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Research article

Evaluating policy mix strategies for the energy transition using an agent-based macroeconomic model

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ABSTRACT

Climate policy analysis has traditionally focused on evaluating individual policy instruments or comparing different instruments, but an increasing number of scholars are emphasizing the advantages of employing a policy mix. In this study, we investigate the combination of a carbon tax and a feed-in tariff policy using the Eurace agent-based model, addressing two primary issues: understanding the interactions between individual instruments within the policy mix and identifying the optimal combination to facilitate the energy transition. To evaluate the effects of each policy, we first examine policies in isolation and then analyse their combined impact. The results indicate that the feed-in tariff policy generally outperforms the carbon tax when considering both climate and economic indicators. Furthermore, when physical climate feedback is not included in the model, the combined policy approach outperforms the individual policies. However, for higher values of the carbon tax and feed-in tariff, the benefits of the policy mix decrease, and this reduction becomes more pronounced when physical climate feedback is considered.

1. Introduction

According to IPCC (2018), the remaining carbon budget to limit warming to 1.5 degrees with probability 50% was 580 $GtCO_2$. This budget will be depleted by about 2032 at a constant 2017 emissions rate. The consensus on the urgency of climate action has grown in the last decades due to both increased evidence of climate change and the rise of recent protest movements such as Fridays For Future[1] or Extinction Rebellion.[2] Many countries have committed to reaching the net zero emission target by 2050 to respond to climate challenges. According to IEA (2021), these commitments cover about 70% of global GDP and CO_2 emissions (although only a tiny fraction is explicitly planned). However, the pathway to transforming proposals into implementable measures remains a topic of ongoing debate in the climate change economics literature.

Most economists believe carbon pricing is the most efficient option to reduce GHGs emissions (Nordhaus, 2007; Weitzman, 2014; Tol, 2017). Under the idealized condition where climate change is the only externality, imposing a price on emissions equal to their marginal cost is sufficient to restore market efficiency (Pigou, 1920). This argument advocates using a single policy, as employing multiple instruments may lead to redundancy and efficiency losses. Consequently, climate change economic research has focused mainly on analysing or comparing individual policies rather than exploring their combined effects, see, e.g. Lehmann (2012).

Nevertheless, a growing number of works point out a policy mix's superiority when a more realistic representation of the economy is used. The Tinbergen rule (Tinbergen, 1952) suggests that achieving multiple climate mitigation objectives requires multiple instruments. According to the second-best theory (Lipsey and Lancaster, 1956), real economies are characterized by multiple market, government, and behavioural failures; targeting only one failure may result in an outcome worse than doing nothing. However, using multiple tools only sometimes leads to better results, and the purpose of this work is to precisely understand when a combination of instruments performs better than isolated tools.

To carry out this work, we believe that the so-called agent-based models (ABM) are more suitable than the more commonly used models to analyse climate policy (IPCC, 2014), namely Integrated Assessment Models (IAM). Indeed, IAMs consist of several interacting parts, including a climate module and an economic module based on classical assumptions such as the representative agent hypothesis or perfect

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[1] https://fridaysforfuture.org/.
[2] https://rebellion.global/why-rebel/.

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and complete information. According to Farmer et al. (2015), IAMs cannot properly represent uncertainties intrinsic to real economies and associated with the climate change impact, as they do not account for the heterogeneity of agents and intra-sector interactions. Additionally, IAMs ignore out-of-equilibrium dynamics and path dependency, and all these factors are relevant for evaluating the distributional impacts of both policies under study.

Adopting overly simplistic assumptions can pose challenges when comparing policy mixes to single policies. For example, consider a model that overlooks at least one crucial feature of its target real economy. Suppose that, according to this model, a climate policy effectively reduces emissions and combining it with another policy results in redundancy. Consequently, the policy mix is expected not to outperform its components. However, if the analysis is repeated using a model that includes the previously neglected factor (in line with second-best theory), the outcome of the first isolated policy may be worse than the do-nothing scenario, and the policy mix could outperform its components.

Agent-based models (ABMs) offer an alternative to the limitations of Integrated Assessment Models (IAMs). Unlike IAMs, ABMs explicitly represent individual agents and their interactions. Rather than aggregating agents into a single representative entity, ABMs incorporate the heterogeneity of agent characteristics and intrasector interactions. By specifying agent parameters, interaction rules, and initial conditions, ABMs simulate the system's evolution through computer simulations. These models avoid the equilibrium assumptions inherent in IAMs and address previously discussed drawbacks. For a more comprehensive discussion on ABM vs. representative agent models, interested readers can refer to Fagiolo and Roventini (2017), Dosi and Roventini (2019), Balint et al. (2017) and Teglio (2024).

Since there is no universal rule for predicting which policy mixes will outperform their components, research on policy combinations must proceed on a case-by-case basis. The goal is to identify commonalities that can inform the development of a more general theory. Our contribution to this field involves examining the combination of a carbon tax and a feed-in tariff using the EURACE agent-based model (Cincotti et al., 2010; Raberto et al., 2012; Teglio et al., 2019). We extended the model by incorporating a climate module to capture economy-climate interactions and calibrated it using the global economy as a reference. Our approach involves analysing each policy in isolation and then studying their joint effects with the climate module activated and deactivated.

The remainder of the paper is organized as follows. The next section provides an overview of the existing literature on policy mixes. Section 3 outlines the additions made to the EURACE model in this study. In Section 4, we then delve into the procedure used to establish the initial conditions and parameters. Section 5 presents the results of our computational experiments. Conclusions and policy implications are discussed in the last section.

2. Review of the literature

This section aims to clarify the paper's position within the existing literature on climate policy mix and to outline how it can effectively address specific gaps in the field. In recent years, several empirical studies have considered combinations of climate policies, seeking to understand their potential benefits. However, these studies are highly heterogeneous, often focusing on different countries or groups of countries and various industrial sectors. In addition, they examine a diverse range of climate policies, both in terms of the number of policies selected and their types. Li and Taeihagh (2020) investigate the policy mix employed by the Chinese government to facilitate its energy transition, demonstrating how the diversity and number of policy instruments in the mix have continuously changed over time, making it difficult to assess the effectiveness of individual combinations. Zha et al. (2023) study the impact of renewable energy policies and their mixes on the carbon intensity of the power sector using China's provincial panel data, finding that the feed-in tariff combined with the trading of carbon emissions has positive synergistic effects and no policy mix exhibits negative synergies. Other studies examine the effects of policy mixes in specific sectors, such as the pulp and paper industry in Scordato et al. (2018). However, these studies are challenging to generalize in a broader macroeconomic context.

Costantini et al. (2017) examine a dataset covering 23 OECD countries that combines the complete set of policies in the energy efficiency domain for the residential sector. They observe that the simple addition of an indiscriminate number of simultaneous policy instruments may reduce the effectiveness of the policy mix without unveiling the sources of potential conflicting effects.

As noted in Howlett and del Rio (2015), existing studies of policy mixes face packages that are increasingly complex and the cumulative impact of empirical studies could have been better. The authors propose a taxonomy to assess the validity and applicability of policy mixes. Following this line, Schmidt and Sewerin (2019) conceptualize and measure the characteristics of policy mixes over time as a precondition to develop meaningful policy design prescriptions. They tested 522 policies in nine countries, showing that the dynamics of the policy mix of countries vary strongly on some dimensions but not so much on others.

Van den Bergh et al. (2021) propose an interesting review of the benefits and drawbacks of combining adoption subsidies with carbon pricing. A drawback is that overall consumption is encouraged compared to an equivalent carbon tax, given that low-carbon options usually involve carbon emissions during production and use (see D'Haultfœuille et al. (2014) for an example in the French car market[3]). However, faster low-carbon diffusion introduces uncertainty about the net effect on emissions in the long run. An advantage is that, instead of imposing a high carbon tax to encourage low-carbon choices (which has been politically challenging), one can combine a lower carbon tax with a subsidy, which may be more politically acceptable. Additionally, the system can be self-financed, with the subsidy funded from fee revenues.

This overview highlights the inherent challenges of deriving general insights about the benefits of policy mixes from empirical studies, which are often very specific. Therefore, it is essential to complement the empirical analyses with theoretical models capable of capturing the complexity and multidimensionality of these phenomena. Adopting a multiple instrument analysis is relevant because countries have other objectives beyond those of climate policies, e.g. the SDGs,[4] which may conflict or align with climate objectives.

As summarized by Bouma et al. (2019), the justifications of a policy mix in the literature are the existence of multiple objectives, the presence of additional externalities, or more generally of market failures. From a neoclassical economic perspective, externalities, market power, and imperfect information are sources of market failure (Bator, 1958; Randall, 1983). In this context, Integrated Assessment Models (IAMs) are the most commonly used models, although their level of abstraction does not always allow for explicit representation of various climate policies. These models typically represent policies through a carbon price, which in an ideal world would align with the social cost of greenhouse gas emissions (Roelfsema et al., 2022). For this reason, analysing a specific policy mix using IAMs can be challenging.[5] Alternatively, some CGE models or partial equilibrium models study

[3] Less polluting cars benefited from a price reduction, whereas the most polluting ones were subject to taxation. Durrmeyer (2021) also finds redistributive effects that interact with emission reductions through consumption.

[4] UN Sustainable Development Goals; https://sdgs.un.org/goals.

[5] It is not always straightforward to express policies as additional constraints in the utility maximization of economic agents, as IAMs typically do.

policy mixes. For example, Cardenas et al. (2016) use a system dynamics model to analyse carbon tax, feed-in tariffs, and combinations of the two. Their study concludes that (i) the carbon tax reduces the installed fossil fuel energy production capacity, (ii) the feed-in tariffs increase investments in green technologies without hindering fossil fuel investments, and (iii) a mix of both achieves both objectives without significantly impacting energy prices. Gillich et al. (2020), on the other hand, employs a brownfield screening curves model to study the mix of three policies: coal phase-out (legally banning coal use), carbon price, and incentives to increase renewable technology capacity. They find that coal phase-out significantly affects emissions contributions from various technologies, and this effect diminishes with higher carbon prices or incentives. Finally, Chateau et al. (2024) use a CGE model to compare policies such as carbon tax, subsidies, feebates, and direct regulation applied to the electricity and energy-intensive trade-exposed sectors. Feebates can be interpreted as a mix of carbon tax and subsidies, where companies finance green activities through carbon tax revenues. The authors analyse climate policies for interconnected economies, each with its climate strategy, studying scenarios where each country adopts a different policy approach.

However, the concept of market failure, implicit in IAMs models, is based on the existence of equilibrium, which is a strong and unrealistic hypothesis. (see Kirman (2016)). Therefore, a policy that appears optimal according to an equilibrium model may not be effective when implemented in real systems due to out-of-equilibrium dynamics. We argue that the task of a climate policy analysis is not to find the condition under which, given the multiple failures, the market equilibrium is restored, but to understand the performance of the policy under analysis in a complex economy that continually evolves out-of-equilibrium.

To this end, this study employs an agent-based model (ABM), which explicitly represents heterogeneous agents, their interactions, and their environment. For a comprehensive review of the literature on the potential of ABMs to provide insight into complex energy transition dynamics, see Hansen et al. (2019), for a conceptual discussion of ABM in macroeconomics, see Cincotti et al. (2022).

