Energy Economics 119 (2023) 106524

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Fossil fuels subsidy removal and the EU carbon neutrality policy ☆

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ARTICLE INFO

JEL classification:
C68
H23
Q54

Keywords:
Clean energy technologies
Climate policy mix design
EU Green Deal
Fit for 55
Fossil-fuel consumption subsidy removal

ABSTRACT

The complexity of the EU carbon neutrality policy is addressed by evaluating the impacts of the interaction among different policy instruments. An energy-economic dynamic CGE model based on GTAP utilities is developed for simulating different policy scenarios starting from a business as usual case where the economic impacts related to the COVID-19 pandemic and recovery measures are included. The instruments tested as part of the EU climate strategy are the removal of fossil-fuel consumption subsidies, a carbon pricing mechanism and the public support to clean energy technologies. The modelling approach is based on a revenue recycling mechanism to finance clean energy technologies. We find that the simultaneous implementation of all instruments under the EU climate strategy including the removal of subsidies to fossil fuels and the reuse of revenues to foster the technological transition of the energy system is a win-win solution for a sustainable and decarbonised EU economy.

1. Introduction

The European Union (EU) is a key player in the international climate negotiations and its efforts in achieving ambitious mitigation targets have been a driving factor in directing the bargaining process towards a global cooperative solution to prevent climate change, as clearly emerged during the Paris Agreement (PA) discussions. Following the recent development of the scientific discourse within the Intergovernmental Panel on Climate Change (IPCC), which produced the sixth assessment report (AR6) in 2022, the global stocktake exercise countries should make under the PA by 2023 appears particularly challenging given the ambitious targets of an almost fully decarbonised economy to be achieved by 2050.

Given that EU institutions often anticipate obligations discussed in the international negotiations with internal (voluntary) measures designed to reduce the transaction costs, the recent climate and energy plan known as the EU Green Deal (EGD) represents an ambitious long-term strategy with the primary objective to ensure the complete decarbonisation of the EU by aligning investors and beneficiaries and achieve considerable societal gains. The underlying rationale of the EGD is achieving a sustainable economic growth, thus the actions listed in the roadmap to make Europe the first climate-neutral continent by 2050 must be accompanied by complementary measures to assist the economic and industrial transformation (EC, 2019b).

Together with standard market-based instruments, as the carbon pricing mechanism already into force under the Emissions Trading Scheme (ETS), the EGD encompasses an investment strategy to sustain key economic sectors with high technological content and a radical shift from fossil fuels to renewable energy sources, according to the proposal for a “Sustainable Europe Investment Plan” (EC, 2020b). Moreover, the recent “Fit for 55” Package is practically implementing the EGD broad objectives with intermediate ambitious targets, such as the reduction by 55% of emissions by 2030 w.r.t. 1990 levels, the increase in renewable share by 40% and additional severe constraints imposed to the transport sector (EC, 2021), in order to speed up the full decarbonisation expected by 2050.

The effectiveness of such a complex policy mix that envisages the simultaneous functioning of several complementary measures is difficult to evaluate, given that multiple economic mechanisms as well

☆ Acknowledgements: Support from the Italian Ministry of University and Research, Scientific Research Program of National Relevance (PRIN) 2017 “Innovation for global challenges in a connected world: the role of local resources and socio-economic conditions”, and the European Commission, DG Trade Chief Economist Tender TRADE 2019/G2/G10 is gratefully acknowledged. The authors are indebted with Andrea Bassi, Lars Nilsson, Stefan Speck and Roberto Zoboli for fruitful discussions on model and scenario development. Suggestions from the Editor and two anonymous reviewers significantly improved the quality of our work. As a general disclaimer, the views expressed in this contribution are those of the authors and do not necessarily reflect an official position of the European Commission.

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https://doi.org/10.1016/j.eneco.2023.106524
Received 8 October 2021; Received in revised form 30 October 2022; Accepted 20 January 2023
Available online 1 February 2023
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as different sectors and agents are involved. The barriers for a successful transition toward a more sustainable pattern depend on the structural features of the economic system, but also on the potential contrasting effects that the multiple interventions planned may activate (Rosenow et al., 2017). Accordingly, policy optimality should be investigated with a broad analytical framework that allows capturing additional aspects such as coherence and consistency (Rogge and Reichardt, 2016).

By considering the EGD as a complex policy mix strategy, in this paper we focus on two specific pillars that have been highlighted as means to increase the effectiveness of the EU decarbonisation trajectory: (i) the removal of subsidies to fossil-fuel consumption; (ii) the revenue recycling mechanism to finance investments in clean energy technologies (CETs).

With respect to the former, fossil-fuel subsidies may be interpreted as a negative carbon price and their removal could entail both climate and economic benefits (Burniaux et al., 2009) by ensuring higher coherence and consistency of the instruments mix. The EGD clearly states that fossil-fuel consumption subsidies should be removed within the revision of the Energy Taxation Directive by phasing out all tax exemptions that indirectly reduce the consumption price of fossil-intensive goods and distort market competition with respect to cleaner energy sources (Galinato and Yoder, 2010). Together with consumption subsidies, there are also several forms of fiscal support provided to the production of fossil fuels, via budgetary transfers and tax breaks, public lending to the sector and capital investment by fossil fuel-related state-owned enterprises (Gençsü et al., 2020).[1]

Despite such negative effects, and although fossil-fuel subsidies have been reduced over the past decade in some countries (Sovacool, 2017), according to the latest values available from the OECD inventory database, at the world level such subsidies remained substantially unchanged in absolute values for the last ten years (OECD, 2021). Even in the EU, subsidies to primary consumption of fossil fuels remain high and, according to last estimates adopting the OECD-IEA computation methodology (OECD, 2018), accounted for about USD 47 billion in 2020 (excluding end-use electricity support). Such financial burden is still double the total investments by the private and public sectors directed to solar and wind power generation (EC, 2020a). Furthermore, according to the specific objective of cutting emissions from the road transport sector claimed in the "Fit for 55" Package, large subsidies to fossil-based sources are exactly the hardest barrier to a rapid decarbonisation.

The motivation behind the resistance to remove these subsidies can be found in the absence of a strong political will, due to the risks of possible regressive impacts on low-income households whose expenditure share for energy commodities on the consumption basket is higher (Reanos and Sommerfeld, 2018), or to the influence played by lobbying efforts carried by large corporations whose activity depends on fossil sources (Catola and D'Alessandro, 2020).

Regarding the second EGD pillar, investment efforts in CETs have been prioritised during the past decade with the aim of improving the leadership of EU firms in producing environmental-friendly technologies. Together with the support to private innovative activities in the form of fiscal incentives, the direct role of public expenditures in research and development (R&D) activities has been recognised at least as important as the other instruments of environmental policy. Given the public nature of knowledge creation and the relevance of positive externalities, the level of private R&D investments may be lower than the social optimum, since part of the social benefits from their innovations is not captured in the market price. Accordingly, government should directly provide support to R&D activities, to increase the overall supply of knowledge creation and innovative outcomes (Golombek et al., 2020).

According to Gerlagh et al. (2014), an optimal climate policy portfolio should include both carbon pricing and public support for CETs because the former can stimulate demand for low-emission technologies, their diffusion and adoption, while the latter can address knowledge-related market failures, thus providing enough incentives for the development of backstop technologies in the long-term.

The recent development of the EU climate strategy has fully integrated the R&D support instrument within the policy portfolio in the form of the Innovation Fund, created as a funding programme for the development of innovative low-carbon technologies to complement EU Members domestic investments (EC, 2019a).

These two pillars of the EU climate policy have been formerly analysed in their effectiveness and efficacy, but the potential benefits coming from their simultaneous implementation have been rarely addressed. The aim of the present analysis is to fill this gap by proposing an empirical assessment of the interaction between the removal of fossil-fuel consumption subsidies and the public support to R&D activities for CETs development, by using a dynamic recursive Computable General Equilibrium (CGE) model. By comparing different combinations of instruments forming the climate policy, we provide a quantification of the cost effectiveness of alternative solutions associated to the more stringent EU decarbonisation pathway adopted as a unilateral climate policy, independently from any eventual abatement effort planned by the rest of the world.

The rest of the paper is organised as follows. Section 2 discusses the main issues related to the monetary quantification of fossil-fuels subsidies and support to CETs. Section 3 presents the main model features and scenario design. Section 4 provides main results from the CGE simulation, with sensitivity analysis on selected parameters tested in Section 5. Section 6 concludes with policy implications for the EU decarbonisation strategy.

2. Fossil-fuel subsidies and CETs financing

The contribution played by removing fossil fuels subsidies in order to accelerate the transition towards a decarbonised economy has gathered renewed attention. Nine governments representing the informal group of non-G20 countries called "Friends of Fossil Fuel Subsidy Reform" (FFFSR, formed by Costa Rica, Denmark, Ethiopia, Finland, New Zealand, Norway, Sweden, Switzerland, Uruguay) and the United Kingdom are calling for a rapid and complete phase out of fossil fuel subsidies. In a document known as "We must act now" they state that, despite the efforts played by several countries in the past five years, fossil fuel subsidies continue to counteract global efforts to reduce greenhouse gas emissions. Such subsidies are also recognised as a source of distortion in directing investments toward the energy-related sectors, ultimately reducing the competitiveness of alternative sources.

Reforming fossil fuel subsidies would generate additional financial sources to the public budget, which could be invested in clean energies or used as compensatory measures for those energy-intensive sectors whose competitiveness could be strongly harmed by decarbonisation policies. According to Monasterolo and Raberto (2019), a gradual phasing out of fossil fuels subsidies could help the sustainable transition, especially if a revenue recycling mechanism is used to shift subsidies from fossil fuels to green energies. Moreover, according to Budolfson et al. (2021) a progressive revenue recycling mechanism can pay large dividends also for reducing inequality and alleviating poverty.

How to quantify the monetary burden associated to fossil-fuel financial subsidies is a long-lasting and still debated issue (Burniaux et al., 1992). Two main consolidated methods are available and were used in simulation modelling exercises (Skovgaard, 2017).

The first one, a more conventional (and conservative) computation method, is developed by the Organisation for Economic Co-operation and Development (OECD) together with the International

[1] Subsidies to fossil fuels are also responsible for indirect negative externalities related to climate change, as health diseases or damages to the building heritage, and the resulting fiscal burden on public budget must be added to the cost of subsidies (Clements et al., 2013; Parry et al., 2014).

Energy Agency (IEA). The OECD-IEA methodology considers all forms of financial measures provided by governments, as budgetary transfers and tax expenditures, that provide a benefit or preference for fossil-fuel production or consumption in different sectors (OECD, 2018). Accordingly, the fiscal burden for public finance is formed by all monetary transfers or tax exemptions that alter market prices.

Burniaux and Chateau (2014) introduce in a systematic way the removal of such subsidies applying the price-gap methodology (OECD, 2000) for the quantification of energy subsidies on the OECD ENV-Linkages CGE model, in order to analyse the impact associated to the multilateral removal of fossil fuels subsidies in 37 countries. Their results show that such policy design would ensure a 8% reduction in global GHG emission by 2050 and a net economic gain (measured in terms of equivalent variation in income) at the world level, although the distribution of economic gain (or losses) across countries is highly unequal.

Despite the OECD-IEA method is particularly accurate from the national account point of view, Timperley (2021) recently emphasised that there are some criticisms to this method since some of the public financing of fossil fuels (e.g., subsidies directed to state-owned enterprises) are not entirely captured. Estimations on such hidden support by the International Institute for Sustainable Development (IISD) highlight that, especially for countries with large public companies producing fossil fuels as China, Russia and Saudi Arabia, the potential distortion on market prices due to subsidies could be higher than the OECD-IEA estimation (Geddes et al., 2020).

The second method is developed by the International Monetary Fund (IMF) and consists in adding the cost of environmental externalities, measured by a shadow price approach, to the direct monetary transfers. Accordingly, the IMF methodology allows distinguishing the direct subsidies to production and consumption of fossil fuels from the additional costs faced by society and sustained by the public budget provoked by negative externalities related to fossil fuels, as for instance the extra-cost paid by the national health system for diseases provoked by air pollution (Coady et al., 2019).

Subsidies quantified by the IMF method have been used by Chepeliev and van der Mensbrugghe (2020) in a GTAP framework CGE exercise to simulate the impact of a potential phasing out on the costs and timing of the PA targets achievement. The removal of fossil-fuel subsidies, modelled as a fiscal reform with progressive reduction of tax exemptions and consumption support, allows quantifying a substantial reduction in emission gaps of a baseline case with respect to the targets.

Similarly, Xiang and Kuang (2020) develop a methodology to simulate fossil fuels subsidies removal in a CGE framework for the Chinese economy also showing public finance benefit from the reform due to a large reduction in negative environmental externalities that cause several economic damages.

Given the emphasis on the large amount of public financial resources that could be potentially available for investing in CETs after a full phase out of fossil-fuel subsidies, in Fig. 1 we report the monetary quantification of OECD-IEA estimates for top-subsidising regions in 2020 as a share of GDP, revealing that the EU is fifth in rank.[2] It is worth mentioning that the monetary quantification of the available resources according to the OECD-IEA method is largely underestimated with respect to the IMF method. Nonetheless, given that the OECD-IEA computation is based on fiscal rules fully compatible with public budget account method, we consider it the best approximation of the monetary quantification of this fiscal reform.

Despite the efforts made by the EU over the last ten years for a progressive reduction of financial resources devoted to supporting consumption and production of fossil fuels, there is still a wide gap with respect to public resources oriented to CETs, measured for instance by the (public) investments in R&D for energy efficiency, renewable energy sources (RW), hybrid technologies and fuel cells provided by the RD&D IEA Statistics that are about USD 3.1 billion (constant 2015 values) in 2020 for the EU (Fig. 2).

As a matter of fact, according with the EU average trend reported in Fig. 2, several EU Members have (at least slightly) reduced the unitary subsidy provided to fossil fuels in the past ten years.[3] Simultaneously, many EU countries have completely removed feed-in-tariff (FIT) support for any type of renewable energy, since they have been recognised as fully competitive with traditional sources. The final picture thus consists in a highly heterogeneous energy support system across EU countries with a common trend in phasing out more rapidly subsidies to renewable rather than to fossil sources, in contrast with the sustainable energy transition pattern envisaged by the EGD. According to Chen et al. (2020), the reduction of these contradictory policy signals, with cuts in distortionary taxation and targeted green investment support, together with the implementation of a more stringent carbon pricing mechanism, could be a way forward at least to reach the more ambitious 2030 target designed by the EU without harming the economic growth pathway.

3. The dynamic CGE model

We develop a recursive dynamic CGE model which combines the latest versions of the GTAP (Global Trade Analysis Project) models and data. Specifically, in order to analyse the main interactions that could be activated by the multiple instruments designed in the EU climate policy mix, we rely on the Dynamic (GDyn), Energy (GTAP-E) and Power versions of the GTAP model.

The starting point is the GDynEP model developed by Corradini et al. (2018) in which the Dynamic-Energy (GDynE) version by Golub (2013) has been enriched with the distinction of the electricity sector into two sub-sectors, one based on fossil fuels inputs and the other on renewable sources. This electricity-detailed extension (*ely* sector in GTAP) is available from the GTAP-Power database (Chepeliev, 2019; Peters, 2016), where the power generation process is disaggregated into: transmission and distribution, seven base load technologies (nuclear, coal, gas, hydroelectric, oil, wind and other power technologies), and four peak load technologies (gas, oil, hydroelectric, and solar).

