a) 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 CO_2 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 CO_2-equivalent. The EU450 is based only on the 450ppm IEA scenario (IEA, 2015) 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 the EU2030 case. 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.

Figure 1

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 a constant rate of emissions reduction is assumed along the time horizon, implying that the reduction is more

[11] The integrated GTAP database used for the Reference year (2011) derives from merging the following databases: GTAP Database 9, GTAP-E Database, GTAP-Power Database (Aguiar et al., 2016; Peters, 2016). For a detailed description of the merging process, see Appendix C in the Supplementary Material. The statistical sources for macro projections are: CEPII macroeconomic projections (Fouré et al., 2013); GTAP macro projections (Chappuis and Walmsley, 2011); IIASA projections used for the OECD EnvLink (Dellink et al., 2017); ILO Labour force projections (ILO, 2017); OECD Long Run Economic Outlook (OECD, 2014); UNDESA Population projections (UNDESA, 2017).

challenging in the early periods with respect to EU2030. Figure 1 also shows a "EU2030 trend" path, calculated assuming a CO_2 abatement trend that enables EU to reach the 40% reduction target (w.r.t. 1990) in 2030 and that remains unchanged in terms of percentage reduction trend until 2050. This is not an emission profile corresponding to a policy scenario but it allows us to visualize the gap in 2050 with the EU abatement target necessary to respect the Paris Agreement. The two emission profiles, EU2030 and EU450, represent the CO_2 abatement targets to be achieved by implementing alternative policy mix designs. Accordingly, the scenarios tested in this analysis are:

1. Business As Usual (BAU);
2. CT: only the EU reduces emissions with a market-based instrument implemented as a homogeneous carbon tax (for both EU2030 and EU450 emission paths);
3. CT-Policy Mix: only the EU reduces emissions with a CT and a percentage of the CTR is invested in CET (for both EU2030 and EU450 emission paths).[12]

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).

Scenario (3) is evaluated also considering alternative values for the share of CTR directed to CET (γ) and for the distribution of financial support (δ) to EE and RS:

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

ii) For each value assumed by (γ), eleven alternative allocations of the resources received for mitigation purpose (δ) (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 ($\delta = 1$).

[12] 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.

Summing up, there are 223 numerical simulations, organized as described in Figure 2, where the BAU scenario corresponds to CO_2 emissions path without implementing any of the three policy pillars, while the EU2030 and EU450 correspond to policy scenarios with reduced emissions. The fulfilment of the overall energy strategy with the three pillars jointly working or not is then tested according to different options in terms of carbon recycling levels and distribution shares between EE and RS.

Figure 2

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, Beverage and Tobacco; Textile; Wood; Pulp and paper; Chemical and petrochemical; Non-metallic Minerals; Basic metals 1 (ferrous metals); Basic metals 2 (non-ferrous metals); Machinery equipment; Transport equipment; Other manufacturing industries; Transport; Water Transport; Air transport and Services, while energy commodities have 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. To the best of our knowledge this is the only contribution available in literature that considers the interaction of the three pillars jointly, but it does not describe the financial mechanism for supporting CETs. Accordingly, the novel modelling options developed in GDynEP for CET investment support and interaction with a carbon pricing mechanism have no comparison terms in the literature.

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 of interest, 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.

Figure 3 reports the carbon price trend with respect to the share of carbon tax revenue invested in CET (γ) and its redistribution between EE and RS (δ) in the EU2030 Scenario.[13] 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 γ and results are available upon request.

Starting with the relation between carbon price and the share of CTR allocated to CET (γ), note first that when γ increases the carbon price decreases. Second, when γ increases, the reaction of carbon price with respect to δ increases too. In other words, the higher is the share of the CTR 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.[14]

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[13] 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.

[14] The numerical simulations help finding an inverse relationship between carbon price and γ 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 3

Let us now look at the relation between carbon price and δ. If resources are entirely allocated to finance renewables ($\delta = 0$), the carbon price remains very high, although it slightly decreases when γ 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 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 decreases the CT significantly. 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 CO_2; in case of a 50% share of the recycling mechanism, the difference between the two policy options increases dramatically (from 528 USD to 176 USD). This is on account of 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 greater 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 ($\gamma\delta$) that result in the lowest emission prices is a scenario in which the recycled CTR is maximum ($\gamma = 50\%$) and it is entirely invested to finance EE ($\delta = 1$).

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 4 illustrates this relation.

Figure 4

Not surprisingly, higher levels of renewable electricity consumption occur with lower values of δ, that is when all or most of resources are invested to increase 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 4), the highest level of renewable electricity consumption, which is a target itself in the EU2030 strategy (Figure 4), 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 5). 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, an increase in RS consumption can be attained without compromising the achievement of the

EE target. At the same time, a reduction in emission prices with respect to a simple CT mechanism is also attained.