ABMs have been used to study the climate change problem and have frequently produced results that complement traditional approaches (Balint et al., 2017; Castro et al., 2020). Models with endogenous diffusion or innovation have been used to study carbon pricing policies (Haas and Jaeger, 2005; Lamperti et al., 2018) or to compare carbon pricing with incentives (Robalino and Lempert, 2000). Unlike traditional IAMs, ABMs can explicitly represent the credit sector and are more appropriate for studying financial and monetary policies (Mazzocchetti et al., 2018; Raberto et al., 2019; Lamperti et al., 2021). Furthermore, ABMs allow for a more realistic representation of climate damage.

The majority of ABM studies on climate change deal with single-instrument analysis or with the comparison of isolated instruments, see, e.g. Safarzyńska and van den Bergh (2017), while to the best of our knowledge only a few works, in particular, Rengs et al. (2020) and Lamperti et al. (2021), investigate the mix of 2 or more policies.

Rengs et al. (2020) combine a carbon tax with alternative uses of its revenues, i.e. subsidies for green innovation, a price subsidy to consumers for less carbon-intensive products, and green government procurement, but do not explicitly model the energy sector, the accumulation of renewable energy capacity and the direct impact of the energy transition on the economy. On the contrary, all these elements are central to our study. Lamperti et al. (2021) explore the effects of three financial instruments in different combinations, which consistently lead to emission reductions but often produce results with complementary benefits that are challenging to compare and prioritize.

Finally, we summarize the innovative features of our study with respect to the previous literature.

- The effects of policies depend on the out-of-equilibrium interaction among all the economic agents involved in a more realistic process where price signals are interpreted differently by various agents.
- Multiple policy objectives are considered, tackling the challenge of interpreting and prioritizing them without a given preference structure. This issue is crucial because one of the hypothesized advantages of mixes over individual policies is their ability to achieve diverse objectives concurrently.
- The process of sizing the energy sector is innovative, as the model accurately reflects the relationships between physical and economic quantities of the real world.
- There exists a government agent, explicitly modelled, whose deficit and debt evolve endogenously, also according to climate intervention. This affects, in turn, the macroeconomic dynamics.
- The absence of budget neutrality does not constrain the combinations of carbon tax and feed-in tariff that the model can explore.

3. Overview of the model

For the purpose of this study, an enhanced version of the Eurace agent-based macroeconomic model has been developed to include an endogenous fossil fuel sector, GHGs emissions related to fossil fuels combustion by the energy sector, a climate module that based on the cumulated emissions gives an average temperature increase and consequent damages to the capital of production firms, and an enriched capital sector characterized by both a brown and a green capital good producer, where the latter producers capital goods with decreasing energy intensity.

The baseline Eurace model[6] is a stock-flow consistent agent-based macroeconomic model that includes the most relevant economic sectors, namely households, consumption goods producers (CGPs), a capital good producer (KGP), banks, a government and a central bank. Agents interact in decentralized and centralized markets and decisions are based on heuristics, adaptive expectations and limited information.

Households play multiple roles as investors, workers and consumers. Their financial decisions, such as asset allocation and consumption budgeting, are crucial for the model's functioning. As traders, they distribute their financial wealth among various assets, including residential dwellings,[7] government bonds, and stocks issued by CGPs, the KGP and banks. Households' role as employees is to supply labour to CGPs, the KGP, and the government in exchange for a monthly wage, while as investors, they receive returns on bonds and stocks in the form of coupons and dividends. Unemployed households receive a monthly unemployment benefit from the government and seek a new job in the labour market; when entering the labour market to evaluate pending job offers, they are randomly queued to apply to the set of available jobs with the highest wages, provided that they are higher than the reservation wage. Given total income, a household's consumption budget is determined by a target wealth-to-income ratio, in line with the buffer-stock saving behaviour theory, see Carroll (2001). Households are randomly queued in the consumption goods market, and the selection of the particular producer to buy from is probabilistic, where probability depends on prices.

CGPs produce and sell to households a homogeneous good. They demand both labour and capital as factors of production. In particular, each CGP estimates the expected demand based on past sales and determines the labour and capital demand. If the number of workers needed to fulfil the planned production is lower than the current employment level, the CGP fires the extra workers. Otherwise, it enters

[6] See Teglio et al. (2019) for a detailed description of the baseline model.

[7] The housing market in the Eurace model and its impact on the economy has been discussed in Ozel et al. (2019).

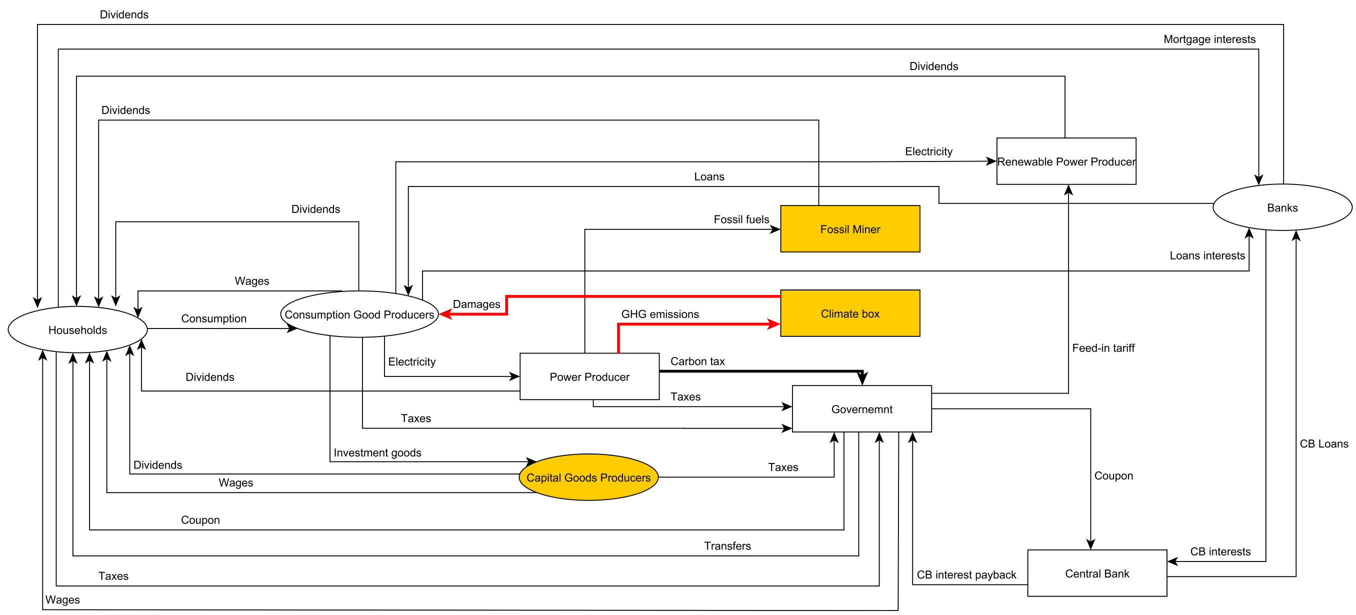

Fig. 1. The figure shows a graphical representation of the enhanced version of the Eurace model used in this work. Ellipses or rectangles represent agent classes, while arrows represent current account monetary flows. Rectangles are used for classes containing only one agent, whereas ellipses represent classes with multiple agents. Yellow boxes refer to newly introduced agents. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the labour market, posting new vacancies. Each CGP sets an initial wage offer, and if it cannot hire all the workers needed, it increases the initial offer by a fixed parameter. The investment decision depends on the planned production; in particular, each CGPS determines a desired level of investment by comparing the net present value of future additional cash flows with the current cost of investment. CGPs try to finance all production costs following the pecking order theory, i.e. according to a priority order given first by retained earnings, then by debt, and finally by issuing new shares. If CGPs are rationed in the credit market, they revise the production plan to align their total financial needs with the available resources in the credit and financial markets. In the case of insolvency, CGPs run into bankruptcy with a related loan write-off and a corresponding equity loss on creditor banks' balance sheets to increase their equity-to-debt ratio. In the case of bankruptcy, the CGP undergoes a period of inactivity, after which it becomes active again with a healthier balance sheet. Therefore, insolvent firms' physical capital is not utilized for a while.

Banks provide credit to private agents, namely CGPs and households. In particular, they evaluate loan and mortgage requests and eventually lend money to private agents at a price that depends on the risk associated with the default probability of the firm or on the creditworthiness of the household. Banks' lending capacity is limited by the obligation to respect a capital adequacy ratio. Finally, it is worth noting that the nature of money in the Eurace model is endogenous, as new deposits are created every time a bank issues new credit.

The government and the central bank are in charge of the fiscal and monetary policy, respectively. Total government income derives from taxation on corporate earnings, consumption, financial and labour income. Government expenditures include public sector wage bills, unemployment benefits, transfers and interest payments on debt. To finance its activity, if in short of liquidity, the government emits perpetuities that pay a monthly fixed coupon. The central bank provides liquidity to the banking sector, acting as a lender of last resort. It also sets the policy rate according to a dual mandate rule, i.e., low unemployment and stable prices.

The scheme reported in Fig. 1 represents the enhanced version of the Eurace model employed in this study, where the original energy sector[8] has been complemented with a fossil fuel sector, GHGs emissions, and a climate module. A new green capital producer has been also designed to address energy efficiency investments. In what follows, we describe synthetically the main enhancements of the Eurace model, which have been developed for this study, while more technical details have been provided in Appendix.

3.1. The new energy and fossil-fuels sectors

Since our goal is modelling a global economy, the energy sector has changed considerably with respect to Ponta et al. (2018), where a foreign economy supplied fossil fuels. In the present study, fossil fuels extraction and sales are endogenous in the model; as explained in the following.

Energy is generated by both a non-renewable energy producer (PP) and a renewable energy producer (RP). The PP is the only GHGs emitter in the economy, with emissions being directly proportional to the fossil fuels burned for energy production. Fossil fuels are supplied endogenously by a miner agent (FM), endowed with a capital stock for the extraction process and setting the fossil fuels price, which is proportional to the capital price. The energy demand is given by the sum of the energy required by each CGP, which depends on the quantity produced multiplied by the average energy intensity of the owned capital stock. Additionally, the energy intensity of each CGP can be enhanced by purchasing new machines with lower energy intensity.

The energy production function of the power producer based on fossil fuels is given by:

$$E_{PP} = \gamma_{en} F \tag{1}$$

[8] The energy sector was initially designed and included in the baseline model by Ponta et al. (2018) and further refined by Raberto et al. (2019), incorporating additional energy efficiency improvements.

where F is the quantity of fossil fuels needed to produce the energy E_{PP} and γ_{en} is the efficiency of the energy transformation process. Burning fossil fuels, the PP agent produces GHGs emissions:

$$\mathcal{E} = i_{\epsilon} F \tag{2}$$

where i_{ϵ} is the carbon intensity of fossil fuels, i.e. the GHGs emissions generated by the combustion of a fossil fuel unit. Fossil fuels are endogenously supplied by a fossil fuel miner agent (FM). The FM agent is endowed with a capital stock K_{FM} to perform the extraction process. The depreciation rate of capital stock is endogenous and depends on the amount of fossil fuels extracted. In particular, we assume that the number ΔK_{FM} of machines deteriorated due to the extraction process is proportional to the level of supply, i.e.,

$$\Delta K_{FM} = \eta F \tag{3}$$

where η is the number of machines that need to be replaced due to the mining of a unit of fossil fuels, and F is the fuel quantity extracted in one month, which we assume is always equal to the amount demanded by the PP agent, see Eq. (1). In order to restore its capital stock, the FM buys new capital by selecting one of the two KGPs. The fuels price p_F is given by a fixed mark-up on the unit costs of depreciation, i.e.:

$$p_F = \left(1 + \mu_F\right) \eta \cdot p_k \tag{4}$$

where μ_F and p_k are the markup used by the FM agent and the capital price of the chosen KGP. Further details have been provided in Appendix.