As a first novelty with respect to the previous GDynEP model version, we introduce the emissions related to both combustion-based and non-energy use of fossil fuels, all measured in homogeneous CO2-equivalent, by combining emissions in GTAP-E database (McDougall and Golub, 2009) with the GTAP-NCO2_V10a database developed by Irfanoglu and van der Mensbrugghe (2015). The original NCO2 database provides emissions for three major non-CO2 gases: CH4, N2O, and the group of fluorinated gases (F-gases), including CF4, HFCs, and SF6. These emissions are associated to three drivers: consumption (by consumers and firms), endowment use (land and capital), and output. Given that the model structure includes mitigation instruments that are strictly connected with the use of fossil fuels, we exclude from final emissions those related to endowment use in agriculture, forestry and livestock sectors, roughly corresponding to land use, land-use change and forestry activities (LULUCF) (Romppanen, 2020).

Additional novelties concern the modelling of policy options. In the GDynE model (Golub, 2013) the market-based instruments were introduced in the form of carbon taxation or emissions permits market.

[2] The OECD-IEA database provides information on 22 EU countries (excluding the UK). The missing values for Bulgaria, Croatia, Cyprus, Malta and Romania have been computed as follows. We have taken the IMF data that are available for all 27 EU members. We have computed the average distance (in % term) with the OECD-IEA values for the 22 EU countries on which we have both data sources. We have then applied the average % distance to IMF data in order to obtain an estimated value of fossil fuels subsidies for the five missing countries comparable with the OECD-IEA methodology. All monetary values have been transformed into constant 2015 USD.

[3] In this analysis we use data elaborated on the basis of the OECD Inventory of Support Measures for Fossil Fuels for detailed single countries (available at https://doi.org/10.1787/3ba86dc1-en).

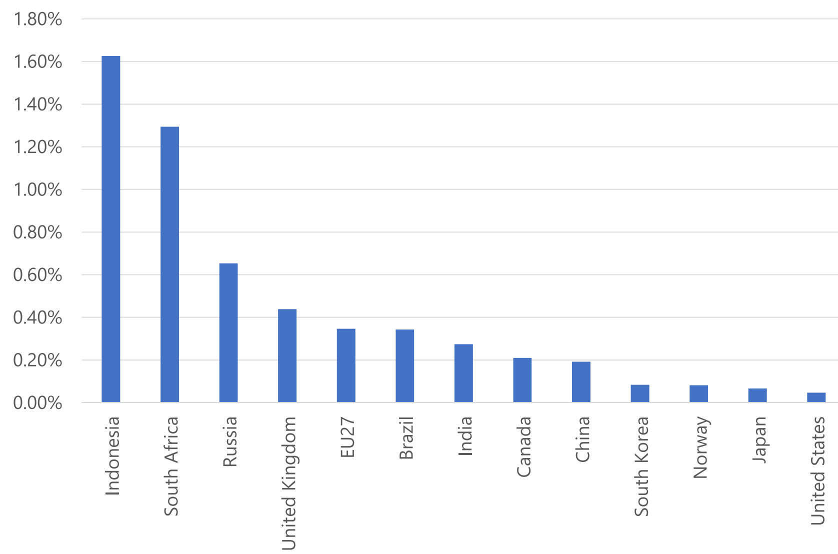

Fig. 1. Fossil-fuel subsidies in 2020 as % of GDP. *Note*: own elaboration on OECD-IEA data.

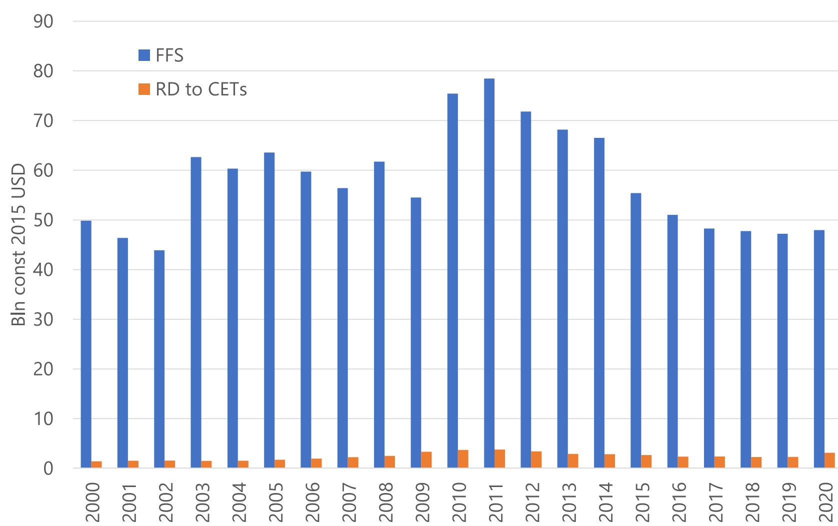

Fig. 2. Fossil-fuel and R&D to CETs subsidies in EU27. *Note*: own elaboration on OECD-IEA data.

In the GDynEP model (Corradini et al., 2018) these instruments were combined with a recycling mechanism of the revenue from carbon pricing. With respect to these previous versions: (i) we introduce a second price-based instrument in the form of a complete phase out of public subsidies to fossil fuels (FF); (ii) we adapt the revenue recycling mechanism to model the functioning of the Innovation Fund (IF) in the form of a totally public fund invested in R&D activities to develop CETs (see Section 3.3).

3.1. Model description

Our model is a dynamic, multi-region and multi-sector model with detailed representation of the bilateral relationships which combines real economic data with a set of equations derived from economic theory. The production side is modelled as a CES function where the inputs used are capital (K), energy (E) distinguished between fossil (FF) and renewable (RW) sources, and all other intermediates inputs as represented in the nesting structure in Fig. 3. The total amount of energy consumption (E) is thus given by the sum of the polluting source (FF), which generate CO2 emissions, and the clean one (RW). In physical terms, the emissions level is proportional to the amount of fossil-based energy input used and a carbon content coefficient (β) in the form: CO2 = $\beta\ FF$.

The distinction of the electricity sector into the sub-sectors based on RW (*ely_rw*) and FF (*ely_f*), requires to include in the model a new parameter associated to the elasticity of substitution (σ) between electricity from fossil and renewable sources (*elfely* in Fig. 3).[4] The substitutability between inputs in the production function is assumed to be symmetric and it is expressed in terms of Allen elasticity of substitution. This implies that FF and RW have a common elasticity value ($\sigma_{FF-RW} = \sigma_{RW-FF}$) and it follows that the two energy sources are also equivalent substitutes with respect to the capital input, resulting in a common capital-energy substitutability σ_{KE} that is also symmetric. The elasticity value of *elfely* has been calibrated with the parameters used in JRC-EU-TIMES model (Simoes et al., 2013); it is region specific and it assumes higher values for those regions that already implement

[4] Electricity from renewables (*ely_rw*) includes hydro, solar, wind and other base load sources (biofuels, waste, geothermal, and tidal technologies). Electricity from fossil fuels (*ely_f*) includes coal, gas, oil, oil product and nuclear.

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       TOTAL OUTPUT NEST           qo(j,r)  [ao(j,r)]
                                     /\
                                    /  \  <----- CES
                                   /    \
                                  /      \
                    endowment-energy       non-energy inputs
Val.-add.-en. nest    /| \                                  /\
    CES ----->       / |  \                                /  \ <------ CES
                    /  |   \                              /    \
                   /   |    \                            /      \
               Land  Labor  K-E subproduct         Domestic     Foreign
                              /\
                             /  \
                            /    \                  Capital-energy nest
                           /      \      <--------- CES (subst. el. ELFKEN)
                          K       energy subproduct
                                                /\         Energy nest
                                               /  \ <--- CES (subst. el. ELFENY)
                                              /    \
                                             /      \
                                      electricity  non-electr. energy
                                          /\             /\
          Electricity energy nest        /  \           /  \
    CES (subst. el. ELFELY)  -----> ely_rw  ely_f      /    \
                                                      /      \
     Non-electricity energy nest                     /        \
     CES (subst. el. ELFNELY)  ------------>non-coal energy   coal
                                                /\
    Non-coal energy nest     ------------>     /  \
    CES (subst. el. ELFNCOAL)                 /    \
                                 crude oil, gas, petr. products
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Fig. 3. Nests in production output with GTAP Energy and Power data.

sustainable energy transition policies and have an electricity mix with a high share of renewables (e.g., parameter for the EU is 60%).[5]

Given the focus on the EU unilateral climate policy, the 64 GTAP sectors have been aggregated into 36 on the basis of three criteria: (i) energy-intensive sectors (according to the EU-ETS definition) particularly at risk of competitiveness loss due to stringent decarbonisation targets; (ii) sectors directly belonging to the energy production system; (iii) sectors with a high technological content in which the capital investments in CETs along with the EGD implementation might provide large benefits. Related to the third criterion, the aggregation of endowments has been also designed to better represent high-tech sectors, by distinguishing labour force into high-skilled and low-skilled workers.

Similarly, the regional aggregation has been designed to represent multilateral economic linkages between the EU and its main trade partners resulting into 33 regions from the 141 originally available in GTAP10 (Aguiar et al., 2019). Specifically, we have regions that represent EU bilateral and multilateral trade preferential agreements, together with the main large economies disentangled (e.g., Brazil, China, Russia and the US). The reason behind this choice is strictly connected with changes occurring along the global value chains when a unilateral climate policy is simulated.[6]

All scenarios share a temporal profile from 2014 to 2050, along with the long-term dimension of the EU decarbonisation strategy. Starting from the base year 2014, the first two steps arrive at 2015 and 2020, respectively, and they are calibrated with historical data. The other five-year steps go from 2025 to 2050 and represent the timeline of our scenarios. Accordingly, data sources on which the baseline and policy scenarios are based can be divided between the current period 2014–2020 and projections for the time span 2025–2050.

3.2. Baseline calibration

The historical pattern for the period 2014–2020 has been calibrated by setting a shock on the following exogenous variables: CO2 and non-CO2 emissions, electricity production disentangled into fossil-based and renewable, GDP, population, skilled and unskilled labour force.[7] Data on population and GDP are taken from Eurostat and the World Development Indicators (WDI) from the World Bank. Data on skilled and unskilled labour force are computed with International Labour Organisation (ILO) information on labour force and Centre d'études prospectives et d'informations internationales (CEPII) statistics on labour market structure based on the methodology developed by Fouré et al. (2013) for projections in macro-models.

Given the focus of the present analysis, the electricity sector has been calibrated with detailed information related to two aggregated sources, namely renewables (*ely_rw*) and fossil fuels (*ely_f*). The evolution over the period 2015–2020 is calibrated exogenously on the basis of Eurostat and IEA energy balances data. Electricity produced by nuclear power plants is here included into the sector aggregate representing traditional sources including fossil fuels. Despite nuclear power is not to be considered among the exhaustible resources, we adopt here a technology-driven classification related to the development options discussed within the EGD, where nuclear power is not included among the key technology options that would benefit from investments by the IF. Moreover, when a carbon pricing mechanism is applied, the presence of nuclear sources among *ely_f* is non-effective since only primary fossil sources are subject to a carbon price.[8]

[5] It is worth mentioning that renewables are used only to produce electricity, while biofuels used for transportation or heating are excluded. Accordingly, the decarbonisation for the other sectors (e.g., industry, transport) occurs due to a reduction in energy use (efficiency improvements) and to an increase in electricity as energy input.

[6] Details on endowment, sector and region aggregation are provided in the Appendix A, in Tables A.1, A.2 and A.3 respectively.

[7] All variables used for building the historical pattern and the projections have been collected at the most detailed available country level. Final shocks used in the model are obtained from singled out values summed over the respective regional aggregate. All details for model and scenario construction are available in the Supplementary material. Data and STATA scripts for replication are fully available upon request from the authors. In Table A.4 in the Appendix A we report a summary of details on the sources and the procedures used for calibrating the baseline.

[8] Electricity as an output from nuclear power plants is carbon free since it does not include fossil fuels as primary inputs. Accordingly, in *ely_f* the CO2

Combustion-based and non-energy CO2-eq emissions have been calibrated with most recent historical information at the country level taken from Eurostat, IEA CO2 emissions highlights and WDI combined together to cover as many countries as possible.

Starting from the year 2020, the BAU case for the period 2025–2050 has been calibrated by combining data on: population, GDP, skilled and unskilled labour force, energy mix (coal, natural gas, oil, oil products, electricity from fossil/nuclear and renewable sources), and emissions. The primary data sources are the Global Energy and Climate Outlook 2021 (GECO) projections (Keramidas et al., 2021) and the European Commission reference case (EUREF) for single EU members based on the JRC-PRIMES model (Capros et al., 2016). The UN world population prospects for demographic trends and the CEPII projections have been additionally used for, respectively, population and for labour forces. The BAU case has been also calibrated with respect to the CO2-eq emissions level and the energy mix composition in the electricity sector in order to be compatible with a *current policy scenario* approach in which all policies already in force (e.g., the EU 2030 energy strategy) are included in the baseline. As a step, the BAU case has been calibrated with the Shared Socio-Economic Pathways (SSPs) scenarios used for the 5th Assessment Report by the IPCC (Dellink et al., 2017; Riahi et al., 2017), resulting into a reference scenario coherent with the SSP2 "Middle of the road" according to the SSPs database (hosted by the IIASA Energy Program at https://tntcat.iiasa.ac.at/SspDb).

Finally, given that the year 2020 is our last historical temporal reference, and it has witnessed the large impacts due to the COVID-19 pandemic, we have updated the reference case with the effects related to the economic crisis and the consequent difference in emissions patterns. According with the assumptions developed in the last World Energy Outlook (IEA, 2020), we have considered the economic downturn as a source of temporarily reduction in emissions (Le Quéré et al., 2020). In technical terms, we have exogenously shocked the GDP level in 2020 according to the most recent estimations provided by IMF (2020) and updated in the Outlook of January 2021 for the economic losses in 2020 with respect to a reference case without the pandemic. Starting from 2025 the economic growth pattern turns to be endogenous and the emissions of CO2-eq follow this growth trajectory.

We also include the effects of a recovery action that in our model is designed as a general investment flow capable of pushing the GDP level in 2025 to a BAU level pre-crisis. Differently from the assumptions in IEA (2020), the recovery measures are introduced as a general increase in financial activities devoted to infrastructures and capital formation, without a specific action to accelerate the clean energy transition.[9]

In order to check that the amount of resources for recovery actions is compatible with feasible policy solutions, we have computed the endogenous increase in capital formation required to recover from the crisis. As a benchmark, we looked at the resources that the EU has allocated in different forms during the 2020 amounting at a recovery package of around EUR 750 billion, that corresponds to around 5% of the EU GDP in 2020 pre-crisis. In 2025, according to a full-recovery scenario, the total resources to be invested in a 5-year period to go back to a GDP pre-crisis amount are around 9.5% of GDP in 2025. Considering that in the years 2021–2025 additional resources could be invested within the Next Generation EU fund according to the recovery plans presented by member States, together with additional private resources, a total of 9.5% of GDP in the form of capital investments is reasonable.[10]

3.3. Policy scenario design

The BAU case with a full-recovery hypothesis is compared with policy scenarios that are based on different combinations of three instruments: (i) a carbon pricing (CP); (ii) the complete phase out of fossil fuels (FF) subsidies; (iii) an innovation fund (IF) financed with the revenues collected by carbon pricing and/or removed subsidies from fossil fuels, and devoted to foster CETs development and deployment. Given these three instruments, policy makers might choose to combine the two price-based instruments CP and FF subsidy removal, and to use the amount of resources available from revenue collection to be directed to CETs via the IF. The policy scenarios tested are represented in Fig. 4.