As already emphasized in aforementioned contributions, however, 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. 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 γ and δ, 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 5

4.2 General equilibrium economic impacts and timing options

We consider as a first evaluation criterion the abatement cost minimization. Figure 6 compares the marginal abatement cost (MAC) curves for alternative policy mixes applied to the two alternative emission paths. The four policies depicted in Figure 6 combine the extreme values of both γ and δ used for graphical representation of results. Accordingly, for each mitigation path, we show the following combinations: i) 10% of CTR entirely directed towards renewables (γ = 10%_RS); ii) 10% of CTR entirely directed towards EE investments (γ = 10%_EE); iii) 50% of CTR entirely directed towards renewables (γ = 50%_RS); iv) 50% of CTR entirely directed towards EE investments (γ = 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 3. By fixing the same abatement target to be reached in 2050 for all scenarios (about 80% reduction in CO_2), Figure 6 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 6

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, marginal mitigation costs are much lower. Furthermore, in this case the parameter γ also 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 6 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 6). 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 most desirable.

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

From Table 1, it is clear that with the current emission path (EU2030) EU never reaches this target by 2030 and is 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 γ. 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. According to our results large investments in EE 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.[15]

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 (δ=0; δ=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 (δ) needed to reach the target decreases when the total amount of available investments increases, that is for higher values of γ. In particular, with γ equal to 40% and 50% it is sufficient to direct 80% of CTR resources to renewables (δ = 20%).

As for scenario EU2030, the EU gets very close to the target in 2035 only if 50% of CTR is entirely

[15] Results on interaction with price of electricity produced with fossil fuels are provided in Appendix D in the Supplementary Material, Figure D.2.

invested in renewables. However, the objective is not completely reached up to 2040, when huge investments in renewables 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 implementing policies.

Table 2

This interaction is also evident when the amount of resources available to finance CET are compared in alternative emission paths. Figure 7 highlights the multiple interactions between the three pillars. Given the dynamic nature of this optimal policy mix design exercise, if the emission price is high, the amount of resources for CTR recycling increases, but when such resources are invested in CETs, then the total available revenues will be reduced due to a reduction in emission prices thanks to CET deployment. If policy makers would adopt the target of maximizing financial resources directed to develop CETs, the optimality of the policy mix would imply to maintain high carbon prices in order to obtain large amount of carbon tax revenues.

Figure 7

The last reflection brings into consideration an additional optimality criterion that addresses 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.[16] Table 3 also compares the EU2030 Scenario with the EU450 one, in order to investigate the 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.[17] 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 γ and δ (as before the turning point is associated to lower values for δ when γ 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 δ 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 3

Furthermore, when γ increases, the shift in convenience from the EU2030 to the EU450 emission

[16] 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.

[17] 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).

path occurs for lower δ. In other words, if a higher amount is invested, it is sufficient to use a minor part of it to finance EE in order to reach a preference for immediate more stringent actions (e.g. when γ = 10%, EU prefers the EU2030 path up to δ = 80%; when γ = 40% and 50%, EU prefers the EU2030 path just up to δ = 20%).[18]

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 result in 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 in gaining 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.[19]

Table 4

First, considering the two CT policy scenarios, and in accordance with GDP results, the EU2030 strategy seems preferable in terms of welfare impact. This is consistent with van der Ploeg (2016) according to which in a second-best perspective (as opposed to the first-best case) a postponed increase in mitigation reduction (and consequently in carbon prices), as in our EU2030 scenario with

[18] It is worth noting that the simplifying assumptions adopted for transforming R&D investments into efficiency gains, namely constant returns to scale over time and the absence of barriers to diffusion and adoption of CETs, might well affect the results. Accordingly, values for GDP gains in Table 3 should be considered only as an indication of how the interactions across the three instruments work. Efforts in linking GDynEP model with bottom-up energy models will constitute the next research agenda in order to provide more robust and reliable results. It is also worth mentioning that these results hold also in case of a discount rate equal to 2% and 6%.
[19] 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.

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. γ = 10%), in the EV case the turning point happens for lower levels of δ, compared to the GDP case.

Nevertheless, some differences also occur. First, while Table 3 shows 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 δ, that is on 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 γ 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, (even a small part, from δ = 10% onwards), the opposite holds: there is a welfare improvement with respect to CT and benefits increase when both γ and δ increase, perfectly in line with what happens in terms of GDP (Table 3).

This result can be 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 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 the 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 also have a 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 delaying or not the more stringent targets to the future also depends on the selected mitigation options. Indeed, when only the carbon price is in place, postponing the achievement of more stringent CO_2 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 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 the selection of the ‘best’ policy mix design to be 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 in terms of the conclusions drawn from the analysis.

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