3.2. The new capital good sector

A new kind of capital good producer, the green KGP, has been designed to separate investment decisions to expand production capacity from investments in reducing capital's energy intensity. The capital goods sector now comprises two producers, green and brown KGP, both of which utilize labour as the sole production factor. The energy intensity of the new capital goods produced by the green KGP, called green machines, decreases at a monthly exogenous constant rate. In contrast, machines from the brown KGP maintain a constant energy intensity equivalent to their initial value. The green KGP allocates a fraction of its workforce to enhance the energy intensity of the new machines. As a result, only the remaining fraction of workers are employed for production, leading to a higher unit cost and, subsequently, a higher capital price.

In particular, the production function of the KGPs reads:

$$Q_k = \gamma_k N_k (1 - d_k) \tag{5}$$

where Q_k is the quantity of new capital produced in a month by the KGP k, where $k \in \{\text{green, brown}\}$, γ_k is the total factor productivity, N_k is the number of employees, and d_k is the fraction of workers employed in the energy intensity improvement process. It is equal to 0 for the brown KGP and fixed to a positive number smaller than one for the green KGP. The energy intensity $i_{E,k}$ of the new capital produced by the green KGP is determined by the rule:

$$i_{E,k} = (1 - g_k) i^{old}_{E,k} \tag{6}$$

where $i^{old}_{E,k}$ is the energy intensity of the machines in the inventories, and g_k is an exogenous parameter. It is equal to 0 for the brown KGP and it is fixed to a positive number for the green KGP. KGPs set the capital price p_k, which depends on a markup on unitary cost:

$$p_k = (1 + \mu_k) \frac{w_k}{\gamma_k (1 - d_k)}, \tag{7}$$

where w_k and μ_k are the average wage offered and the markup put by the KGP k. Given the average identical salary and markup among the green and brown KGP, the green capital price is higher than the brown one because of the term $(1 - d_k)^{-1}$, greater than one if $d_k > 0$.

Every quarter, CGPs can choose to buy new capital goods to meet the new production plans determined by expected demand evaluation. CGPs evaluate investments based on the Net Present Value (NPV), which decreases with the capital price and is higher when the energy intensity of the new machines is lower. Each CGP calculates the NPV for green and brown machines and selects the type with the highest positive NPV. If neither NPV associated with the two types of investments is positive, no investment is made.

The new investment made by a CGP changes its average energy intensity by an amount Δi_{Ef}, which depends on its present intensity i_{Ef} and on the intensity of the new machines, as follows:

$$\Delta i_{Ef} = -\frac{\Delta K}{K + \Delta K} (i_{Ef} - i_{E,k}) \tag{8}$$

where K is the firm's capital stock before the investment, ΔK is the number of new machines bought and $i_{E,k}$ is the energy intensity of the latest machines purchased from the chosen KGP. Note that the energy intensity decreases only if the green KGP is chosen, i.e. $i_{E,k} < i_{Ef}$. CGPs select the brown or the green KGP as the supplier of new machines by assigning 90% probability to the type of investment that has the highest positive NPV, given by:

$$NPV_k(\Delta K_f) = -p_k \Delta K_f + PV^{old} + PV^{en}_k \tag{9}$$

where the first addend is the cost of the investment, PV^{old} is the present value of future cash flows implied by the investment as defined in Teglio et al. (2019), and PV^{en} is the present value of the net energy cost savings implied by the new capital. Technical details about how these terms are computed are provided in the Appendix.

3.3. The climate module

The climate module is based on the DICE model (Nordhaus, 1993), representing the climate system as three overlapping layers: the atmosphere, the upper ocean, and the lower ocean. Each layer exchanges greenhouse gases (GHGs) and heat only with adjacent layers. GHG emissions from the economy are released into the atmosphere. Although the oceans partly absorb them, the accumulation of GHGs in the atmosphere alters the net energy flux between layers, increasing atmospheric temperature. Physical damages are expressed as capital reduction, i.e., every year, the climate damages every firm, destroying a fraction of its capital. This fraction is equal for all firms and given by a quadratic function of the atmospheric temperature (see Appendix for further details).

4. Dimensioning of the energy sector

The values of the model's parameters and initial conditions have been chosen to match the order of magnitude of the corresponding real-world counterparts. To this purpose, we first identify the target system, a simplified real-world description relevant to our goals. Then, we impose a set of physical and economic constraints that tie the model to the target system.

The target system is an economy in which agents' activities cause emissions of GHGs in the environment. Since three-quarters of actual anthropogenic GHG emissions come from the production and use of energy, we assume that there are only energy-related emissions in the target system. Energy is produced from two sources: non-renewable sources, whose combustion generates GHG emissions, and renewable ones, which we assume do not generate emissions. Besides GHG emissions, our target system is characterized by real GDP, total energy supply (TES) and total energy final consumption (TFC),[9] and renewable

[9] The TFC is defined as the global energy consumption by end-users, while the TES, or primary energy production, also includes the energy used by the energy sector to produce, transform and distribute the energy. The ratio between the two quantities sets the energy transformation and distribution efficiency within the energy sector since the TES is the input necessary to produce TFC as output.

Table 1
Actual data used for the dimensioning procedure.

Symbol	Description	Value	Source
GDP_W	Yearly real GDP	10^{14}\$	Our World in Data
$\mathcal{E}_W$	Yearly GHG emissions	50 $GtCO_2e$	Our World in Data
TES_W	Total energy supply	166 PWh	IEA (2020)
TFC_W	Total final consumption of energy	115 PWh	IEA (2020)
s_{RP_W}	Share of renewable energy	20%	IEA (2020)

Table 2
Initial conditions determined according to the dimensioning procedure.

Symbol	Description	Value	Reference
GDP_{M0}	Yearly real GDP	$10^5 E\$$	Arbitrary choice
$\mathcal{E}_{M0}$	Yearly GHG emissions	$\mathcal{E}_W$	Eq. (10)
$\frac{\mathcal{E}_{M0}}{GDP_{M0}}$	Carbon intensity of GDP	$\frac{\mathcal{E}_W}{GDP_W}$	Eq. (11)
Q_{y0}	Yearly CGPs output	10^5 units	Arbitrary choice
TES_{M0}	Total energy supply	TES_W	Section 4
E_0	Total final consumption of energy	TFC_W	Section 4
$i_{E0,f}$	Energy intensity of production	$\frac{TFC_W}{Q_{y0}}$	Eq. (12)
s_{RP}	Share of renewable energy	20%	Eq. (14)
p_{K0}	Capital good price	1 E\$	Arbitrary choice
p_{F0}	Fossil fuel equivalent price	18.64 E\$/PWh	Table 3
n_{s0}	Number of renewable stations	$\cdot 10^4$	Section 4

energy share. Their values are set close to the corresponding actual values; see Table 1 for reference.

The first two constraints tie the model to the target system regarding initial emissions and the carbon intensity of GDP. In particular, the initial model (M0) emissions have been aligned with actual (W, world) emissions, i.e.,

$$\mathcal{E}_{M0} = \mathcal{E}_W = \mathcal{E}\,. \tag{10}$$

Second, since emissions are associated with the production and consumption of goods, we assumed that the carbon intensity of the GDP of the model (the emissions generated by the unit of real GDP) is equal to the current carbon intensity when measured in actual currency (\$), i.e.

$$\frac{\mathcal{E}}{GDP_{M0}} = \frac{\mathcal{E}}{GDP_W}\,, \tag{11}$$

where $\mathcal{E}$ are the yearly global GHG emissions, GDP_W is the actual real GDP expressed in \$ and GDP_{M0} is the first year real GDP of the model, measured in Eurace dollar, namely $E\$$, the currency of the model. Assuming $GDP_{M0} = 10^5 E\$$, the equality between the model and the target system GDP, gives a currency exchange identity between Eurace dollars and real dollars, i.e, $1E\$ = 10^9\$$. This means that a unit of real GDP of the model corresponds to a billion real GDP units since it generates the same amount of GHG emissions.

The third constraint sets the initial TES and TFC of the model equal to the actual ones, i.e. TES_W and TFC_W. To meet this constraint, since CGPs are the only energy end-users, the initial energy intensity of production $i_{E0,f}$ (initialized equal for any firm f) is set as follows:

$$i_{E0,f} = \frac{TFC_W}{Q_{y0}} \quad \forall f \tag{12}$$

where Q_{y0} is the total production of consumption goods in the model's first year (estimated through preliminary simulations).

The fourth constraint imposes energy transformation efficiency in the model, the ratio between TFC and TES, say γ_{en}, equal to the actual one, and its constancy during simulation. According to IEA (2020), TES_W in 2018 was 166 Petawatt-hour (10^{15} Wh) while TFC_W was 115 Petawatt-hour, then γ_{en} is approximately set to 0.7, i.e.

$$\gamma_{en} = \frac{TFC_W}{TES_W} = 0.7 \tag{13}$$

Table 3
Fossil fuels TES by source. The equivalent fuel is a 'mean' fuel with the same TES given by all the fossil fuels and whose price is given by the weighted average.
Source: Data are referred to the year 2018 and are taken from IEA (2020).

Source	TES (PWh)	Price	Conversion factor	Price $\left(\frac{\$}{\text{MWh}}\right)$
Coal	45	$60\ \frac{\$}{\text{tonne}}$	$0.12\ \frac{\text{MWh}}{\text{tonne}}$	7
Oil	52	$50\ \frac{\$}{\text{Boe}}$	$0.59\ \frac{\text{MWh}}{\text{Boe}}$	29
Natural gas	38	$5\ \frac{\$}{\text{MBtu}}$	$3.4\ \frac{\text{MBtu}}{\text{MWh}}$	17
Equivalent fuel	135			18

As the fifth condition, we assume that the actual and model initial renewable energy share s_{RP} are equal, i.e.

$$\frac{E_{RP0}}{E_0} = \frac{TFC_W^R}{TFC_W} = s_{RP}\,, \tag{14}$$

where E_{RP0} and E_0 are the first-year values of the model's renewable and total energy consumption, respectively, and TFC_W^R is the actual renewable component of TFC_W, i.e. currently about 20%. This condition also fixes the share of fossil energy and, together with the first constraint, it fixes the carbon intensity i_ϵ of the non-renewable energy in the model, i.e.,

$$i_\epsilon = \frac{\mathcal{E}_W}{TFC_W^F} \tag{15}$$

where TFC_W^F is the total final consumption of energy supply by fossil fuels and $TFC_W^R + TFC_W^F = TFC_W$.

The sixth condition sets the initial cost of increasing the renewable production capacity in the model equal to the actual one. Unlike fossil fuels, the fixed installation cost mainly determines the unit cost of renewable energy production. According to Our World in Data,[10] the annual investment in renewables is about 250 billion \$ for an average increase of renewable energy supply that can be generated in a year of 750 TWh. We can set the cost of increasing yearly renewable energy supply by 1 TWh in the target system equal to $\frac{250}{750}\frac{10^9\$}{\text{TWh}}$, i.e. $\frac{1}{3}\frac{1E\$}{\text{TWh}}$. Since we identified renewable power stations with capital goods in the model with the initial price set to 1E\$, we can dimension accordingly the energy supply of any single renewable power station, i.e. 3 yearly TWh or 0.25 TWh monthly. Considering the energy transformation parameter γ_{en}, we can similarly state that each renewable power station provides $1.75 \cdot 10^{-4}$ PWh energy available for consumption monthly. Finally, in order to account for the variability of renewable sources, we lowered this amount to $m_s = 1.5 \cdot 10^{-4}$ PWh, as reported in Table 4.