For designing the first price-based instrument, we assume that there is a common permits market where all agents participate and no free allowances are provided. Such a design roughly corresponds to a full implementation of the EU-ETS with complete auctioning for all sectors.[11] It is worth mentioning that the implementation of the CP and/or the FF subsidy removal instruments should be taken as benchmark scenarios where no additional exogenous improvement to technological trajectories is embedded. Accordingly, the corresponding scenarios provide a *ceteris paribus* estimation of the highest abatement costs in the absence of additional technical change.

emissions are related only to the use of fossil-based primary sources. Given that the carbon price is applied directly to the primary sources of emissions, electricity generated from nuclear energy is carbon free, it is not subject to abatement targets and it pays no carbon price. This modelling choice might bring to an underestimation of the economic impacts on *ely_f* sector since it is implicit the substitutability within this sector between fossil and nuclear sources. Indeed, the ad valorem equivalent on the price of *ely_f* aggregate is lower when including nuclear, as the carbon content of the not-renewable electricity output is lower. Nonetheless, given the input substitutability in *ely_f*, the final effect in terms of the choice of the economic system on which source to be used for producing electricity when carbon price is applied to coal, gas and oil is exactly the same.

[9] This means that no changes in behavioural parameters related to efficiency in production and consumption processes are imposed as subjective assumptions in these specific simulations, in line with the uncertainty over final effects of the Next Generation EU and Recovery Fund in EU countries. We are aware that a large part of the recovery plan in EU should be directed towards a sustainable energy transition and our conservative modelling approach is not able to capture all possibilities from investments in CETs. At the same time, in order to make results comparable with the IF financing mechanism here tested, a similar revenue collection channel should be modelled. Nonetheless, there is still uncertainty and heterogeneity in the way EU countries will pay back public debt required for financing the recovery measures. The integration of such investment flows into our modelling approach will be part of next research agenda.

[10] The same mechanism is applied to all regions belonging to the GDynEP model, with examples of resources invested in other large economies as a 4% of GDP in China and an 8% in the US. In Section 4 we report results of the BAU case with a full-recovery assumption, but results with a pre-crisis BAU and a no-recovery case are available from the authors. In the Appendix A, we report in Figs. A.1–A.2 the GDP trend in alternative BAU scenarios for the EU region and the rest of the world, while in Figs. A.3–A.4 the CO2-eq emission trends are reported for the pre-crisis, the no-recovery and the full-recovery BAU cases. Given the dynamic nature of GDynEP, although the GDP level in 2025 in the full-recovery case is equal to the pre-crises by construction, losses in capital accumulation occurred in 2020–2024 provokes a reduction in GDP growth patterns after 2025. Clearly, if additional recovery sources would be invested to sustain GDP growth above the pre-crisis expectations, the gap in growth rates could be reduced.

[11] As a general remark, by modelling EU as an aggregate and covering all sectors, the two available market-based policy options, a carbon taxation or a carbon pricing under the ETS, are perfectly equivalent, since the Pigouvian carbon taxation 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 the ETS without free allowances. 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).

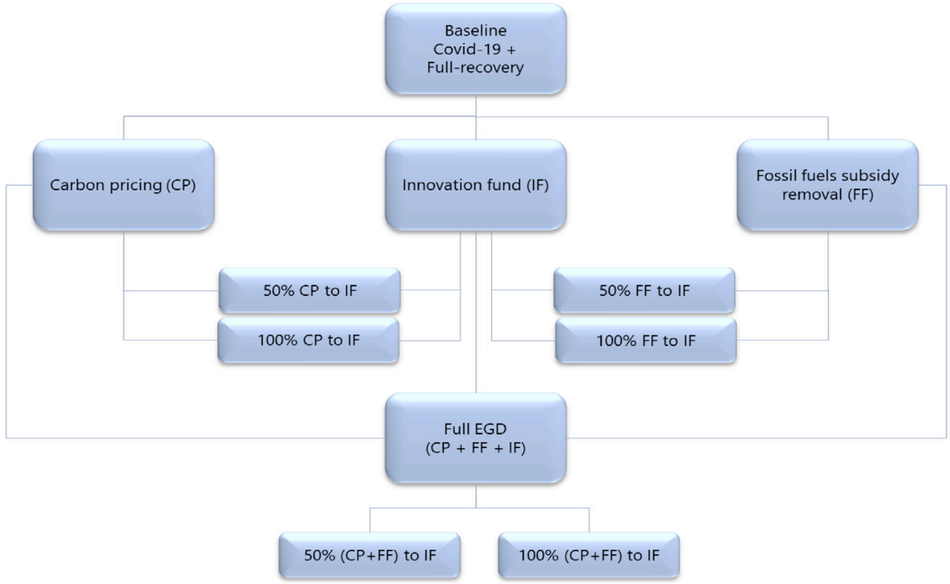


Fig. 4. Simulation design.

We model the EU abatement target as exogenous and set the amount of emissions that the EU needs to cut in each period with respect to the baseline trend in order to be on track with the carbon neutrality path. Then the model endogenously determines the equilibrium carbon price (CP) required to be on track with the decarbonisation pattern considering all the emissions associated to the FF inputs used by all agents. The *ad valorem* equivalent of the carbon price (τ) that results from changes in fossil-based energy input price (P_{FF}) is:

$$\tau = \frac{CP\,\frac{CO2}{Y}}{P_{FF}} = \frac{CP\,\frac{\beta\,FF}{Y}}{P_{FF}} \tag{1}$$

Second, the removal of FF subsidies is modelled in the form of a phase out of exemptions and tax rebates and introduced as an exogenous shock applied to the agent price level of fossil fuels on the commodity market according to the price-gap method (Burniaux and Chateau, 2014). Hence, the reduction in fossil-fuel subsidy, or in other terms the increase in the taxation level, results into an increase in the price faced by agents for using FF as inputs or final consumption goods.

In the GTAP10 database agent prices for energy commodities already includes the *ad valorem* equivalent of the FF subsidies. In order to practically simulate the policy instrument, fossil fuel subsidies are thus considered as an exogenous tax variable. By reducing the subsidy rate as an external shock, the model endogenously determines the overall value of fossil fuel subsidies at the region level, thus leaving the market mechanisms to adjust at the equilibrium point without *a priori* assumptions on a specific target in terms of fossil fuels consumption (Chepeliev et al., 2018). This is in line with the price-gap method which compares end-user consumer prices with reference prices corresponding to the full cost of supply excluding the subsidy.

The removal of subsidies is modelled as a single step, meaning that within the period 2020–2025 subsidies are completely phased out, considering as a benchmark the value of subsidies for the EU according to the OECD-IEA method equal to around USD 47 billion in 2020. Given that the starting year of the input–output database includes all distortions related to taxation and/or subsidies in the form of pre-tax agent prices, the removal of subsidies in this case corresponds to an increase in the agent price of fossil fuels, given that all agents now pay the same tax rate on each fuel without any diversified exemption.[12]

Since only fossil fuels are subject to the carbon pricing mechanism and/or the removal of the public direct subsidy to consumption, the two (FF and RW) energy inputs are not homogeneous with respect to the introduction of climate policies. The indirect demand equation for a generic fossil-based energy input (FF) demanded to produce good Y is augmented with the inclusion of both the *ad valorem* equivalent of the carbon price (τ) and the subsidy removal in the form of the *ad valorem* equivalent of phasing out the exemptions (s). On the other hand, the demand for RW is not affected by the two factors. In analytical terms the equations for FF and RW inputs demanded to produce good Y are:

$$p_{FF} = -\frac{\alpha_K}{\sigma_{KE}} ff - \frac{\alpha_{RW}}{\sigma_{EE}} ff + \frac{\alpha_{RW}}{\sigma_{EE}} rw + \frac{\alpha_K}{\sigma_{KE}} k + p_Y - \tau - s \tag{2}$$

$$p_{RW} = -\frac{\alpha_K}{\sigma_{KE}} rw - \frac{\alpha_{FF}}{\sigma_{EE}} rw + \frac{\alpha_{FF}}{\sigma_{EE}} ff + \frac{\alpha_K}{\sigma_{KE}} k + p_Y \tag{3}$$

where α_i represents the factor share of the generic input i, σ_{ij} is the Allen elasticity of substitution between inputs i ad j, while ff and rw represent, respectively, the changes in the fossil and renewable inputs. It is worth mentioning that Eq. (2) represents the change in the final price for the commodity, including all existing taxation levels except for the carbon price, in line with the price values available in the GTAP database. Accordingly, p_{FF} is a net change in price w.r.t. the

[12] The absolute values of subsidies for the EU27 used for calibrating the CGE model exclude subsidies directed to end-use electricity for two reasons. First, such subsidies are relatively small in amount but largely heterogeneous across EU countries. Considering that supports benefiting fossil fuels as power generation inputs are already aggregated under their respective fuel type (petroleum, coal and natural gas), the remaining direct support to end-use electricity is reduced (around 10% of total subsidies). Second, given that electricity in GDynEP is excluded from carbon pricing (as only primary use of fossil fuels are taxed on the basis of the carbon content of production/consumption processes), by excluding end-use electricity support from the removal policy is a way of imposing the two instruments exactly on the same commodities. See a sensitivity analysis on this point in Section 5. The calibration of the *ad valorem* component of p_{FF} to be used as an exogenous shock to s has been obtained by running preliminary simulations with the tax revenue from removing the subsidies in EU as endogenous. The final value of s corresponds to the collection of a revenue equal to USD 47 billion for the EU region in 2020, in line with OECD-IEA data. In order to respect the relative composition of subsidies directed to different energy commodities in OECD-IEA data, we calibrate the shocks with equal values assigned to coal, oil and oil products, and a lower shock for natural gas.

pre-policy level that included the eventual subsidies provided in the form of direct support or exemptions to energy taxation. Along with the linear notation of the equilibrium model, p_Y represents the output price (as an indirect demand notation).

Given that the reduction in fossil-fuel subsidy (s) results into an increase in market price for the FF input ($p_{FF} > 0$) and a consequent reduction in market demand as represented by Eq. (2), according to Eq. (1) and given a fixed abatement target ($\overline{CO2}$), the carbon price is expected to decrease when the subsidy is removed. Accordingly, the first policy decision shaping different scenarios is the adoption of a single price-based mechanism, whether the CP or the FF subsidy removal, or the combination of the two.

The second decision concerns whether and to what extent directing revenues coming from the price-based instrument(s) to the Innovation Fund (IF) to foster input-augmenting technical efficiency for the energy input and output-augmenting technical change for renewable sources. Along with the recent phasing out proposal by the FFFSR group, the financial gain resulting from removing subsidy payment is here considered as part of the public budget together with the government revenues from carbon pricing, and modelled with full auctioning. These two sources are thus collected as a tax revenue to be used for public spending as:

$$TAX_{REV} = CP\, \text{CO2} + s\, FF = CP\, \beta\, FF + s\, FF = FF\, (CP\, \beta + s) \quad (4)$$

Given that the removal of fossil subsidy produces a reduction in the *ad valorem* equivalent of the carbon price, the simultaneous introduction of the two instruments affects their relative contribution to the total tax revenues. As a result, the budget collected when the two instruments are combined could not correspond to the sum of the revenues obtained by separately applying the two instruments. In addition, given the multiple forces influencing the fossil-based energy input market outside the EU borders (the only region applying a unilateral climate policy), the final effect on the total amount of taxes collected is unpredictable.

Although the TAX_{REV} value is uncertain, the policy maker decides the exact quota of revenues to be directed to the IF and the development and deployment of CETs. We consider CETs to be a pure public good, completely funded by public investments, with no barriers to adoption and with constant returns to scale. Thus, considering an exogenous parameter γ ranging between zero and one, we roughly simulate the functioning of the Innovation Fund (IF) as follows:

$$IF = \gamma\, TAX_{REV} \quad (5)$$

In this exercise we assume γ to be equal to 100%, 50% and zero, corresponding to either all, half or no revenues collected from carbon taxation and/or the removal of FF subsidies are used to finance the IF. Along with the standard structure of the energy version of the GDyn model (GDynE), the share of revenues not redirected to the IF (1-γ) are distributed as lump sum to the regional households in the welfare computation of the equivalent variation.[13]

An additional policy decision is represented by the distribution of resources collected under the IF among different technology options. Therefore, depending on the value assumed by the exogenous parameter δ (with $0 < \delta < 1$), resources devoted to energy efficiency are given by $IF_{EFF} = \delta\, IF$, while renewable sources receive $IF_{RW} = (1 - \delta)\, IF$. In this exercise we apply a dichotomous distinction between CETs devoted to improve energy efficiency and/or to increase the production of renewables and, for the sake of simplicity, we model the IF as equally directed to the two CETs, with $\delta = 0.5$.[14] As a general remark, by taxing carbon-intensive energy sources and subsidising efficiency in energy consumption and cleaner sources, we can expect a change in the relative price of clean and dirty energy sources, and a simultaneous reduction in the net energy price increase (Galinato and Yoder, 2010; Golombek et al., 2020).

Following Carraro and De Cian (2013), investments from the IF are then generically transformed into technical change outcomes as follows:

$$tc_{EFF} = \varphi\, IF_{EFF} \quad (6)$$

$$tc_{RW} = \theta\, IF_{RW} \quad (7)$$

where φ and θ represent the elasticities with respect to IF investments, tc_{EFF} is the input-augmenting technical change for energy efficiency and tc_{RW} the output-augmenting technical change for RW.

In order to transform the IF_{EFF} (which is measured in USD Mln) into input-augmenting technical change in energy efficiency (tc_{EFF}) we calibrate parameter φ with a standard elasticity computation method based on changes of total innovation efforts (here represented by R&D flows) and gains in energy efficiency expressed as energy service increases. We assume that energy efficiency improvements are homogeneous in all sectors and that the diffusion path is not affected by technical barriers. In the same vein, the transformation of the IF_{RW} into output-augmenting technical change in renewable electricity production is calibrated considering the elasticity between public R&D investment in renewable electricity and the corresponding increase in installed capacity in renewable electricity in EU countries during the same period. For both parameters we have used data for the period 1995–2015 from IEA Energy Balances for energy consumption and installed capacity in electricity, and IEA RD&D statistics for public investments in energy-related technologies in the efficiency and renewable electricity domains. The values assumed by φ and θ correspond to an increase by 0.0005% in energy efficiency and by 0.0003% in installed capacity for USD 1 million expenditure in R&D activities on average of the time range 2025–2050, respectively.[15]

Following Parrado and De Cian (2014), we include the input-augmenting technical change (tc_{EFF}) in the modelling framework as changes of the demand equations for FF and RW. Accordingly Eqs. (2)–(3) become respectively:

$$p_{FF} = -\left(\frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_{RW}}{\sigma_{EE}}\right) ff\ tc_{EFF} + \frac{\alpha_{RW}}{\sigma_{EE}} rw\ tc_{EFF} + \frac{\alpha_K}{\sigma_{KE}} k + p_Y - \tau - s \quad (8)$$

$$p_{RW} = -\left(\frac{\alpha_K}{\sigma_{KE}} + \frac{\alpha_{FF}}{\sigma_{EE}}\right) rw\ tc_{EFF} + \frac{\alpha_{FF}}{\sigma_{EE}} ff\ tc_{EFF} + \frac{\alpha_K}{\sigma_{KE}} k + p_Y \quad (9)$$

[13] The representation of government is quite simplified in global CGE model like the GTAP version we use. There is not an explicit public sector budget constrain where government income (e.g., from taxes) is required to be equal to expenditures plus public deficit. Indeed, government expenditure is one of the components of regional final demand, and government savings are set to zero which implies that the government balance is zero. All taxes and subsidies that are included in the agent prices in GTAP database for the base year 2014 are collected by the government and then directly used as compensation for welfare changes in the form of an equivalent variation. This means that by changing the agent prices with a carbon price and/or subsidies removal there is a direct revenue effect related to tax collected by the government (according to the value assumed by γ) that are transferred as lump sum to households as welfare compensation, without any impact on government budget. A potential future development of this analysis could introduce a more complex public sector as suggested by Parrado et al. (2020).

[14] It is worth mentioning that the distribution of public R&D investments across these two technological domains for the EU as an average of the last five years (2016–2020), according to IEA statistics is 51% of energy efficiency and 49% for renewables. For a detailed discussion on the impact of different values assumed by γ and δ on carbon price level see Corradini et al. (2018).

[15] In this analysis we assume a conservative approach with a unique shock activating the two elasticity parameters starting from the year 2020, in order to start collecting revenues and redirecting them to CETs from 2021. This means that the efficiency improvements are permanent (i.e., stopping the fund in a given time step would maintain the technology as it was in the previous period). According to Corradini et al. (2018), in this model the policy support is not detailed and we jointly include all aspects of technology development, deployment, diffusion and adoption under a unique mechanism.

Table 1
Scenario description.

Scenario	Description
BAU_FR	Baseline + Covid-19 + Full recovery
CP	Carbon pricing
CP+IF ($\gamma = 50$)	Carbon pricing + Innovation Fund financed with 50% of the revenues collected by carbon pricing
CP+IF ($\gamma = 100$)	Carbon pricing + Innovation Fund financed with 100% of the revenues collected by carbon pricing
FF	Complete phase out of fossil fuels subsidies
FF+IF ($\gamma = 50$)	Complete phase out of fossil fuels subsidies + Innovation Fund financed with 50% of the revenues collected by removed subsidies from fossil fuels
FF+IF ($\gamma = 100$)	Complete phase out of fossil fuels subsidies + Innovation Fund financed with 100% of the revenues collected by removed subsidies from fossil fuels
CP+FF	Carbon pricing + Complete phase out of fossil fuels subsidies
Full EGD: CP+FF+IF ($\gamma = 50$)	Carbon pricing + Complete phase out of fossil fuels subsidies + Innovation Fund financed with 50% of the revenues collected by carbon pricing and removed subsidies from fossil fuels
Full EGD: CP+FF+IF ($\gamma = 100$)	Carbon pricing + Complete phase out of fossil fuels subsidies + Innovation Fund financed with 100% of the revenues collected by carbon pricing and removed subsidies from fossil fuels

On the other hand, the output-augmenting technical change (tc_{RW}) enters in the supply function for the RW energy inputs demanded for producing output Y. Hence, the supply function (i.e., $p_{RW} = \frac{1}{\psi_{RW}} rw$) for RW becomes:

$$p_{RW} = \left(rw + tc_{RW}\right) \frac{1}{\psi_{RW}} \tag{10}$$

where ψ_{RW} is the supply elasticity for renewable sources.

A detailed summary of the policy scenarios we use for analysing the interactions across the multiple instruments in the EU climate policy mix is reported in Table 1.

4. Results

Results are organised in order to gradually introduce the three instruments (namely the phase out of fossil fuels subsidies, a carbon pricing, and the financing mechanism of the IF with revenue recycling), and to compare the additive effects when they are simultaneously implemented. In Fig. 5 we describe different emission patterns associated to the reference case (reported as a full-recovery baseline) and to the emissions trend required for respecting the EU decarbonisation target along the “Fit for 55” Package, with an intermediate target of 55% cut by 2030 w.r.t. 1990 level (corresponding to a 26% cut w.r.t. BAU) and a final target of 90% cut by 2050 w.r.t. BAU.[16] By phasing out subsidies to fossil fuels there is a small gain in terms of emissions reduction w.r.t. BAU determined by the increase in agent prices for fossil fuels sources at the domestic level due to the term s in Eq. (2). Despite the positive contribution of tax exemptions and direct support to the competitiveness of fossil-based sources in sustaining consumption, in line with findings by Jewell et al. (2018) the phasing out action has the main effect of reducing market distortion but not to substantially decrease fossil fuels consumption and related emissions.

Once the subsidies are removed, there is a larger benefit in terms of emissions reduction if revenues collected from the reform, formally represented by the term sFF in Eq. (4), are invested into the second instrument, here represented by the IF, directed to sustain the development and deployment of CETs. According to Eqs. (8)–(10), the financial resources managed through the IF directly influence the market demand for energy commodities by reducing the overall demand for energy inputs via the input-based technical efficiency channel, and by sustaining the production of renewable sources due to output-augmenting technical change.

The overall emissions reduction by 2050 when the two instruments (FF subsidy removal and IF) are jointly implemented and parameter γ is equal to 100% (meaning a full reuse of the revenues for CETs deployment) is around −11% w.r.t. BAU, at least partly contributing to closing the emissions gap with respect to the carbon neutrality target. GDP changes w.r.t. the reference case, as shown in Fig. 6, reveal that the implementation of the FF subsidy removal instrument alone would cause a (small) negative impact on GDP due to the increase in fossil-fuel prices on the domestic EU market.

Given that the starting year of the input–output database includes all distortions related to taxation and/or subsidies, the removal of subsidies in this case corresponds to an increase in the agent price of fossil fuels, given that all agents now pay the same amount of tax rate on each fuel without any diversified discount. From the modelling perspective, this corresponds to an increase in the agent price faced by those consumers (including firms) that were benefiting from the subsidy. Especially energy-intensive sectors pay extra-costs for intermediates, resulting into an increase in production costs and a negative impact on GDP.

This result explains the strong opposition by lobbies representing energy-intensive industries that might lose competitiveness after the phasing out. However, when the two instruments are jointly implemented, the GDP losses turned into gains w.r.t. the reference case.

The issue is to move the debate from the potential negative effects related to subsidies removal toward the benefits originating from the complementarity of the two instruments. If, from the one side, lobbies might argue that benefits from CETs deployment due the IF investments are not directed to those energy-intensive sectors facing the largest portion of economic losses, some forms of direct compensation to the losers might complement the support to CETs to improve the acceptability of the subsidy removal proposal, resulting into a win-win solution.

The impact of investing in CETs via the IF is progressive, as the additional increase in GDP change with $\gamma = 100\%$ is higher than the improvement for $\gamma = 50\%$. This result is influenced by the cumulative nature of knowledge creation associated to investments in CETs. Accordingly, even if decreasing returns to scale are observed for additional financial resources dedicated to CETs deployment, there is

[16] In Fig. 5 the slight increase in emissions in 2025 (from 3168 to 3241 Mln ton of CO2-eq) is caused by the strong impulse to GDP growth provided by recovery investments. We assume here that although the sustainable energy transition process is at work, the technological evolution is slower than the increase in energy demanded for the recovery actions, thus provoking a temporary shift upwards in emissions trend.

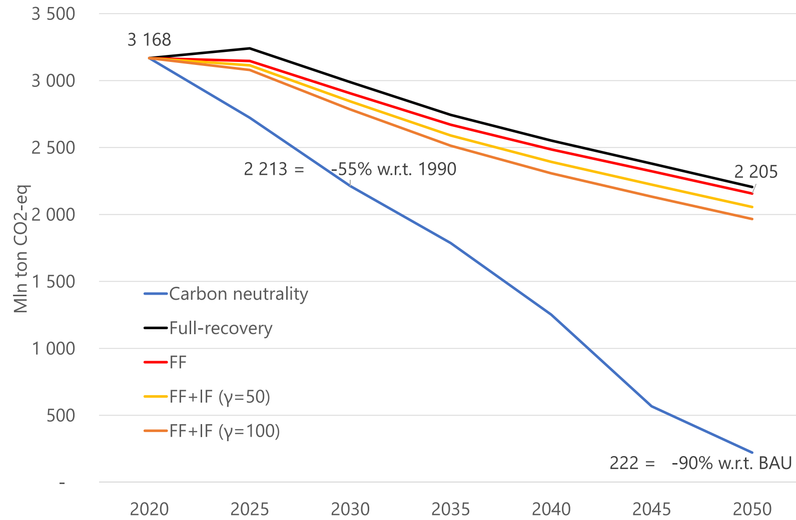


Fig. 5. CO2-eq emissions in EU27 (Mln ton of CO2-eq). *Note*: own elaboration on GDynEP results.

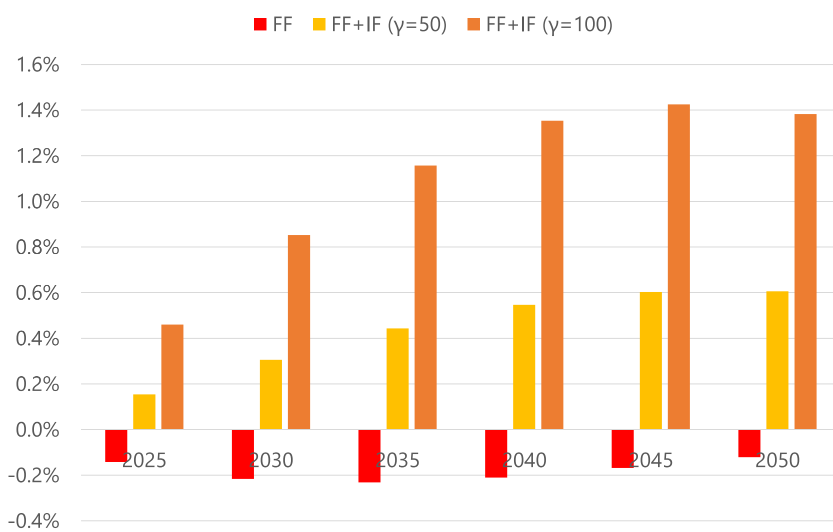


Fig. 6. GDP changes w.r.t. BAU in EU27 with subsidy removal (%). *Note*: own elaboration on GDynEP results.

a relatively higher increase in the economic impact due to the stock of capital investments made over the whole period.[17]

Given that the implementation of these two instruments is insufficient for respecting the carbon neutrality target, the EU should also reinforce the policy mix with a carbon pricing mechanism. Accordingly, in Fig. 7 we report changes in GDP level over time for selected scenarios including the CP. Three issues are worthwhile.

First, the adoption of a carbon pricing policy as the only instrument for respecting the carbon neutrality by 2050 provides a rough approximation of the upper bound marginal abatement cost to be sustain by the EU27 economy over time to respect the full decarbonisation target. The increase in fossil-based energy agent prices related to the incremental value of CP as expressed in Eq. (2), when no additional efforts are invested in technological development, brings a GDP decrease by around 13% in 2050 w.r.t. the reference case. The increase in production costs related to the burden of abatement effort combined with the absence of any support to technological shift is the main direct mechanism explaining the GDP loss. Such burden is also imposed on fossil fuels imported from the international market, as the CP is the unitary cost of CO2 emissions whatever is the production source.[18]

Our estimation of the carbon price level required to achieve the full EU decarbonisation is higher with respect to previous studies. Following Tol (2020), the divergence can be explained by three differences in modelling assumptions. First, for a given target ambition (e.g., 2 °C or 1.5 °C global warming), whether a global agreement or unilateral mitigation policies are included in the model contributes to determining the magnitude of the abatement costs. If poorer countries are (initially) exempt from implementing mitigation strategies, abatement costs will be significantly higher. In addition, differences across countries/regions explain heterogeneous abatement costs. Since we are assuming that only the EU introduces a mitigation policy (*CP*), we should expect our abatement costs estimations to be in the upper (pessimistic) bound.

[17] It is worth mentioning that in all simulations the values for parameters φ and θ remain unchanged, but the results from the simulations are sensitive to all additional elements included in the general equilibrium outcome, such as the increase in the cost of substituting fossil-based electricity with renewable sources or the technical barriers in reducing energy intensity. Complete results with values for all scenarios related to energy intensity, revenues invested in CETs via the IF and GDP change are available in the Appendix A, Tables A.6–A.9.

[18] For detailed results on the evolution of CP and the corresponding impact in percentage change in fossil-based energy prices w.r.t. BAU in all policy scenarios see Tables A.5–A.14 in the Appendix A.

Fig. 7. GDP changes w.r.t. BAU in EU27 with alternative policy mix (%). *Note*: own elaboration on GDynEP results.

This is also in line with Tol (2021), according to which carbon price is likely to be higher in the EU than elsewhere by implementing the current climate strategy. Second, in our CP scenario we do not impose any assumption about the (differentiated) rate of technological change. This implies that in this scenario the benefits coming from differentiated speeds of advancement in clean energy technological domains in lowering abatement costs cannot be exploited. In addition, the role of end-of-pipe technologies (e.g., carbon capture ad storage) or hydrogen fuel cells is also excluded, which is a further reason behind the relative higher costs generated by the model. Third, with respect to the timing of reduction effort, Tol (2021) suggests that emission paths starting with modest abatement and adopting more stringent targets lately allow cost savings. In our unilateral EU abatement scenario, we adopt the 2030 and 2050 targets set by the EU current policy, which imply an almost linear CO2 emission reduction (Fig. 5).

Second, when we introduce the additional effect of the subsidies reform, the negative impact on the economic performance is slightly worsened, despite the reduction in the carbon price level for the first periods provoked by subsidy removal. This apparently counter-intuitive impact can be explained as the outcome of an overlapping regulation effect (Böhringer et al., 2016), as the additional costs associated to support the phase out more than compensate the reduction in the CP level. Several mechanisms related to the structure of the economic system might explain such contrasting effects (Del Rio, 2017). Given that the GDynEP is a trade-based model, one reason can be traced back by considering that the direct and the pass-through effects of subsidy removal on the domestic market are linked to the global value chains, and the additional negative impact depends on a larger competitiveness loss associated with this specific policy mix design (Moerenhout, 2020).