Inserting this value in Eq. (A.10) and using the actual share of total renewable energy consumption set by Eq. (14), we get the initial number of renewable power stations n_s.

The seventh constraint imposes that the model fossil fuels initial price p_{F0} equals the actual one. Since there are various fossil fuel sources, we define a single fossil fuel equivalent whose price is expressed as a weighted average over the prices of the 3 main fuels, i.e. coal, oil and natural gas. The weights are given by the relative TES of each fossil fuel type over the total TES supplied by all fossil fuels, set approximately to 135 PWh. All the values are reported in Table 3, the model single fossil fuel equivalent price p_{F0} is then set to 18 $\frac{\$}{\text{MWh}}$. Rearranging the terms in Eq. (4), one obtains the number η of machines depleted in the extraction process of one unit of fossil energy, i.e.

$$\eta = \frac{1}{\left(1+\mu_F\right)}\frac{p_{F0}}{p_{K0}} \tag{16}$$

where p_{K0} is the initial capital price, equal for the two KGPs. The value computed for p_{F0} and the initial capital price p_{K0} set to 1 E\$ gives the value of η reported in Table 4.

[10] https://ourworldindata.org/renewable-energy.

Table 4
The table presents the parameters' values resulting from the dimensioning procedure.

Symbol	Description	Value
i_ϵ	Carbon intensity of fossil energy	$3.7\ 10^{-1}\ \frac{GtCO_2}{PWh}$
γ_{en}	Efficiency of fossil energy transformation	0.7
m_s	renewable energy available from a single power station	$1.5\ 10^{-4}\ \frac{PWh}{month}$
η	Consumed capital per PWh	$17\ \frac{1}{PWh}$
$\frac{\Delta\gamma}{\gamma}$	exogenous capital productivity growth rate (%)	0.25
d_{green}	fraction of green KGP workers employed in R&D (%)	5
g_{green}	energy intensity degrowth rate (%) of green capital goods	0.2

Finally, the exogenous capital productivity growth rate, as well as the parameters regulating the production and energy intensity of green capital goods (namely the fraction d_{green} of worker that the green KGP devotes to energy intensity improvements and the energy intensity degrowth rate g_{green}, see Section 3 for details) are set to produce an economy characterized by strong growth of GDP (growth rate of real GDP in the range from 2% to 4%), decreasing energy intensity and increasing energy consumption and GHG emissions, as requested at the beginning of this section.

Tables 2 and 4 summarize the initial conditions and parameters' values of the energy and capital sectors determined through this calibration procedure.

5. Computational experiments

5.1. Objectives and methodology

Evaluating whether a policy mix is preferable to its components through empirical studies poses challenges. Ideally, one would compare the effects of the mix with those that would arise if one of its components were implemented independently. However, practically implementing the mix in a specific economy, studying its effects, and then reverting the economy to the same initial state to study the alternative policy is not feasible. Instead, simulation models provide a means to explore such scenarios despite their inherent limitations as simplified representations of reality.

Therefore, we conducted four experimental series, each starting from the same initial state: (1) business as usual, or no policy; (2) carbon tax; (3) feed-in tariff; (4) a mix of the previous two.

To compare and rank the different cases, we draw upon (Drews et al., 2020), who posit that two climate policies are independent if the emission reduction achieved by their mix equals the sum of the emission reductions produced by each policy in isolation. Conversely, if the emission reduction from the mix surpasses the greatest reduction achieved by the individual parent policies, then the policy mix is considered beneficial.

Unlike Drews et al. (2020), who do not consider the costs of policies, including their negative impact on various economic and social aspects, our study takes these factors into account. We consider two policies independent if their combined emission reduction equals the sum of reductions each policy achieves at a cost corresponding to the sum of the individual costs. An advantageous interaction occurs when the mix achieves equal or greater emission reduction than the highest reduction achieved by the parent policies, while maintaining a cost lower than the most "expensive" single policy.[11]

[11] The interaction is advantageous also when the cost of the mix is equal to or lower than the highest of cost, provided that the emission reduction of the mix is higher than the highest of the single policies emission reduction.

Note that Drews et al. (2020) argue that if a policy mix achieves emission reduction equal to the highest reduction achieved by individual policies, it is considered redundant. In contrast, our perspective favours the mix if its cost is lower than the most costly single policy. However, in complex scenarios where the mix's reduction exceeds the highest individual reduction but its cost is higher, or when the mix's reduction falls between the isolated policies' reductions, we require an explicit preference structure to determine dominance.

Various metrics can assess climate policy costs, often by comparing the value of a variable (e.g. consumption or GDP, see IPCC (2014)) in policy implementation with its value in a business-as-usual scenario (BAU). In our study, we focus on consumption loss as a cost and on emission reduction as a benefit.

We associate each policy with a benefit–cost pair[12] for each Monte Carlo simulation. By averaging total emissions and consumption loss, we represent policy performance on a graph with the x-axis showing average cumulative emissions and the y-axis representing average consumption loss. A policy is considered dominated if another policy achieves lower cumulative emissions and consumption loss. The Eurace model enables us to go beyond cost–benefit evaluation, allowing us to analyse the channels that drive emission reduction and consumption reduction for each policy, thus explaining interactions within a policy mix.

5.2. Definition of policy scenarios

In the feed-in tariff (FIT) scheme, the government sets a guaranteed price p^r_E for renewable energy and finances the difference between p^r_E and the market energy price p_E, if positive, for every unit of energy sold by the RP. Then, the cost of the FIT policy for the government is calculated as $\max(0,(p^r_E - p_E)E_{RP})$. See Ponta et al. (2018) for further details. In the carbon tax (CT) policy scenario, the government sets a price p_ϵ on the unit of GHGs emission and collects the corresponding revenues $p_\epsilon \mathcal{E}$. Since the PP is the only GHGs emitter, it is also the only agent that pays the tax. Therefore, the energy price increases under a CT, and it reads

$$p_E = \frac{1+\mu_{PP})}{\gamma_{en}}(p_F + i_\epsilon p_\epsilon) \tag{17}$$

The characteristics of the two implemented policies lead to restrictions on the possible combinations. Indeed, if CT makes the energy price higher than the FIT guaranteed price, FIT will not be active, and such a mix will be completely equivalent to the corresponding CT scenario. However, as long as the energy price is lower than p^r_E, the FIT cost for the government in the policy mix scenario is lower than that in the corresponding isolated FIT scenario.

A series of Monte Carlo experiments have been performed with the Eurace model: each of the 22 considered scenarios was simulated ceteris paribus using 50 different seeds of the pseudo-random number generator. Scenarios differ for the values of the guaranteed renewable energy price p^r_E and for the carbon price value p_ϵ that are held constant during the 30-year time span of each simulation.

Table 5 presents the values of the two policy parameters that characterize each of the 22 scenarios. In the first scenario, the so-called business as usual (BAU), no climate policy is implemented. Scenarios 2 to 8 are characterized by an increasing carbon tax p_ϵ. In scenarios 9 to 15, a feed-in tariff is implemented. Finally, in the last seven scenarios, both policies are active, so a policy mix (PM) can be considered. All scenarios are simulated with and without physical damage feedback.

Both the values of the carbon tax and the feed-in tariff are chosen to produce moderate to extreme emission reduction. The carbon tax

[12] Note that costs and benefits do not share a common unit of measure, which complicates the identification of a net benefit measure. Therefore, we approach this as a multi-dimensional problem, which is why we represent it as a 'pair'.

Table 5
Scenarios definition.

Policy	Scenario	p_e ($\frac{E\$}{GtCO_2e}$)	p^r_E ($\frac{E\$}{PWh}$)
BAU	1	0	0
CT	2	15	0
	3	25	0
	4	30	0
	5	45	0
	6	60	0
	7	75	0
	8	90	0
FIT	9	0	50
	10	0	60
	11	0	65
	12	0	70
	13	0	75
	14	0	90
	15	0	120
PM	16	15	60
	17	15	75
	18	15	120
	19	30	75
	20	30	90
	21	60	90
	22	60	120

values are chosen in the range [15, 90] $\frac{E\$}{GtCO_2e}$,[13] which includes the majority of the carbon prices actually implemented in the world, and covers the range recommended by High-Level Commission on Carbon Prices (2017). To facilitate the comparison between the two single policies, feed-in-tariff values are selected to achieve emissions reductions similar to those obtained with the considered carbon taxes, while adhering to the constraint $p^r_E > p_E$. As said in Section 3, the FIT guaranteed price is greater than the market energy price; otherwise, the RP would consider the energy price to calculate the net present value of investment and not the guaranteed price (see Eq. (A.11)), and the government would not subsidize the renewable energy, being the difference $p^r_E - p_E$ negative.

Policy mix values are selected first by excluding those combinations that provide results indistinguishable from the CT, then considering that the advantages of the policy mix are lower, the higher the intensity of the single policies.

5.3. Analysis of results

Computational experiments are discussed according to the following steps. In the first section, we explain how results are presented. In the second and third sections, we examine the effects of the carbon tax and the feed-in tariff as single policies. The fourth section compares these two policies, while the next one, i.e., Section 5.3.5, analyses the effects of the policy mix. These initial analyses are conducted without the physical damage feedback mechanism, while in the last section (i.e., 5.3.6), we examine how the presence of physical damage alters the previous outcomes.

5.3.1. Presentation methods

Results are presented using a variety of tools, including time series graphs, box plots, tables, statistical tests, and more sophisticated graphs to compare policy mixes. Given the stochastic nature of the Eurace model, we need to explicitly represent the statistical properties of the output, because single realizations may be not representative.

Figs. 9 and 10 show the temporal evolution of the ensemble average of the several variable under exam in four different scenarios: the BAU, the PM(15,90) and its CT and FIT components. The shaded area around each solid line reflects the standard deviation. Although the plots provide visually useful information to guide the analysis, they are not suitable for evaluating the results. In fact, the ensemble average of time trajectories, standard deviation, or higher-order moments of the observable distribution can be informative but are inadequate for detecting small differences in cumulative quantities. Therefore, we also used boxplots for aggregates throughout the experimental period, as they provide a direct overview of the distribution. However, if the distributions of an observable in different scenarios overlap significantly, interpreting boxplots becomes challenging. In such cases, we employed statistical tests to support our analysis, with results presented in tables.

Boxplots 2–8 show the 30-year time-span average distribution for all relevant variables, except temperature and atmospheric carbon stock, which are considered by looking at the distribution of their final-year values. The physical damage feedback is absent. The lowest and highest extremes of each box represent the 25th and 75th percentile of the distribution. The dashed line extends from the minimum to the maximum value, except outliers (represented with +), and the horizontal line dividing the box is the median of the distribution. The boxes have different colours to identify policies: black boxes are the BAU scenario, red boxes are the CT scenarios, blue ones are the FIT, and magenta boxes are the PM scenarios.

Figs. 13–16 compare the boxplots of the relevant variables for all policy scenarios, with and without physical damage feed-back. For readability, the 10 (out of 22) most representative scenarios are extracted: BAU, 3 CT scenarios, 3 FIT scenarios, and 3 PM scenarios. Empty boxes refer to the no-damage scenarios, while the filled ones are relative to the scenarios with climate damage.