Third, economic losses associated to the decarbonisation pathway turn to be a net benefit in terms of economic growth thanks to the positive impulse given by the massive investments in CETs through the revenue recycling mechanism. The simultaneous adoption of the three instruments (the CP, the FF subsidy removal and the IF financial mechanism) represents the policy mix design with the highest gain at the general economy level. This is in contrast with the previous result, as the combination of a carbon pricing and subsidy removal without the support to technological development is the worse case in terms of GDP losses. Notice that in the *CP* and *FF* scenarios we do not impose any assumption about future advancement in CETs. Following Copeland and Taylor (2004), in absence of improved technological possibilities which allow reducing the pollution intensity of production and consumption processes, reductions in environmental pressure are mostly driven by two channels: the scale effect (i.e., the reduction of the scale of production/consumption) and the composition effect (i.e., the shift of production/consumption towards less pollution intensive sectors and goods). To stress this point, in Fig. A.7 we compute the changes in sectoral value added (VA) with respect to BAU scenario. The results show that the *CP* and *CP+FF* scenarios entail a large drop in VA in pollution intensive sectors (e.g., energy, transport, chemical, mineral and metal industries), suggesting that these scenarios mostly reflect the scale and composition effects. On the other hand, when introducing CETs support, VA reductions turn into gains.[19] Overall, this evidence suggests that development and deployment of CETs (i.e., fostering the technique effect) is crucial to achieve the carbon neutrality at lower costs given that it allows reducing the amount of emissions per unit of output.

The full implementation of the EGD turns out to be an effective sustainable transition strategy, with the Innovation Fund as the key element for enhancing the competitiveness of the EU economy. Indeed, resource efficiency enhanced by CETs deployment will benefit all production processes as well as households' consumption, while the output augmenting technical change in renewables will allow a higher substitutability with fossil-based electricity thus reducing the final cost of consuming electricity in general.

It is worth mentioning that in our exercise we assume that resources invested in CETs are all managed via the IF instrument. Accordingly, the value of the revenue recycled from model results cannot be directly compared with the current EU plan for financing the IF, given that together with the public support (that is expected to amount around EUR 10 billion of direct State aid), also private resources should be mobilised. Accordingly, the financial burden from our results could be taken as a benchmark in order to approximately quantify the total amount of public and private resources to be spent for the EU sustainable energy transition.

Even from a global climate perspective, the full implementation of the EGD with the three instruments into force is the best option. By computing the carbon leakage rate for the aforementioned scenarios, from Fig. 8 it is clear that the adoption of the two market-based instruments of CP and FF subsidy removal, without an adequate support to the development of CETs, would imply an increase in emissions provoked by the rest of the world neutralising the EU abatement efforts by around 50% by 2050.[20]

[19] The only exception is the energy sector, but the negative variation in this case is mostly driven by the fossil fuel industries.

[20] Detailed results on carbon leakage rate for all scenarios are available in the Appendix A, Table A.12. The current GDynEP model can be easily updated with an additional policy instrument related to the Carbon Border Adjustment Mechanism (CBAM), whose practical implementation is still debated.

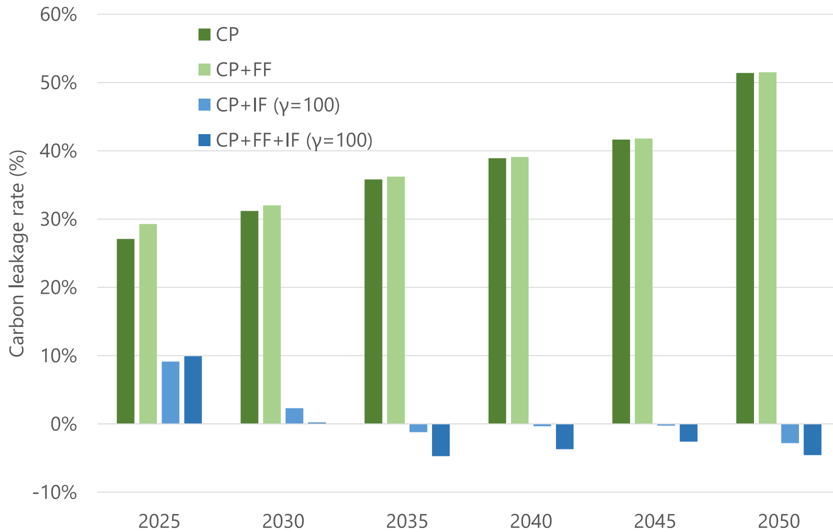


Fig. 8. Carbon leakage effect (%). *Note*: own elaboration on GDynEP results.

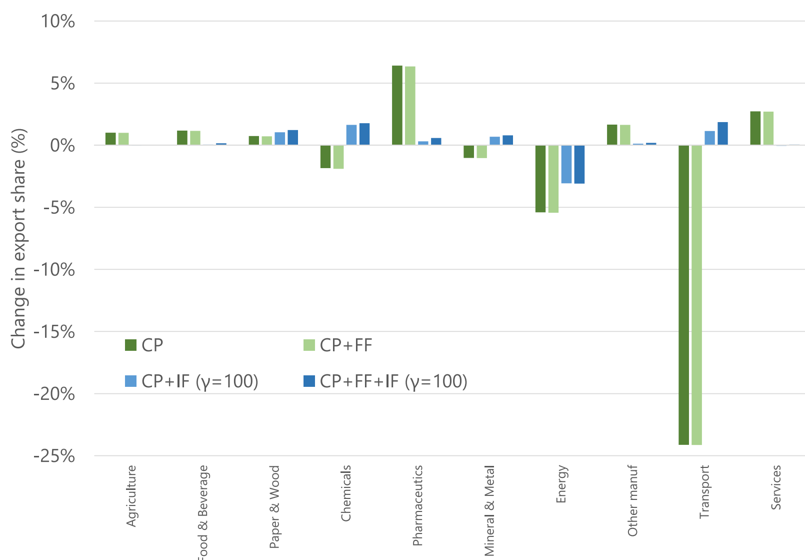


Fig. 9. Change in EU27 export share w.r.t. World (2050). *Note*: own elaboration on GDynEP results.

The carbon leakage effect is mostly explained by the competitiveness loss of the EU production in energy intensive sectors due to the prohibitive abatement costs entailed by the $CP+FF$ policy mix option. The reduction of EU carbon-intensive products on the international market is partly replaced by the increase of energy-intensive goods produced in countries with lower technology standards, thus bringing to a partial compensation of the EU emissions reduction by the rest of the world. This is consistent with the observed changes in the EU sectoral export, measured as share of global export, which show that in absence of CETs financing, the energy-intensive sectors are subject to large losses on the global market (i.e., chemicals, minerals and metal products, energy and transport, as in Fig. 9).

In this exercise, differences in technologies and emission intensities explain the increase in emissions from the rest of the world as a consequence of international outsourcing or shifting the production of carbon-intensive goods (Hertwich, 2020). Accordingly, emissions saved at home would be replaced by emissions embedded into import flows along the global value chain.[21]

On the opposite, when the full EGD is implemented, the leakage effect is reversed and become slightly negative resulting in a reduction in carbon emissions for the whole world (including EU) by around 5%. The main explanation along with the economic mechanisms activated within a CGE trade-based model refers to the positive effect of investments from recycling the CTR to improve resource efficiency for the EU, thus resulting into a reduction of the outsourcing dynamics that is responsible for the increase in foreign emissions. Indeed, the higher efficiency of EU production processes due to CETs deployment reduces the demand for foreign intermediate (carbon-intensive) inputs and consequently the leakage rate (Marin and Zanfei, 2019; Wan et al., 2015).

The complexity of the policy mix design under the full EGD implementation implies that there are several characteristics and direct and indirect effects that should be considered in order to detect the optimality of the policy strategy. This is in line with van den Bergh et al. (2021) that suggest to evaluate climate policies based on multiple criteria in

[21] The additional leakage channel related to the potential reduction in international prices of fossil sources due to the decreased demand by decarbonising countries (Antoci et al., 2021) is here negligible given the relative low impact of EU decrease on global fossil fuels demand.

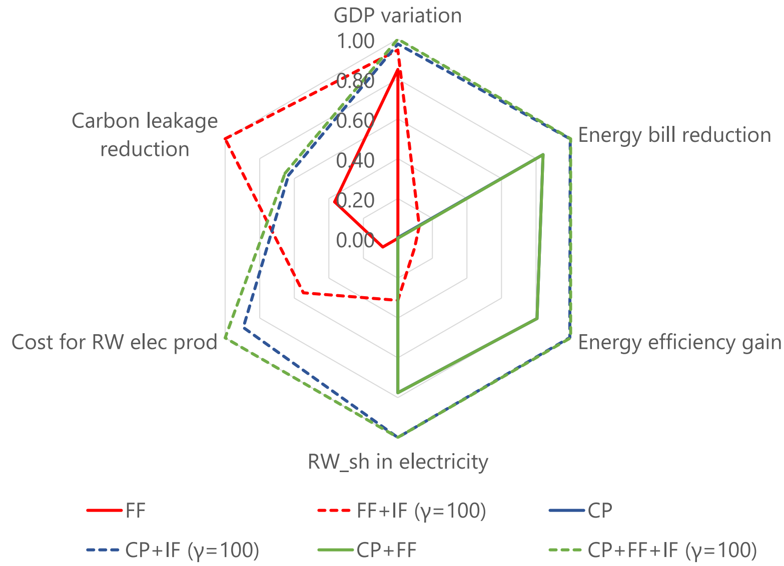
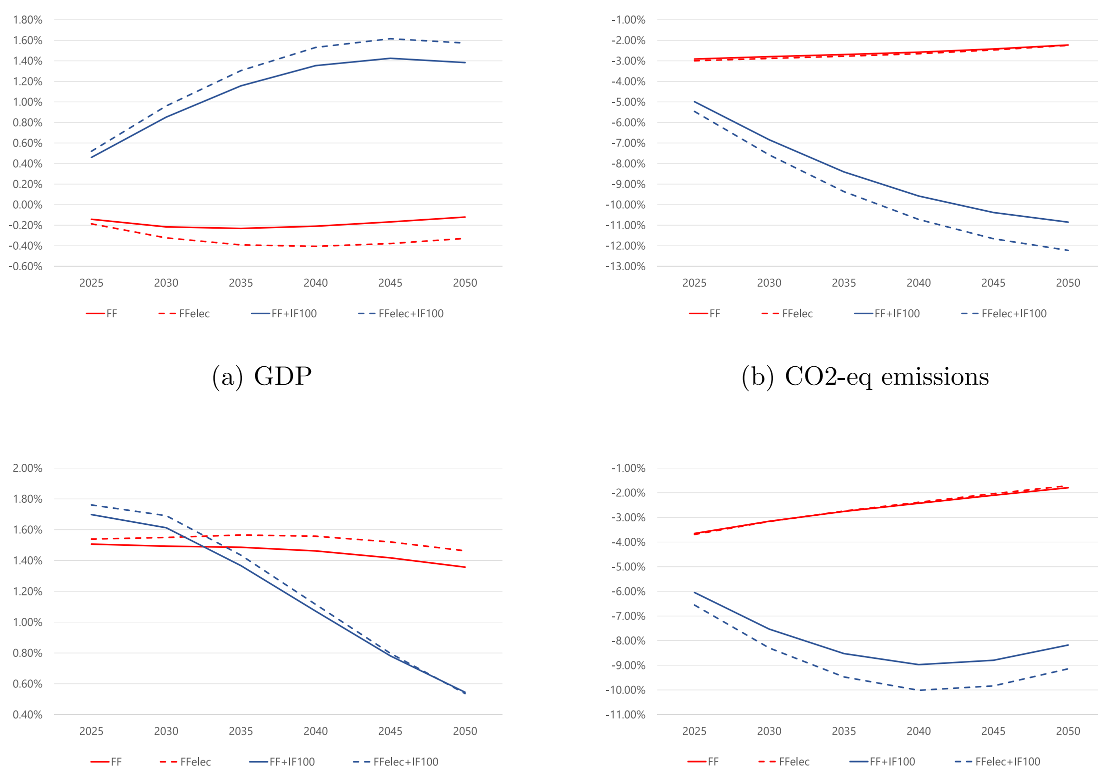


Fig. 10. Optimal policy mix evaluation (EU by 2050). *Note*: own elaboration on GDynEP results.



(a) GDP

(b) CO2-eq emissions

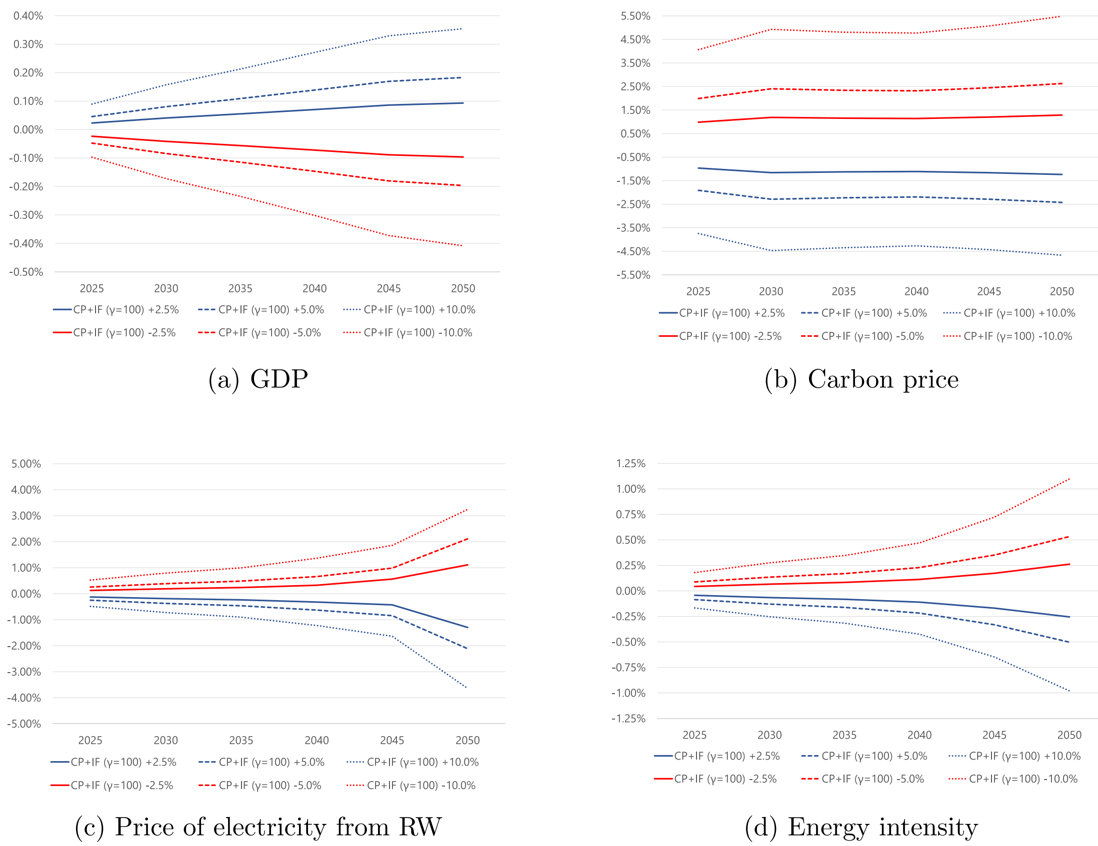
(c) Price of electricity from FF

(d) Energy intensity

Fig. 11. Alternative measures of fossil fuels subsidies (EU27).
Note: all lines represent the percentage change of each scenario with respect to the BAU full-recovery case. Solid lines refer to the scenarios used in this work while dashed lines report results associated to the inclusion of end-use electricity subsidies.

order to quantify and weight the interactions between instruments in the policy mix (especially if three or more instruments are applied). As an example, starting from our results, we propose a comparison of all potential combinations of the three instruments under investigation by computing for the EU region in year 2050 six indicators commonly used to evaluate effectiveness, efficacy and feasibility of climate strategies.

The six indicators are all computed as differences with respect to a common benchmark, here taken as the value of the index assumed in the BAU case, and refer to: (i) the change in GDP value; (ii) the change in the monetary value of total energy imports (hereafter called energy bill); (iii) the energy efficiency gain (computed as the reduction of energy intensity); (iv) the share of renewable sources in the electricity production; (v) the unitary cost of electricity produced by renewable sources; (vi) the reduction in the carbon leakage rate. In so doing, all indicators are normalised with a *min–max* function in order to be in the range 0–1, and are constructed such that larger values indicate



(a) GDP
(b) Carbon price
(c) Price of electricity from RW
(d) Energy intensity

Fig. 12. Sensitivity to changes in φ and θ (EU27).
Note: all lines represent the percentage change of each scenario where shocks to GDynEP parameters corresponding to φ and θ are $\pm$2.5%, 5%, 10% with respect to the $CP + IF$ ($\gamma = 100\%$) case.

better performances. In Fig. 10 we show how each scenario performs in terms of the six normalised indicators considering the EU by 2050, while Table A.13 in the Appendix A reports the single value assumed by the aforementioned indicators.[22]

Scenarios that are better ranked are those reporting the higher number of indicators approximating to 1, with the scenario representing the full implementation of the EGD (i.e., $CP + FF + IF(\gamma = 100)$) with the simultaneous application of the three instruments (namely the carbon pricing, the complete phase out of subsidies directed to fossil fuels and a full recycling of 100% of revenues from the two market-based instruments directed to the development and deployment of CETs) as the optimal policy mix design, given the six targets here considered.

It is also interesting to observe how the three instruments of the policy mix perform with respect to specific targets. From an environmental point of view (i.e., higher energy efficiency gain and larger share of electricity from renewable sources), the CP clearly outperform the FF subsidy removal, whether the revenue recycling mechanism is included or not. When looking at the energy market, the unitary production cost of electricity from renewables is substantially reduced by the introduction of the financing mechanism through the IF, while it remains almost unaffected by the implementation of the carbon pricing or the subsidy removal alone.[23]

A final interesting result is related to the international linkages resulting from the unilateral implementation of the EU climate and energy plan. From one side, the CP allows to significantly reduce the energy bill and the dependency from import, which concur to enhance the EU energy security. However, in the absence of the IF as an additional complementary measure, CP poorly performs in terms of carbon leakage rate, as the competitiveness losses on international markets are, at least partly, converted into gains for other regions.[24]

Quite obviously, this ranking is directly influenced by the indicators used for the comparison, that in this case are defined on the basis of the main targets described within the legislative text of the EGD. If, however, additional elements would be introduced among the targets in the future EU climate strategy, as for instance related to the distributional impacts on different income groups or to a more detailed investigation on specific sectors, the same empirical framework can be applied to results coming from different models and/or scenarios.[25]

[22] In Tables A.7 to A.12 in the Appendix A we also report the original value based on model results for the six variables, in each scenario and year.

[23] See Figs. A.5–A.6 in the Appendix A for a comparison in trends of prices for electricity produced by fossil and renewable sources with different scenarios.

[24] See Table A.12 in Appendix A.

[25] In this paper we have not included any considerations about political feasibility, equity or the distribution impacts associated to different policy

5. Sensitivity analysis

We run a sensitivity analysis on selected modelling choices made on three relevant issues for this work: (i) the computation of the monetary value of subsidies directed to fossil fuels (FF); (ii) the elasticity parameters used to transform the investments from the IF into input-augmenting technical change for energy efficiency (φ) and output-augmenting technical change for electricity production from renewable sources (θ); (iii) the Armington elasticity parameters used to model bilateral trade flows.

With respect to the first point, we report the effects of including or not among subsidies those directed exclusively to end-use electricity, amounting at around 10% of total EU subsidies in 2020. In Fig. 11 we compare scenarios with complete phase out of FF subsidies and with the recycling mechanism into IF with $\gamma = 100\%$ by projecting four variables (GDP, CO2-eq emissions, price of electricity produced by fossil fuels, energy intensity) as percentage change with respect to the BAU case.

The two scenarios where also end-use electricity subsidies computed on the basis of the OECD-IEA methodology are removed are referred as $FFelec$. As a general result, despite such additional subsidies amount at 10% of total fossil-fuel related public support, the relative impact is negligible both from an economic point of view (as revealed by the small distance in GDP and price of electricity form FF change w.r.t. BAU case), and from an environmental point of view (as revealed by the small distance in the CO2-eq emissions and the energy intensity change w.r.t. BAU case).

Second, with respect to modelling assumptions on exogenous parameters, we measure the impacts of changes in such parameters on the outputs of the model by comparing the value of fluctuations in parameters with changes in results. More precisely, the sensitivity to the elasticity parameters used in GDynEP to represent φ and θ as in Eqs. (6)–(7) has been carried by changing the shocks for the parameters simultaneously by alternatively $\pm 2.5\%, 5\%, 10\%$. In Fig. 12 we report the percentage change with respect to the $CP + IF(\gamma = 100\%)$ policy scenario used in this analysis with a carbon price and a full reuse of revenues for financing CETs. Results clearly highlight that the fluctuations in model outputs are substantially lower than the corresponding changes imposed to parameters, providing evidence on the robustness of the assessment of policy mix scenarios comparison here presented. Finally, fluctuations in output results when sensitivity is tested alternatively on φ or θ are similar in direction and reduced in magnitude.

The third sensitivity check is based on the implementation of a Systematic Sensitivity Analysis (SSA) applied to the values of parameters representing the Armington elasticities for trade substitutability. We have tested three different percentage changes (+/−2,5,10%) applied to the two parameters ESUBD (Armington CES for domestic/imported allocation) and ESUBM (Armington CES for regional allocation of imports) for the EU27 region for the scenario $CP + IF(\gamma = 100\%)$. By comparing the change in volume of GDP (Table A.15) and of sectoral exports of EU towards the rest of the world (Table A.16), the average percentage change across 2025–2050 w.r.t. the mean value assumed by the variable is always lower than the shock assigned to the parameters.[26] Additionally, considering the values for export of single sectors, the average values across 2025–2050 of the mean to standard deviation ratio is always very high, validating the robustness of results.

mix designs. These issues are out of the scope of this paper, but could be addressed in future research agenda. For example, a possible extension is given by considering the case in which part of the revenue directed to the IF could be used for redistributive purposes, as suggested by Klenert et al. (2018).

[26] The only exceptions are the Machinery sector for the +/−2% shock (2.25% average change), and the Other manufacturing sector for the shock +/−2,5% (2.63% and 5.28% average change, respectively).

6. Conclusions

The EU has recently launched the EGD as an ambitious energy and climate strategy with the aim of achieving long-term environmental targets and considerable societal gains without compromising the economic competitiveness of the European economy. In this paper, we develop a dynamic CGE model with a detailed representation of the energy sector in order to analyse how the different pillars introduced under the EGD contribute to the ambitious path to make EU a climate-neutral economy by 2050. Given the complexity of the EGD policy mix design, we compare the optimality of alternative climate strategies accounting for different dimensions and both direct and indirect effects.

Our results show that the best performances are obtained if the EGD is fully implemented, meaning that in addition to a properly functioning ETS, subsidies directed to fossil fuels are completely phased out, and the revenues resulting from the carbon pricing together with the budget saving from the removed subsidies are devoted to foster CETs development through the Innovation Fund. In this way, the resulting policy mix allows the EU to achieve the environmental targets at the lower costs. The synergies arising from energy efficiency gains, the larger contribution of renewable sources and the reduction in fossil fuels consumption all contribute in reducing the cost of transition. When the three pillars are simultaneously included, we reach the most favourable condition also in terms of economic growth and register the highest GDP gain with respect to the BAU case.

Additional positive effects can be highlighted by looking at the global externalities resulting from the implementation of the unilateral EU climate policy. Without an adequate support scheme for the development of CETs (or, in other terms, excluding the revenue recycling mechanism operating through the IF), the EU climate targets set under the Paris Agreement can be achieved only at the cost of increasing emissions elsewhere in the world. On the opposite, the positive indirect effects resulting from the implementation of the full EGD policy mix through trade-induced knowledge spillover will lead to a net carbon reduction at the world level. Developing countries might gain significant macro-economic benefits from this knowledge transfer effect, improving their technological capabilities and fostering the domestic deployment of green technologies to reduce their mitigation costs (Paroussos et al., 2019).

From our results we can synthesise two main policy implications. First, given the contribution of the Innovation Fund in enhancing the international competitiveness of the EU system, it is highly recommended to direct resources under the recovery packages towards green investments. Otherwise, fiscal stimulus packages directed to an undefined growth trajectory might further entrench fossil fuels use deepening the emissions gap. Second, given the positive impulse to a long-term growth from the EGD policy mix design, it is worth stressing that similar policy packages should be adapted to emerging and developing countries to speed up the sustainable transition process at the global level and reduce the emissions gap worldwide.

CRediT authorship contribution statement

Alessandro Antimiani: Conceptualization, Methodology, Data curation, Writing. **Valeria Costantini:** Conceptualization, Methodology, Data curation, Writing. **Elena Paglialunga:** Conceptualization, Methodology, Data curation, Writing.

Appendix A

See Figs. A.1–A.7 and Tables A.1–A.16.

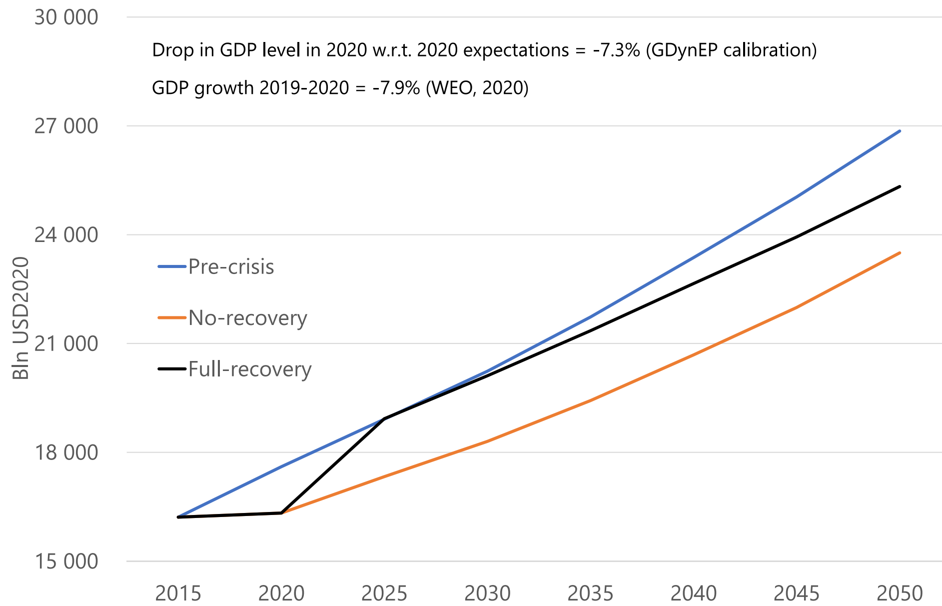


Fig. A.1. GDP shock calibration with COVID crisis (EU27). *Note*: own elaborations on GDynEP results.

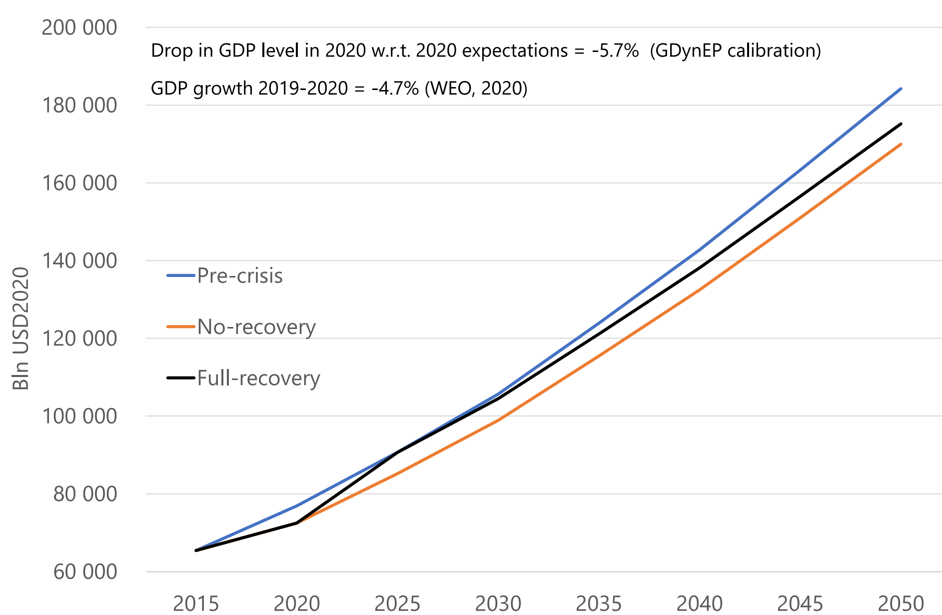


Fig. A.2. GDP shock calibration with COVID crisis (RoW). *Note*: own elaboration on GDynEP results.

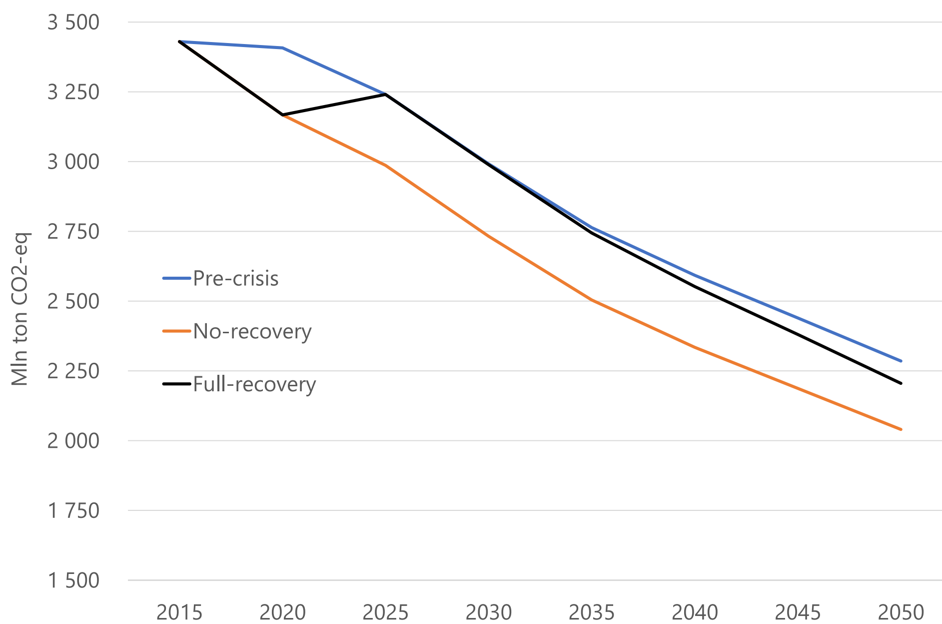


Fig. A.3. CO2-eq emission projections with COVID crisis (EU27). *Note*: own elaboration on GDynEP results.