Tables from 6 to 9 report for each variable the results of the two-sided Wilcoxon rank-sum test, which tests the null hypothesis that the simulation outcomes relative to two different scenarios are originated from distributions with the same median against the hypothesis that they are not. Tables also report p-values: when the p-value is lower than 5% (1%) the null hypothesis is rejected with a 5% (1%) significance level.

Fig. 12 shows the cost–benefit representation of the adopted policies, with or without physical damage feed-back. In each panel, the x-axis represents the average cumulated emission and the y-axis the average consumption loss. The red squares represent the CTs, the blue triangles represent the FITs, and the purple circles represent the PMs. The green-shaded region represents all the policies that lead to cumulative emissions lower than the remaining 580 $GtCO_2$ carbon budget to limit warming (IPCC, 2018).

Finally, Figs. 11 and 17 show in a more compact and sophisticated way the comparison of each policy mix with its single component.[14]

5.3.2. Carbon tax analysis

As shown in Fig. 2, both CT, FIT and their combination effectively reduce the impacts of economic activities on climate. However, emission reduction comes at the cost of slower economic growth, as shown in the figures from 5 to 6. In the case of the carbon tax, both economic costs and climate benefits (emission reduction) come from the impact on the energy price; as shown in Fig. 3(a), the higher the carbon price, the higher the energy price. A higher energy price fosters energy intensity improvements (Fig. 3(c)), because it increases the net present value of green capital (see Eq. (A.24)) and then the share of the less energy-intensive capital (Fig. 3(d)). Furthermore, a higher energy price also increases the share of renewable energy, as shown in panel (b) of Fig. 3, because it increases the net present value of investments in new renewable power stations (see Eq. (A.11)).

In summary, the CT policy's environmental performance is determined by three causes: lower energy intensity, higher share of renewables, and the slower growth rate of the economy (see Eq. (A.17)).

[13] Note that since the Eurace dollar is equal to a billion of \$, the unit $\frac{E\$}{GtCO_2e}$ is equal to $\frac{\$}{tCO_2e}$.

[14] See Section 5.3.5 for details.

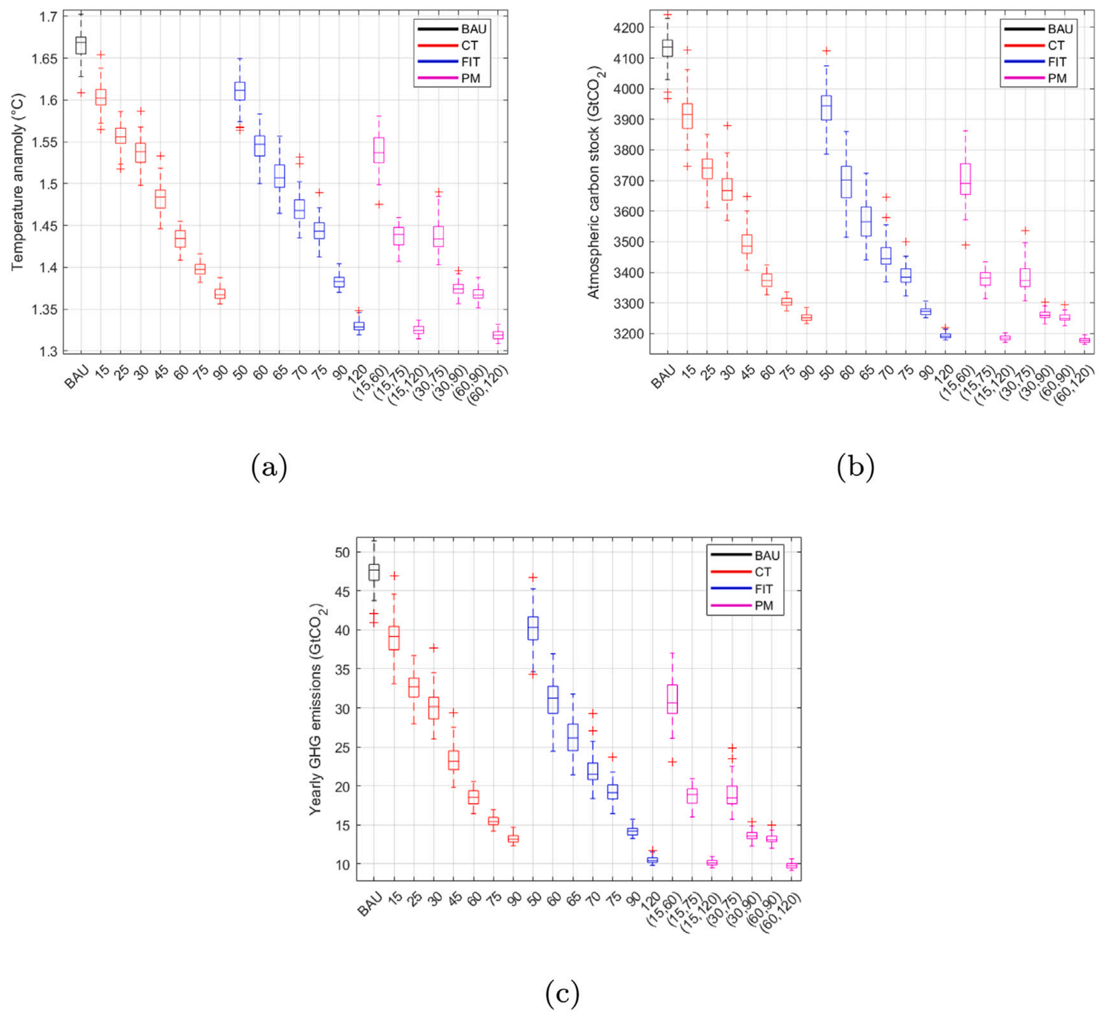

Fig. 2. The figure shows the boxplots of the final value or the temporal mean of the variables of interest for all the scenarios without physical damage feedback considered. In particular, it shows: (a) the final value of the temperature anomaly, (b) the final value of the atmospheric carbon stock and (c) the mean value of yearly GHGs emissions.

However, energy intensity improvements have a minor impact on emission reduction relative to the other two causes. In particular, Fig. 4(c), (b), and (d) show that the percentage differences in energy intensity of CT scenarios relative to BAU are much smaller than the percentage differences in the share of renewable energy and the consumption level, taken as a proxy for the quantity of production of CGPs.

The consumption loss relative to the BAU emerges from the ripple effects triggered by higher energy prices. Indeed, the cost of the tax is charged to the consumer via higher production costs and then higher consumption prices (Fig. 5(a)). This determines a reduction of real consumption (Fig. 5(b)) and then, in particular with the highest CTs, a reduction of the employment rate in the private sector, see Fig. 6(a,b,c), and a reduction of household purchasing power (Fig. 6(d)). The reduction of the demand for consumption goods also leads to a reduced capital goods demand, as shown in (Fig. 5(d)). Instead, there is not a recognizable trend in capital prices (Fig. 5(c)), meaning that other factors govern their dynamics than higher energy prices, such as the reduced demand from CGPs and the competition in the labour market between the two KGPs and the CGPs. Consider that both KGPs set the capital price as a mark-up on the unitary costs, given by the average wage divided by the TFP; therefore, capital price increases when KGPs have to raise the wage offer to hire new employees (to face higher demand) or to avoid employees subtraction by the other producers.

At the highest values of CTs the reduction of consumption affects the government budget since the CT revenues are more than offset by the reduction of general tax revenues due to lower GDP. Furthermore, to reduce the deficit, the government sets a higher general tax rate (Fig. 7(a)) that exacerbates the economic slowdown, determining a further reduction of consumption and an increase in unemployment, despite the reduction of the interest rate set by the central bank (Fig. 7(b)).

We also observe a higher inflation rate for the highest CT values (Fig. 7(c)). We argue that this depends both on higher energy prices and on a lower total factor productivity (Fig. 7(d)), determined by lower investments with respect to the BAU scenario.

5.3.3. *Feed-in tariff analysis*

Concerning the FIT, emission reduction is achieved by the higher share of renewables and the reduced energy demand, corresponding to a lower consumption level. Since the RP is remunerated with the guaranteed price, the FIT increases the NPV of investments in new renewable power stations. Then, ceteris paribus, FIT determines a higher share of renewables. However, the FIT policy does not affect energy intensity, as shown by Fig. 3(c) and by Table 6.

The economic cost (consumption loss relative to BAU) emerges mainly via the increased government expenditure due to the FIT policy cost (the incentive to the renewable energy paid by the government): to finance the additional cost of the FIT policy, the government increases the general tax rate that, as in the case of high CT values, leads to

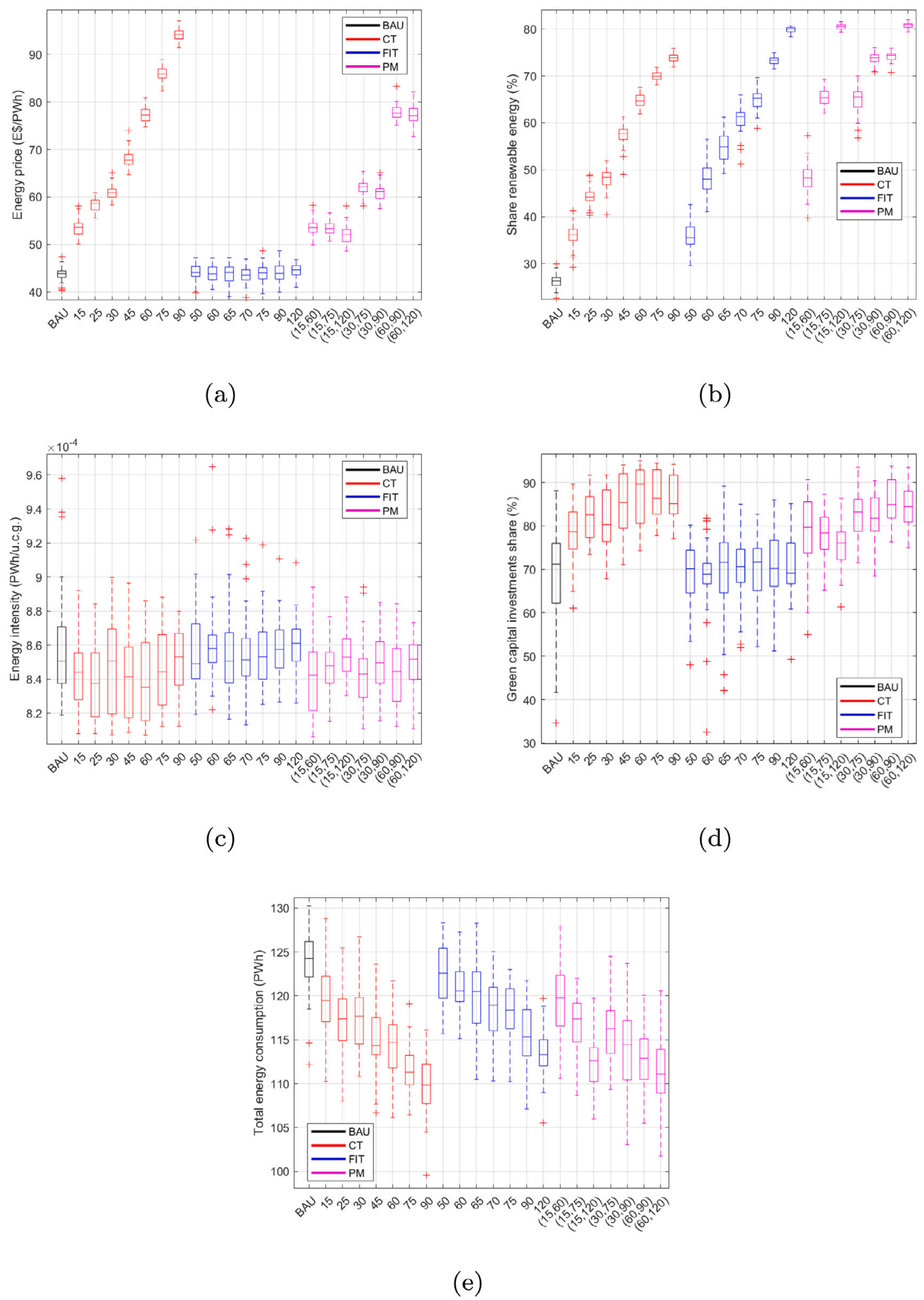

Fig. 3. The figure shows the boxplots of the temporal mean of the variables of interest for all the scenarios without physical damage feedback considered. In particular, it shows: (a) the energy price, (b) the share of renewable energy, (c) the energy intensity, (d) the share of green investments and (e) the total final consumption of energy.