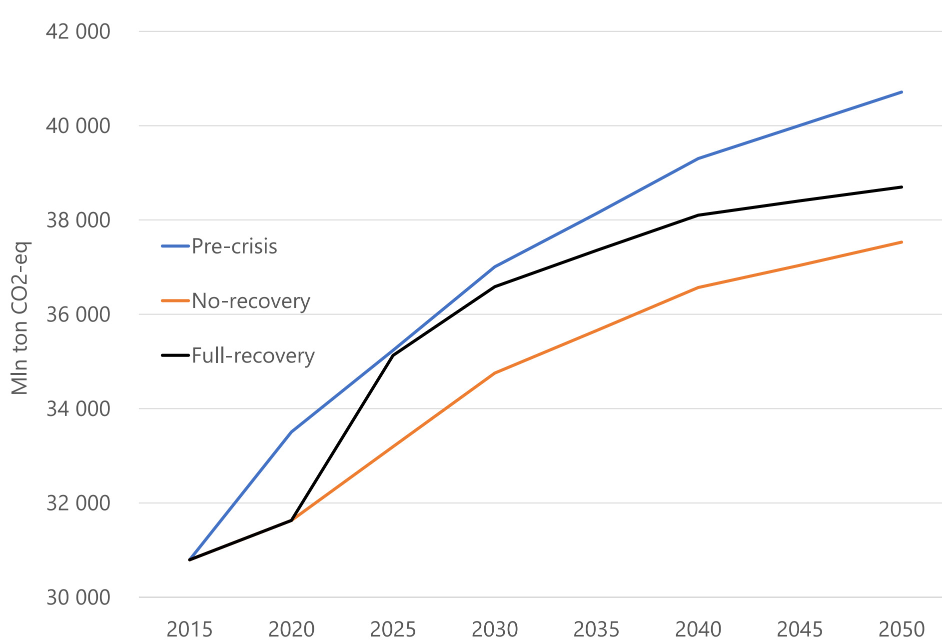
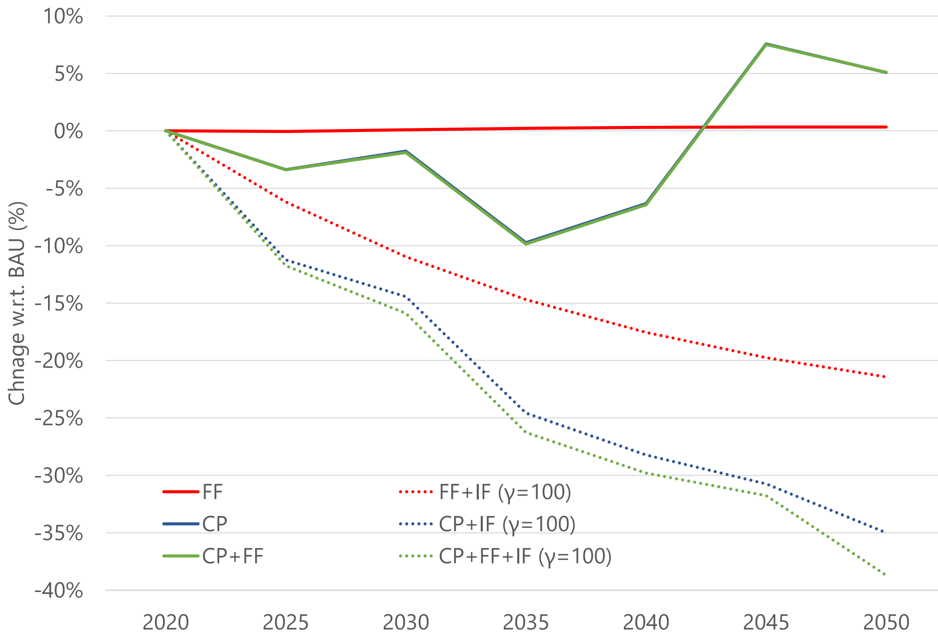


Fig. A.4. CO2-eq emission projections with COVID crisis (RoW). *Note*: own elaboration on GDynEP results.



Note: own elaboration on GDynEP results

Fig. A.5. Change in price of electricity from RW w.r.t. BAU (EU27). *Note*: own elaboration on GDynEP results.

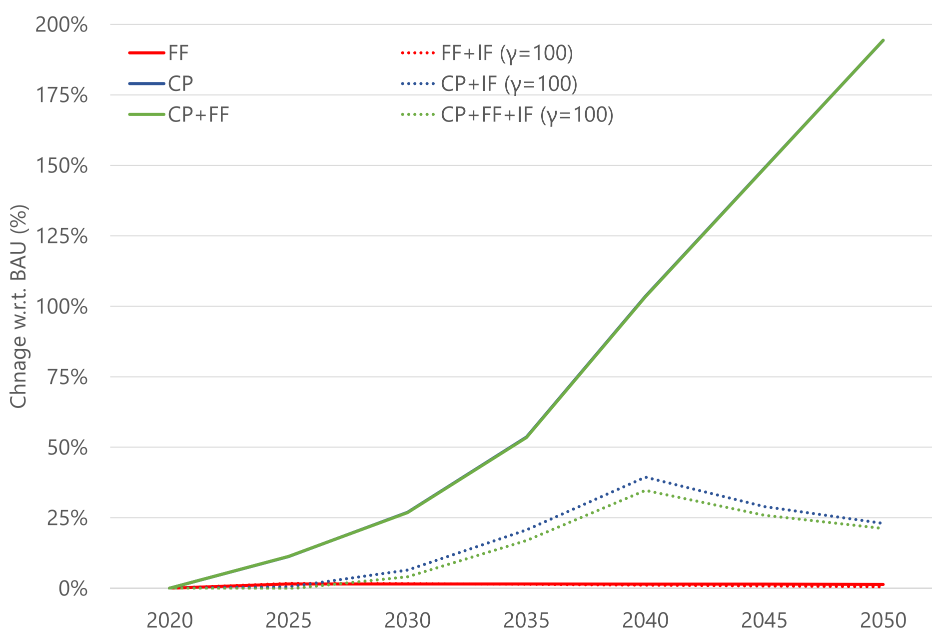


Fig. A.6. Change in price of electricity from FF w.r.t. BAU (EU27). *Note*: own elaboration on GDynEP results.

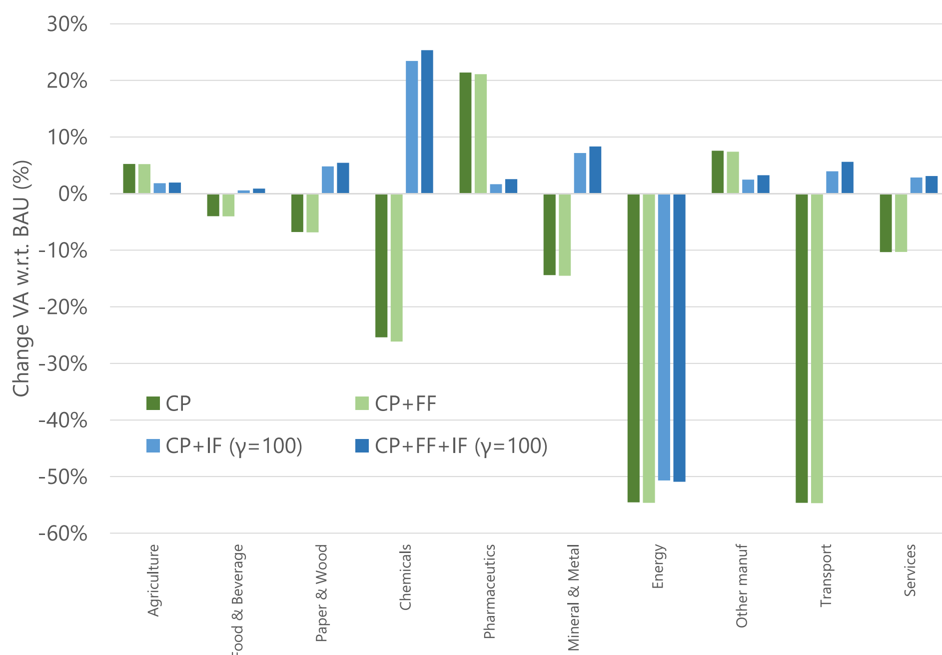


Fig. A.7. Change in sectoral VA w.r.t. BAU (EU27). *Note*: own elaboration on GDynEP results.

Table A.1
GDynEP aggregation of endowment sector.

No.	Model code	Description	GTAP endowment code
1	Land	Land	Land
2	SkLab	Skilled labour force	tech_aspros, off_mgr_pros
3	UnSkLab	Unskilled labour force	service_shop
4	Capital	Capital	Capital
5	NatRes	Natural resources	NatlRes

Note: aggregation run with FlexAgg utility.

Table A.2
GDynEP aggregation of production sector.

No.	Model code	Description	GTAP sector code
1	rice	Rice	pdr, pcr
2	cer	Cereal grains	wht, gro
3	o_prim	Other primary	osd, pfb, ocr, wol
4	veg	Vegetable and fruit	v_f
5	liv	Livestock	ctl, oap
6	r_meat	Rumin meat	cmt
7	o_meat	Other meat	omt
8	fish	Fishery	fsh
9	dai	Dairy	rmk, mil
10	bev_t	Beverages and tobacco	b_t
11	food	Processed food	vol, ofd
12	sug	Sugar	c_b, sgr
13	tex	Textile	tex, wap, lea
14	pap	Paper and publishing	ppp
15	wood	Wood	frs, lum
16	chem	Chemical	chm, rpp
17	phar	Pharmaceutics	bph
18	min	Mineral	nmm, oxt
19	mot	Motor vehicles	mvh
20	tr_eq	Transport equipment	otn
21	elect	Electronics and electronic equipment	ele, eeq
22	metal	Metal product	fmp
23	mach	Machinery	ome
24	fer	Ferrous metal	i_s, nfm
25	o_man	Other manufacturing	omf
26	coal	Coal	coa
27	oil	Oil crude	oil
28	gas	Natural gas and LNG	gas, gdt
29	ely_f	Electricity from fossil fuels	NuclearBL, CoalBL, GasBL, OilBL, OilP, GasP
30	ely_rw	Electricity from renewables	HydroBL, HydroP, OtherBL, SolarP, WindBL
31	oil_p	Oil products	p_c
32	r_transp	Road and railway transport	otp
33	a_transp	Air transport	atp
34	w_transp	Water transport	wtp
35	serv1	Service private	TnD, ofi, ins, rsa, obs, whs, cmn, trd, cns, afs
36	serv2	Service public	ros, osg, hht, edu, wtr, dwe

Note: aggregation run with FlexAgg utility.

Table A.3
GDynEP regional aggregation.

No	Model code	Description	GTAP code region
1	AFDC	Africa developing countries	cmr, zwe, bwa, nam
2	AFEX	Africa energy exporters	egy, xnf
3	AFNorth	Africa North	mar, tun
4	AS1	Rest of East Asia	aze, geo, isr, jor, xws
5	AS2	Asian countries (rest of)	twn, xea, brn, khm, sgp, tha
6	ASEX	MiddleEast & Asian energy exp.	kaz, bhr, irn, kwt, omn, qat, sau, are
7	Australia	Australia	aus
8	Brazil	Brazil	bra
9	Canada	Canada	can
10	ColPeru	Colombia and Peru	col, per
11	China	China plus Hong Kong	chn, hkg
12	EBA	Everything but arms countries	lao, xse, bgd, npl, xsa, ben, bfa, gin, sen, tgo, xwf, xac, eth, mdg, mwi, moz, rwa, tza, uga, zmb, xec, xsc
13	EFTA	EFTA countries	xna, che, nor, xef
14	EU27	European Union members	aut, bel, bgr, hrv, cyp, cze, dnk, est,fin, fra, deu, grc, hun, irl, ita, lva, ltu, lux, mlt, nld, pol, prt, rou, svk, svn, esp, swe
15	GSP	GSP countries	xoc, vnm, tjk, xsu, civ, gha, nga, xcf, ken, mus
16	GSPplus	GSP plus countries	mng, pak, lka, bol, kgz, arm
17	India	India	ind
18	Indonesia	Indonesia	idn
19	Japan	Japan	jpn
20	Korea	South Korea	kor
21	Malaysia	Malaysia	mys
22	Mexico	Mexico	mex
23	NewZealand	New Zealand	nzl
24	Philippines	Philippines	phl
25	RestAndean	Rest of Andean countries	chl, ecu, ven, xtw
26	RestEurope	Rest of Europe	alb, blr, ukr, xee, xer
27	RestLatAmer	Rest of Latin America	xsm, cri, gtm, hnd, nic, pan, slv, xca, dom, jam, pri, tto, xcb
28	RestMercosur	Rest of Mercosur	arg, pry, ury
29	Russia	Russian Federation	rus
30	SouthAfrica	South Africa	zaf
31	Turkey	Turkey	tur
32	UK	UK	gbr
33	USA	USA	usa

Note: aggregation run with FlexAgg utility.

Table A.4
Data sources and reference scenario for BAU calibration.

Variable	2014–2020	2021–2050
Population	GTAP10 Eurostat WDI	GECO Reference scenario EUREF for EU countries UN world population prospects
GDP	GTAP10 Eurostat WDI	GECO Reference scenario EUREF for EU countries SSP2 data
Skilled Labour	GTAP10 ILO CEPII	GECO Reference scenario EUREF for EU countries CEPII
Unskilled Labour	GTAP10 ILO CEPII	GECO Reference scenario EUREF for EU countries CEPII
CO2 emissions	GTAP-E 2014 Eurostat IEA&WDI	GECO Reference scenario EUREF for EU countries SSP2 data
Non-CO2 emissions (CH4, N2O, fluorinated gases)	GTAP-NCO2V10a Eurostat IEA&WDI	GECO Reference scenario EUREF for EU countries SSP2 data
Electricity production (RW and FF)	GTAP Power 2014 Eurostat IEA&WDI	GECO Reference scenario EUREF for EU countries SSP2 data

Note: EUREF is the European Commission Reference scenario (Capros et al., 2016). GECO is the Global Energy and Climate Outlook from the EU (Keramidas et al., 2021). WDI stands for World Development Indicators from the World Bank. Projections for regions outside the EU27 and the UK have been adjusted with the SSP2 "Middle of the road" scenario (database hosted by the IIASA Energy Program at https://tntcat.iiasa.ac.at/SspDb).

Table A.5
Carbon price in EU27 (USD per ton CO2).

Scenario	2025	2030	2035	2040	2045	2050
CP	62	66	78	227	1197	4611
CP+IF ($\gamma = 50$)	31	35	88	148	686	2244
CP+IF ($\gamma = 100$)	26	31	40	112	504	1580
CP+FF	51	65	78	227	1197	4610
CP+FF+IF ($\gamma = 50$)	35	41	50	144	674	2214
CP+FF+IF ($\gamma = 100$)	26	29	36	108	494	1558

Note: own elaboration on GDynEP results.

Table A.6
Financial support for CETs in EU27 (constant 2020 mln SD).

Scenario	2025	2030	2035	2040	2045	2050
FF+IF ($\gamma = 50$)	23,672	18,177	13,802	10,625	8318	6533
FF+IF ($\gamma = 100$)	47,043	35,693	26,839	20,510	15,971	12,495
CP+IF ($\gamma = 50$)	45,795	42,583	78,989	92,616	194,414	248,752
CP+IF ($\gamma = 100$)	71,210	69,359	72,250	140,710	286,001	350,352
CP+FF+IF ($\gamma = 50$)	70,416	61,665	55,420	97,318	194,740	246,755
CP+FF+IF ($\gamma = 100$)	115,153	95,588	85,653	149,025	287,476	347,870

Note: own elaboration on GDynEP results.

Table A.7
GDP change w.r.t. BAU in EU27.

Scenario	2025	2030	2035	2040	2045	2050
FF	−0.14%	−0.22%	−0.23%	−0.21%	−0.17%	−0.12%
FF+IF 50RD	0.15%	0.31%	0.44%	0.55%	0.60%	0.61%
FF+IF 100RD	0.46%	0.85%	1.16%	1.35%	1.42%	1.38%
CP	−0.40%	−1.33%	−2.45%	−4.25%	−7.86%	−13.1%
CP+IF 50RD	0.34%	0.42%	0.44%	0.12%	−0.51%	−1.28%
CP+IF 100RD	1.24%	1.89%	2.20%	2.32%	2.24%	1.85%
CP+FF	−0.51%	−1.46%	−2.59%	−4.36%	−7.94%	−13.1%
CP+FF+IF 50RD	0.62%	0.87%	0.87%	0.60%	−0.05%	−0.88%
CP+FF+IF 100RD	1.27%	2.09%	2.55%	2.77%	2.68%	2.22%

Note: own elaboration on GDynEP results.

Table A.8
Energy bill as share of GDP in EU27.

Scenario	2025	2030	2035	2040	2045	2050
BAU_FR	4.27%	3.42%	2.74%	2.24%	1.87%	1.55%
FF	4.12%	3.32%	2.68%	2.2%	1.84%	1.54%
FF+IF (γ = 50)	4.06%	3.23%	2.57%	2.1%	1.74%	1.45%
FF+IF (γ = 100)	4.01%	3.15%	2.48%	2.01%	1.65%	1.37%
CP	3.82%	2.74%	1.96%	1.28%	0.66%	0.42%
CP+IF (γ = 50)	3.96%	2.91%	1.87%	1.18%	0.52%	0.24%
CP+IF (γ = 100)	3.7%	2.61%	1.83%	1.13%	0.49%	0.22%
CP+FF	3.77%	2.72%	1.95%	1.27%	0.66%	0.42%
CP+FF+IF (γ = 50)	3.69%	2.63%	1.85%	1.16%	0.52%	0.24%
CP+FF+IF (γ = 100)	3.63%	2.57%	1.81%	1.12%	0.48%	0.21%

Note: own elaboration on GDynEP results.

Table A.9
Energy intensity in EU27 (toe per constant 2020 mln USD).

Scenario	2025	2030	2035	2040	2045	2050
BAU_FR	107	90	75	65	57	50
FF	103	87	73	63	55	49
FF+IF (γ = 50)	102	85	71	61	53	47
FF+IF (γ = 100)	101	83	69	59	52	46
CP	96	74	57	42	27	22
CP+IF (γ = 50)	100	77	55	39	24	17
CP+IF (γ = 100)	94	71	54	38	22	16
CP+FF	95	73	57	41	27	22
CP+FF+IF (γ = 50)	93	71	54	38	23	17
CP+FF+IF (γ = 100)	92	69	53	37	22	16

Note: own elaboration on GDynEP results.

Table A.10
RW as share of electricity consumption in EU27.

Scenario	2025	2030	2035	2040	2045	2050
BAU_FR	41.3%	46.5%	50.5%	54.9%	60.1%	64.7%
FF	41.6%	46.7%	50.7%	55.2%	60.3%	64.9%
FF+IF (γ = 50)	42.2%	48.0%	52.4%	57.2%	62.6%	67.3%
FF+IF (γ = 100)	42.9%	49.2%	54.1%	59.2%	64.8%	69.6%
CP	43.8%	50.9%	59.7%	67.1%	71.5%	76.6%
CP+IF (γ = 50)	43.8%	51.1%	60.0%	68.2%	73.7%	80.0%
CP+IF (γ = 100)	43.9%	51.1%	60.2%	68.4%	73.9%	80.0%
CP+FF	43.8%	50.9%	59.7%	67.1%	71.5%	76.6%
CP+FF+IF (γ = 50)	43.8%	51.1%	60.1%	68.2%	73.7%	80.0%
CP+FF+IF (γ = 100)	43.9%	51.2%	60.2%	68.5%	73.9%	80.0%

Note: own elaboration on GDynEP results.

Table A.11
Production cost index, electricity from RW in EU27.

Scenario	2025	2030	2035	2040	2045	2050
BAU_FR	78.47	66.20	59.13	52.34	44.12	38.40
FF	75.83	65.03	53.37	49.02	47.46	40.35
FF+IF (γ = 50)	71.89	59.48	47.45	40.95	34.54	28.30
FF+IF (γ = 100)	69.66	56.65	44.60	37.57	30.56	24.96
CP	78.43	66.27	59.27	52.49	44.27	38.53
CP+IF (γ = 50)	75.97	62.46	54.62	47.51	39.49	34.00
CP+IF (γ = 100)	73.62	58.94	50.45	43.15	35.40	30.17
CP+FF	75.81	64.96	53.31	48.97	47.44	40.36
CP+FF+IF (γ = 50)	71.66	58.82	46.72	40.31	34.14	26.72
CP+FF+IF (γ = 100)	69.25	55.68	43.60	36.74	30.10	23.54

Note: own elaboration on GDynEP results.

Table A.12
Carbon leakage rate with EU27 unilateral climate policy.

Scenario	2025	2030	2035	2040	2045	2050
FF	51.01%	45.03%	38.18%	31.3%	25.28%	20.09%
FF+IF ($\gamma = 50$)	23.21%	7.06%	−5.95%	−14.38%	−19.7%	−22.54%
FF+IF ($\gamma = 100$)	13.14%	−6.84%	−21.06%	−29.1%	−33.26%	−34.31%
CP	27.08%	31.18%	35.8%	38.91%	41.63%	51.39%
CP+IF ($\gamma = 50$)	17.36%	14.29%	13.34%	13.42%	12.13%	9.87%
CP+IF ($\gamma = 100$)	9.12%	2.29%	−1.21%	−0.35%	−0.26%	−2.82%
CP+FF	29.26%	32.02%	36.21%	39.09%	41.78%	51.5%
CP+FF+IF ($\gamma = 50$)	17.12%	11.33%	8.99%	9.72%	9.65%	8.07%
CP+FF+IF ($\gamma = 100$)	9.91%	0.19%	−4.73%	−3.7%	−2.6%	−4.57%

Note: own elaboration on GDynEP results.

Table A.13
Normalised indicators for policy mix evaluation (EU27 in 2050).

Scenario	GDP_var	Ene_bill	Ene_eff	RW_sh	RW_cost	Carb_leak
FF	0.848	0.000	0.000	0.000	0.088	0.366
FF+IF ($\gamma = 50$)	0.895	0.067	0.052	0.160	0.324	0.863
FF+IF ($\gamma = 100$)	0.945	0.124	0.097	0.311	0.547	1.000
CP	0.003	0.840	0.805	0.775	0.000	0.001
CP+IF ($\gamma = 50$)	0.772	0.980	0.957	0.997	0.666	0.485
CP+IF ($\gamma = 100$)	0.976	0.998	0.996	1.000	0.895	0.633
CP+FF	0.000	0.840	0.805	0.775	0.000	0.000
CP+FF+IF ($\gamma = 50$)	0.798	0.983	0.962	0.998	0.771	0.506
CP+FF+IF ($\gamma = 100$)	1.000	1.000	1.000	0.999	1.000	0.653

Note: own elaboration on GDynEP results.

Table A.14
Price change w.r.t. BAU in energy commodities subject to direct carbon taxation.

Fossil fuel by scenario	2025	2030	2035	2040	2045	2050
Coal						
FF	3.89%	3.80%	4.02%	4.45%	4.76%	4.90%
FF+IF ($\gamma = 100$)	3.15%	2.83%	3.15%	3.71%	4.14%	4.36%
CP	108.10%	220.49%	348.16%	679.98%	2270.44%	7516.26%
CP+IF ($\gamma = 100$)	62.63%	123.32%	193.58%	365.48%	1067.34%	2958.06%
CP+FF	91.69%	159.06%	242.99%	464.71%	1380.36%	3850.51%
CP+FF+IF ($\gamma = 100$)	45.96%	97.26%	161.17%	329.99%	1027.20%	2908.07%
Crude oil						
FF	2.98%	3.05%	3.51%	4.21%	4.72%	4.91%
FF+IF ($\gamma = 100$)	2.37%	2.20%	2.71%	3.51%	4.12%	4.37%
CP	125.58%	178.77%	230.26%	345.11%	759.93%	1681.36%
CP+IF ($\gamma = 100$)	73.98%	105.13%	136.48%	203.21%	415.59%	817.35%
CP+FF	106.36%	161.68%	213.98%	328.13%	733.84%	1630.23%
CP+FF+IF ($\gamma = 100$)	54.27%	83.93%	114.34%	181.80%	393.36%	787.55%
Natural gas						
FF	3.35%	3.36%	3.42%	3.50%	3.56%	3.58%
FF+IF ($\gamma = 100$)	3.07%	2.89%	2.78%	2.79%	2.83%	2.87%
CP	22.39%	46.42%	75.55%	163.22%	640.02%	2509.13%
CP+IF ($\gamma = 100$)	12.72%	24.96%	39.95%	83.40%	288.78%	959.13%
CP+FF	21.60%	45.23%	74.56%	162.54%	639.98%	2512.82%
CP+FF+IF ($\gamma = 100$)	11.82%	21.90%	35.14%	76.78%	278.33%	940.99%
Oil products						
FF	7.82%	7.75%	7.68%	7.59%	7.41%	7.16%
FF+IF ($\gamma = 100$)	7.32%	7.06%	6.96%	6.86%	6.66%	6.38%
CP	16.51%	41.22%	79.04%	191.15%	812.89%	3425.64%
CP+IF ($\gamma = 100$)	8.74%	21.70%	41.94%	98.69%	367.43%	1284.27%
CP+FF	21.37%	45.17%	82.56%	194.68%	817.94%	3437.25%
CP+FF+IF ($\gamma = 100$)	13.36%	23.73%	41.19%	94.89%	358.31%	1263.96%

Note: own elaboration on GDynEP results.

Table A.15
Percentage change (+/−) in GDP for EU due to variation by +/−2,5,10% of Armington elasticities parameters ESUBD and ESUBM in policy scenario $CP + IF(\gamma = 100\%)$.

QGDP	2025	2030	2035	2040	2045	2050
+/−2%	0.000%	0.000%	0.001%	0.001%	0.001%	0.005%
+/−5%	0.006%	0.015%	0.019%	0.026%	0.021%	0.036%
+/−10%	0.012%	0.030%	0.034%	0.043%	0.036%	0.040%

Note: own elaboration on GDynEP results.

Table A.16
Average percentage change (+/−) in VXWFOB and average MN/SD ratio for 2025–2050 for EU due to variation by +/−2,5,10% of Armington elasticities parameters ESUBD and ESUBM in policy scenario $CP + IF(\gamma = 100\%)$.

	+/−2%	+/−2%	+/−5%	+/−5%	+/−10%	+/−10%
	Mean_ch	MN/SD ratio	Mean_ch	MN/SD ratio	Mean_ch	MN/SD ratio
1 rice	0.32%	169.42	0.71%	77.15	1.34%	41.98
2 cer	0.07%	1079.7	0.18%	394.3	0.25%	285.97
3 o_prim	0.08%	1443.54	0.19%	568.89	0.35%	306.15
4 veg	0.05%	1207.94	0.11%	506.49	0.13%	437.97
5 liv	0.1%	516.78	0.25%	202.33	0.2%	308.15
6 r_meat	0.27%	340.06	0.5%	127.08	0.83%	68.69
7 o_meat	0.34%	235.63	0.65%	96.84	1.19%	51.72
8 fish	0.07%	1012.32	0.18%	385.5	0.31%	323.43
9 dai	0.36%	169.48	0.9%	70.43	0.54%	96.1
10 bev_t	0.08%	1090.53	0.21%	543.92	0.17%	624.4
11 food	0.19%	274.21	0.48%	111.93	0.91%	58.88
12 sug	0.32%	158.47	0.68%	95.06	1.32%	46.94
13 tex	0.62%	89.24	1.27%	43.27	2.67%	22.24
14 pap	0.17%	795.88	0.36%	195.72	0.72%	88.4
15 wood	0.33%	160.22	0.86%	62.42	1.3%	39.56
16 chem	0.5%	104.43	1.6%	36.48	2.86%	19.46
17 phar	0.28%	1080.36	0.56%	441.25	1.4%	90.91
18 min	0.12%	569.19	0.3%	199.93	0.59%	96.3
19 mot	0.36%	262.61	0.77%	111.95	1.55%	54.72
20 tr_eq	1.1%	123.75	2.47%	39.11	4.58%	19.36
21 elect	1%	54.04	2.78%	21.1	4.92%	10.95
22 metal	1.46%	40.68	3.47%	15.96	6.89%	8.11
23 mach	2.25%	31.27	3.78%	15.59	7.28%	7.33
24 fer	0.4%	126.04	0.96%	52.96	1.78%	28.46
25 o_man	2.63%	23.95	5.28%	11.91	7.55%	7.17
26 coal	0.26%	251.5	1.39%	182.96	2.07%	170.74
27 oil	0.17%	328.44	0.41%	150.74	0.72%	114.41
28 gas	0.29%	181.55	0.72%	78.73	0.71%	71.41
29 oil_pcts	0.24%	246.25	0.39%	147.85	0.8%	72.66
30 ely_f	0.56%	95.5	1.53%	98.49	2.84%	99.09
31 ely_rw	1.1%	61.57	1.63%	33.12	1.12%	77.64
32 r_transp	0.29%	188.9	0.66%	79.75	1.01%	61.14
33 a_transp	0.2%	279.6	0.59%	100.88	1.03%	67.71
34 w_transp	0.1%	534.59	0.31%	168.39	0.39%	146.28
35 serv1	0.11%	765.79	0.3%	972.1	0.66%	201.09
36 serv2	0.36%	152.17	0.9%	60.47	1.89%	29.47

Note: own elaboration on GDynEP results. For each value in parameter change we report two columns: the first represents the average percentage change across 2025–2050 w.r.t. the mean value assumed by the variable; the second is the average values across 2025–2050 of the mean to standard deviation ratio (MN/SD).

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2023.106524.

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