higher consumption prices, lower real demand of consumption goods and, therefore, of production inputs, i.e. labour (Fig. 6) and capital (Fig. 5(d)). Note that we do not observe the migration of workers from the CGPs to the KGPs, as observed in Ponta et al. (2018). In Ponta et al. (2018), the total factor productivity (TFP) is fixed during all simulations, while here the economy is characterized by TFP growth; consequently, if the productivity of KGPs is fixed, satisfying a higher capital demand is possible only by increasing the KGPs workers, i.e. by subtracting workers to the CGPs when the unemployment rate is lower (or when it is mainly determined by the out-of-equilibrium behaviour of

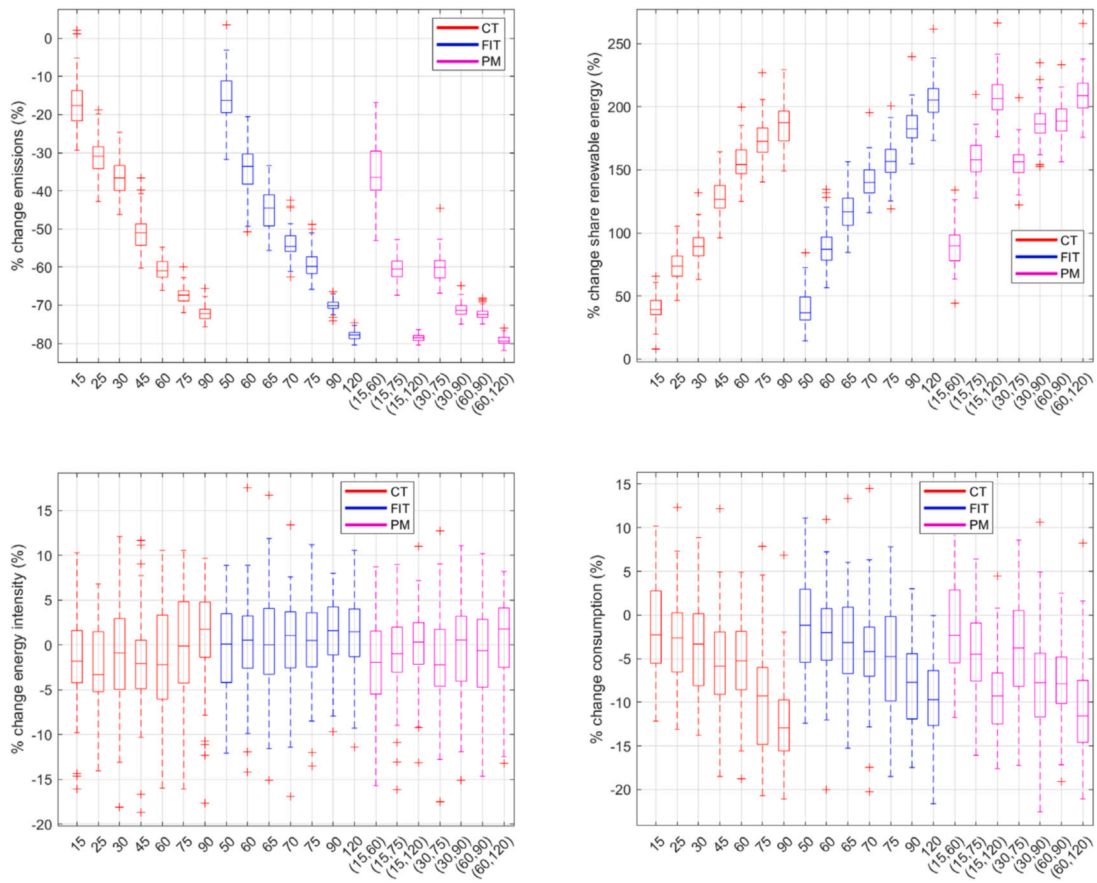

Fig. 4. The figure shows the boxplots of the percentage difference with respect to the BAU of: (a) total emissions, (b) share of renewable energy, (c) energy intensity and (d) real consumption.

the labour market[15]). Finally, in line with the CT policy, the FIT policy leads to a higher inflation rate (determined by higher prices and lower TFP) and a lower policy rate, as shown in Fig. 7.

5.3.4. Comparison between single policies

Given that both the CT and the FIT policies effectively reduce GHGs emissions, which of the two is better?

Focusing only on CT and FIT, from Fig. 12(a), we can conclude that, first, there is no CT policy that the other CTs dominate; second, the same holds for the FIT policy; third, five of the seven CTs are dominated by the FITs. Once the dominated policies have been excluded, there is no way to select the best policy without further expliciting the preference structure of the choice between reducing emissions more or paying less. Furthermore, since every single policy has many possible consequences, the analysis has to consider the variability of emissions reductions and consumption loss.

5.3.5. Policy mix analysis

The channels through which the costs and benefits of individual policies arise provide the basis for analysing their mix. In particular, investments in renewable power stations are determined by the FIT value. At the same time, consumption loss arises from the increase in the price of consumption goods due to the increased energy price via CT and from the rise in the general tax rate due to the need to finance FIT expenditures. However, the CT can mitigate the consumption loss given by the FIT financing costs because CT revenues can, in part, compensate them and because the higher market energy price decreases the cost $(p_E^r - p_E)$ of each unit of renewable energy paid by the government.

Fig. 2 shows that the PM environmental performances are equal to, or better than, those of the corresponding FITs. This result is mainly due to the impact on the renewable share (Fig. 3(b)). Due to the energy price increase (Fig. 3(a)), the PM also influences the share of green investments in less energy-intensive machines (Fig. 3(d)) and therefore it leads to higher energy intensity improvements relative to the BAU (Fig. 3(c)); however, this progress has minor effect on emissions reduction, as clarified before. Fig. 3(a) shows that the energy price increase is very similar to that implied by the CT component of the PM. However, the rise of consumption goods price is higher than in the CT scenario because of the higher tax rate increase due to the FIT policy cost. Comparing PMs with the same FIT in Fig. 8(b) shows that the higher the carbon price, the lower the FIT policy cost due to the higher energy price. Therefore, the general tax rate increase due to the FIT policy cost is milder in the PM than in the isolated corresponding FIT, see Fig. 7(a). The above analysis is confirmed by Figs. 9 and 10, which show the dynamic behaviour of the model. Note, however, that the distance between the trajectories of different scenarios is such that cumulative analyses and statistical tests are necessary to confirm that there is a substantial difference.

Using the criterion cited in Section 5.3.1 to evaluate PM performance, we found that all the PMs except one are preferred to their components. The analysis results are shown in Fig. 11. In each panel, the x-axis represents the negative of emission reduction relative t to the BAU $(-\frac{\mathcal{E}-\mathcal{E}_{BAU}}{\mathcal{E}_{BAU}})$, the y-axis represents the negative of the consumption loss relative to the BAU $(-\frac{C-C_{BAU}}{C_{BAU}})$. In each graph, the average values over all seeds of the emission reduction and consumption loss relative to the PM under exam (magenta circles) and to its CT (red squares)

[15] In the economy represented by the EURACE model there can be unemployment even when all the workforce is required for the production needs.

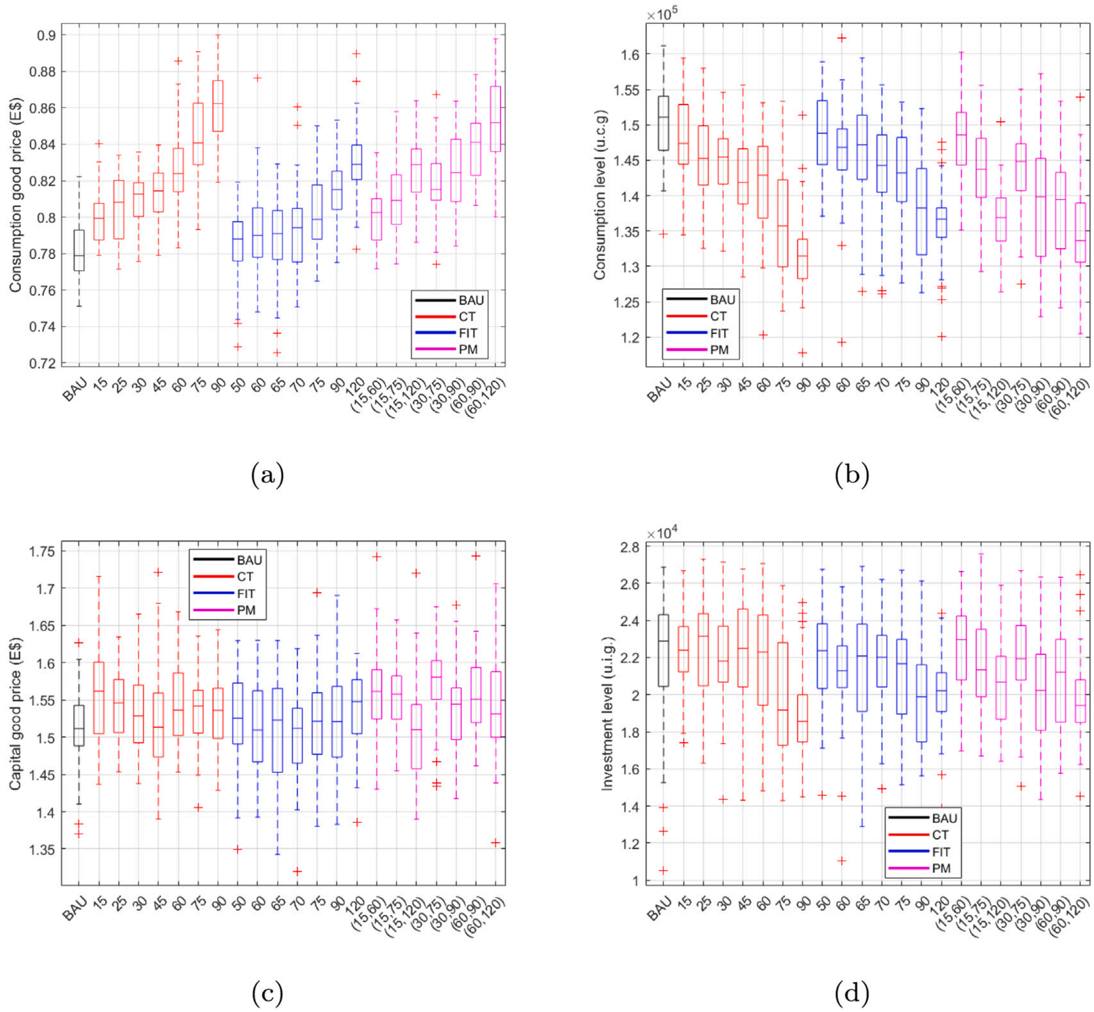

Fig. 5. The figure shows the boxplots of the temporal mean of the variables of interest for all the scenarios without physical damage feed-back considered. In particular, it shows: (a) the consumption price, (b) the real consumption, (c) the capital price and (d) the real investments.

and FIT (blue triangles) components are represented. The shaded area represents the region where the policy mix is preferred to its parent policies. Each graph shows an enlargement at the top left of the figure that helps evaluate the policy mix's performance with respect to the shaded region. Only the PM(60, 120) is out of the shaded region. However, it is necessary to explicitly establish a preference structure to ascertain if this mix is better or worse because both the emission reduction and the cost of the mix are higher than those of the components.

Furthermore, from Fig. 12(a), the PMs dominate almost all the component policies (dominate all the CTs and all FITs but two). The advantages of the policy mix decrease as the intensity of the component policies increases, as can be seen comparing FITs and PMs with the same tariff in Fig. 2 and in Fig. 5.

Similarly as for the parent policies, to choose among the non-dominated policies and deal with the uncertainty of the outcomes, the analysis cannot be restricted to mean values, and a preference structure must be explicitly expressed.

5.3.6. The impact of physical damage feedback on climate policies

Policies have better performance under damages because they lead, on average, to lower total emissions (Fig. 2(c)) at similar costs.

The main effect of the damages to capital stock is the productive capacity reduction that leads to lower consumption levels than in the no-damage case. Since firms' production plans are based on past sales, the input demand (labour and capital) decreases, and scenarios with physical damage feed-back are characterized by higher unemployment rates (Fig. 16(c)) relative to the no damages scenarios. The lower the consumption (Fig. 15(b)), the higher the deficit to GDP ratio and then, the higher the tax rate that exacerbates the economic growth reduction.

The differences between the damage and no-damage scenarios decrease with the intensity of the policies, as shown in Fig. 13(c). This is because lower emissions lead to lower climate damage. Then, given the damages function used, the most effective policies can reduce the negative consequences of the damages. However, this is not granted if a function that leads to more significant damages for every temperature anomaly value is used, because more significant damages require higher reduction. Eventually, if damages are higher enough, no emission reduction will succeed in avoiding damage consequences. A similar reasoning applies if the simulation period is changed from 30 to 80 years.

The effects of the damages are different for each of the 3 types of policies considered. Comparing the two individual policies again leads to results similar to those relative to the no-damage case (see Fig. 12(b)): only two of the CTs are not dominated by the FITs. Note, however, that there is a FIT that another FIT dominates. Including PMs, we can see that damages negatively affect their performances relative to those of the FITs: a FIT dominates two PMs.

The analysis of the interactions between the mix components confirms this result. Fig. 17, the analogous of Fig. 11 for the scenarios with physical damage feed-back, shows that most of the PMs lie outside the shaded region, and since both emission reduction and costs of the PMs

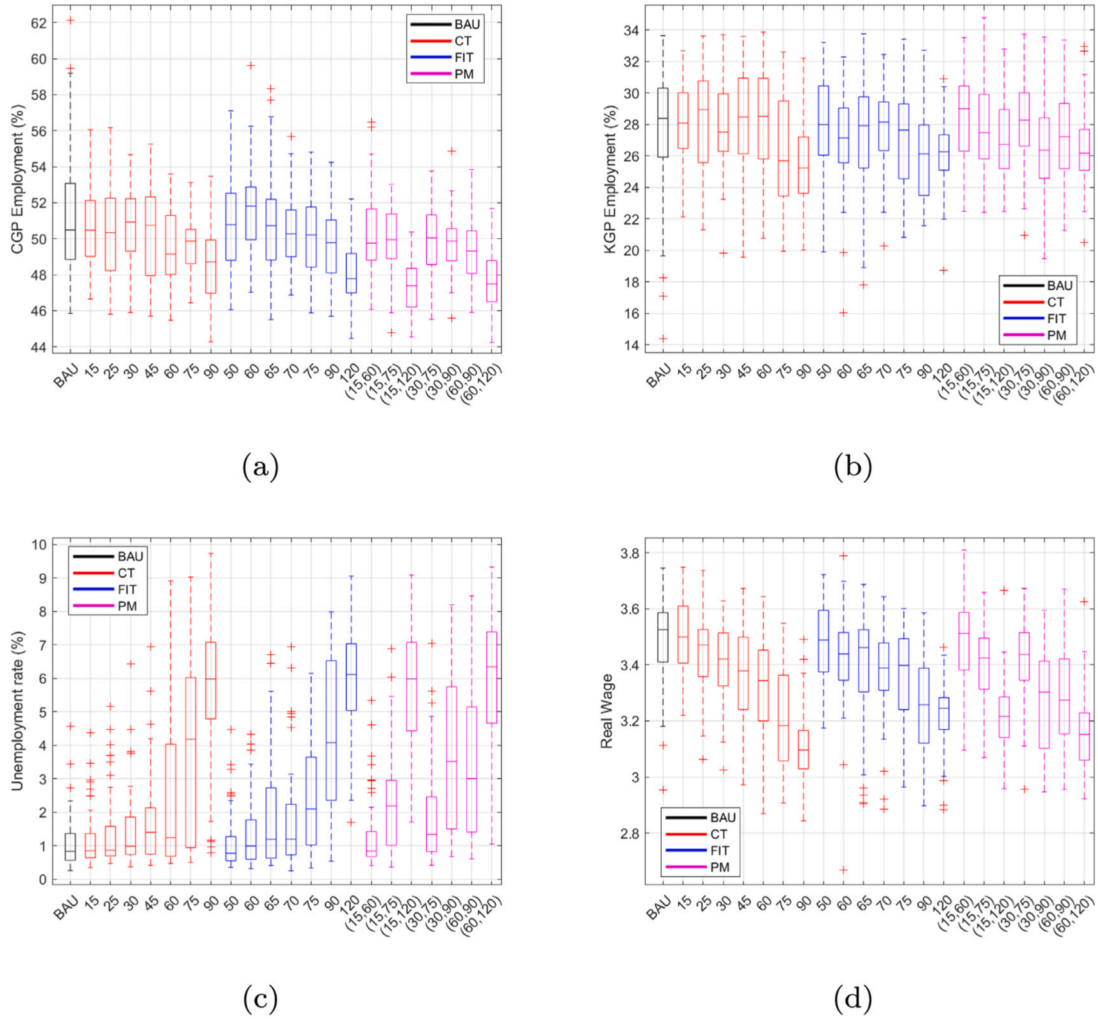

Fig. 6. The figure shows the boxplots of the temporal mean of the variables of interest for all the scenarios without physical damage feed-back considered. In particular, it shows: (a) the employment rate of the consumption goods sector, (b) the employment rate of the capital goods sector, (c) the unemployment rate and (d) the mean real wage.

are higher than those of their components, it cannot be concluded that PMs are better or worse without defining a preference structure.

Damages affect the PM more negatively than the FIT. This result can be explained by looking at the effects of damages on the interaction between the two single policies. As shown in the previous section, consumption losses relative to the BAU scenario in the PM scenario are determined by two potential causes, each related to one of its components and a third one related to the interaction between the components:

- (CT) the increase in energy price leads to an increase of the consumption goods price and therefore to a lower **real** consumption goods demand;
- (FIT) financing the FIT increases the government deficit, the government increases the general tax rate τ to hold the deficit below 3% of GDP, and this leads to:
  - higher consumption prices (prices are proportional to $1+\tau$)
  - lower **nominal** demand[16] because the disposable income is proportional to $1-\tau$;
- (Interaction) Since the carbon tax increases the energy price p_E, the cost of the FIT, given by $(p^r_E - p_E)E_R$, is reduced for every unit of renewable energy sold relative to the scenario in which only the FIT policy is implemented. Then, the government deficit is lower in the policy mix scenario than in the FIT scenario, and the average tax rate is lower. Therefore, the interaction between the two policies mitigates consumption losses due to the previous cause.

The policy mix's consumption loss can be considered the sum of the three causes mentioned above. Note that the "interaction" term has the opposite sign with respect to the other two since the consumption loss of the PM is always lower than the sum of the consumption losses of the other two policies. When climate damage is considered, the unemployment level is higher for all the policies. Therefore, the deficit to GDP ratio shift under the 3% threshold is countered by an increase in the deficit due to an increase in the unemployment benefits that the government has to pay. This results in a lower contribution of the interaction term in reducing the consumption loss of the PM.

6. Conclusion and policy implications

Several studies (e.g. Görlach (2014), Lehmann (2012) and Jaffe et al. (2004)), showed that a mix of instruments is more appropriate for climate mitigation because of the multiple objectives of climate

[16] if $\tau \geq 0.3$ otherwise the increase of the consumption budget due to the increase of unemployment benefits is greater to the decrease of the consumption budget due to the decrease of disposable income.

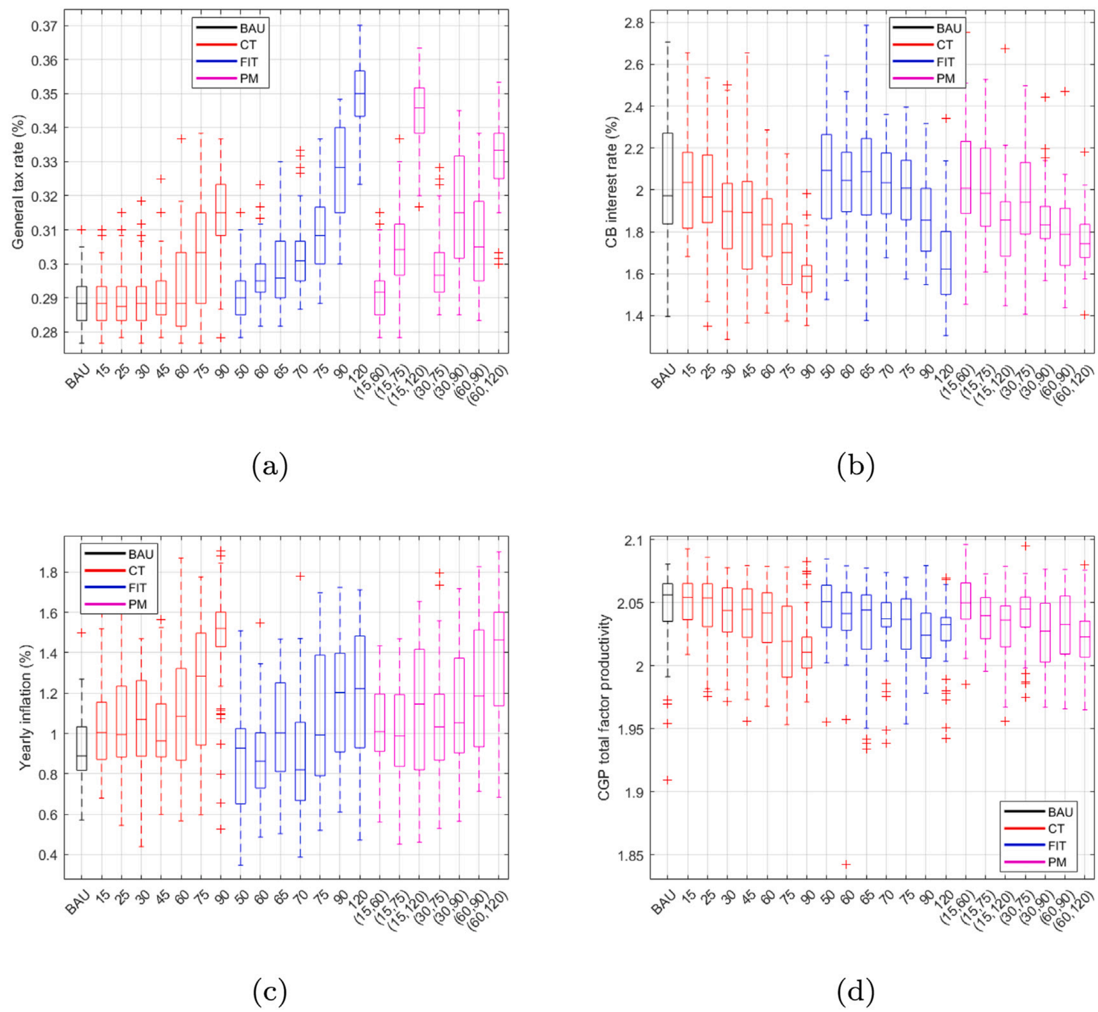

Fig. 7. The figure shows the boxplots of the temporal mean of the variables of interest for all the scenarios without physical damage feed-back considered. In particular, it shows: (a) the general tax rate, (b) the central bank interest rate, (c) the inflation rate and (d) the mean TFP of the CGPs.

policies. The definition and study of the optimal policy mix is important (Bouma et al., 2019), but the current state of the art is still preliminary (Krogstrup and Oman, 2019). This paper contributes to this research by examining a policy mix (PM) of a carbon tax (CT) and a feed-in tariff (FIT) through the EURACE model. To analyse policy mix effects, we first assessed individual instruments relative to a business-as-usual (BAU) scenario. Then, we studied their interaction within the policy mix.

Computational results allow us to identify the multiple channels that lead to the desired emissions reduction and the costs (consumption loss relative to the BAU) for each of the policies considered. We found that both economic costs and emission reduction generated by the carbon tax policy come from the impact on the energy price. A higher energy price fosters energy intensity improvements and increases the share of renewable energy. However, it also determines an increase in the price of goods that reduces real consumption, the employment rate in the private sector, and household purchasing power. For the highest values of CT, the reduction in consumption affects the government budget as the increase in tax revenue from CT is more than offset by the decrease in general tax revenue due to the lower GDP. Furthermore, to reduce the deficit, the government sets a higher general tax rate that exacerbates the economic performance reduction.

Under the feed-in tariff policy, the renewable power producer is remunerated with the guaranteed price p_E^r, given that this is higher than the energy price. Therefore, it increases the share of renewable energy (Fig. 3(b)), reducing the emissions generated by the unit of energy produced by the economy. The economic cost (consumption loss compared to the BAU) emerges mainly via the increased government expenditure due to the FIT policy cost (the incentive to the renewable energy paid by the government): to finance the additional cost of the FIT policy, the government increases the general tax rate that leads to higher consumption prices, lower real demand of consumption goods and then of production inputs, i.e. labour and capital.

When both policies are implemented, emissions are reduced through the increase in renewable share, the reduction of energy demand via energy intensity improvements, and consumption reduction. As for the carbon tax, the energy intensity improvements lead to negligible emission reduction. The feed-in tariff component determines the renewable energy share increase because the guaranteed price for renewable energy is greater than the energy price; otherwise, the feed-in tariff would not be active. The energy intensity improvement is determined by the increase in energy prices due to the carbon tax component. The consumption loss arises from the consumption price increase due to the higher energy price (carbon tax component) and the higher tax rate due to the feed-in tariff policy cost. However, comparing policy mixes with the same feed-in tariff in Fig. 8(b) shows that the higher the carbon price, the lower the feed-in tariff policy cost. Therefore, the increase in the general tax rate due to the feed-in tariff cost is milder in the policy mix than in the isolated corresponding feed-in tariff (Fig. 7(a)).

Based on our findings, we can deduce the following implications for an effective climate policy:

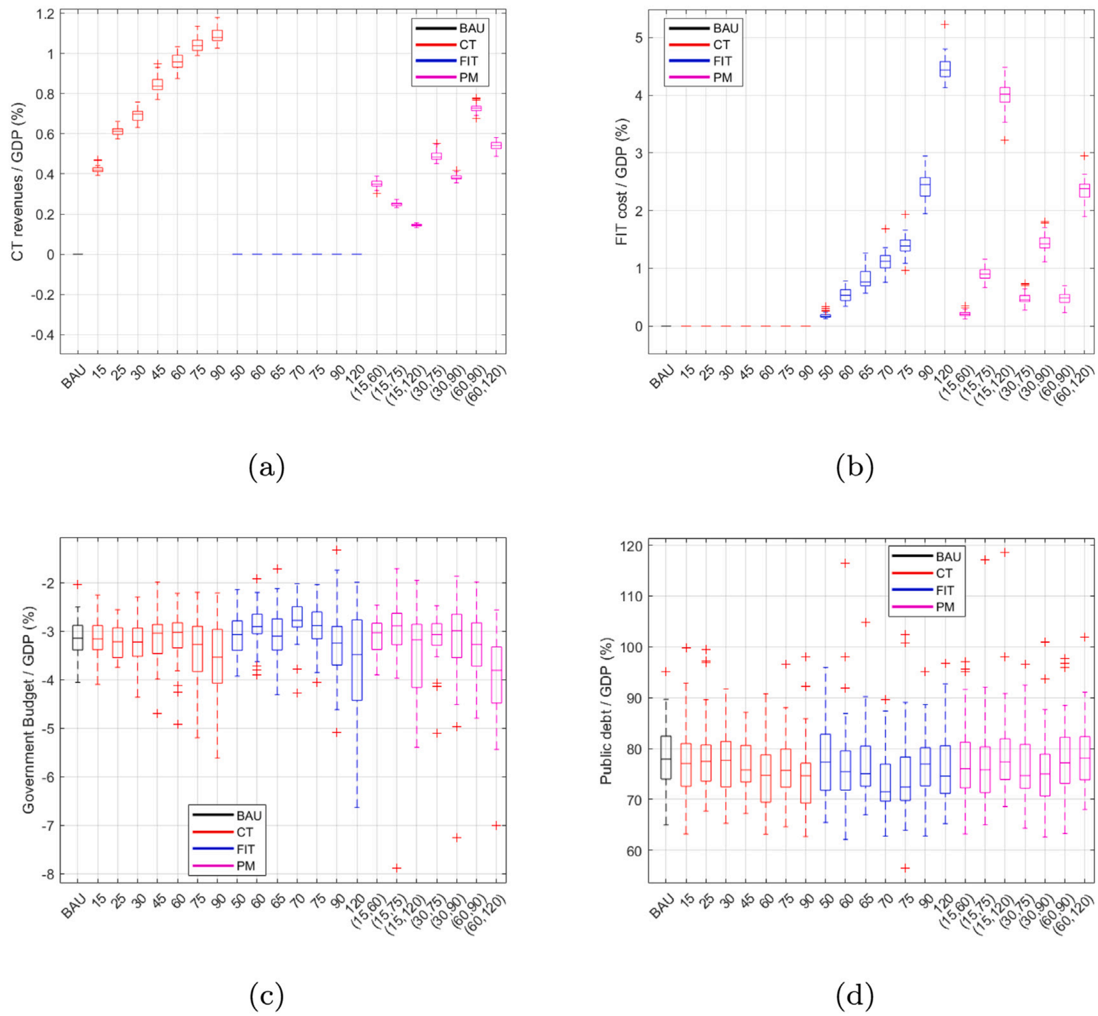

Fig. 8. The figure shows the boxplots of the temporal mean of the variables of interest for all the scenarios without physical damage feedback considered. In particular, it shows: (a) the CT revenues over GDP, (b) the FIT expenditure over GDP, (c) the government budget over GDP and (d) the government debt over GDP.

- There may be more effective policies than the carbon tax. While the CT has multiple channels for reducing emissions, each channel has varying levels of efficiency. The carbon tax reduces emissions because higher energy prices encourage capital investments that consume less energy and investments in renewable energy production. However, our research shows that increasing energy efficiency has a minimal impact on reducing emissions compared to switching from fossil fuel to renewable sources. As a result, part of the economic cost of the carbon tax is used to reduce energy efficiency, which is not an effective way to reduce emissions.
- It might be more beneficial to focus on policies that target the most efficient channels (or the most relevant ones), such as offering subsidies for specific types of investments. Indeed, the Feed-in Tariff policy only fosters investments in renewable energy, making it more efficient than the carbon tax in reducing emissions.
- Combining FIT policy with a low carbon tax could minimize the economic impact. The policy mix approach would have two main benefits: the government would generate more tax revenue, and the carbon tax would increase the price of energy and related goods, narrowing the gap between the profitability of environmentally harmful investments and that of environmentally friendly ones.
- The combination of policies is more effective than individual policies, even if they address the same externality. The literature advocating for policy combinations tends to view the mix in this case as unproductive or, at best, redundant. However, our findings show that combining the two policies can produce similar results with lower policy intensity (establishing an emissions price for carbon taxes and ensuring energy prices through government feed-in tariffs). This finding is significant when considering transition risks, which our model does not account for. As a result, the costs of policies are underestimated, and this underestimation grows with higher policy intensity. Therefore, using policies with lower intensities becomes even more advantageous.

Finally, our research, which compares policies' performance in emission reduction and consumption loss to the BAU scenario implied by each policy, underscores the need for further investigation. We argue that explicitly defining a preference structure is relevant to determining the effectiveness of a policy mix and selecting the best policy. This is a key area that research must urgently address to guide future policy decisions.

Future developments of this study should include policy mixes composed of fiscal instruments and financial ones, e.g., green Basel-type capital requirements, the green supporting factor, or the brown penalty.

Table 6
The table shows the p-Values of the two-sided Wilcoxon rank-sum test, which tests the null hypothesis that the values of one of the relevant variables relative to two different scenarios come from distributions with the same median against the hypothesis that they are not. The test has been performed between the data relative to the single policy scenarios listed in the column indices and the data relative the BAU. All data are relative to scenarios without physical damage feed-back. When the p-Value is lower than the 5% (1%) the null hypothesis is rejected with a 5% (1%) significance level.

	Carbon tax (p_ϵ)							Feed-in tariff (p^r_E)						
	15	25	30	45	60	75	90	50	60	65	70	75	90	120
p_k (capital goods price)	0.000	0.004	0.066	0.909	0.016	0.021	0.025	0.329	0.844	0.904	0.467	0.368	0.471	0.024
K (capital stock)	0.844	0.471	0.085	0.149	0.329	0.002	0.000	0.617	0.012	0.033	0.021	0.004	0.000	0.000
s_g (green investments share)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.682	0.176	0.574	0.791	0.733	0.647	0.970
CT revenues/GDP	0.000	0.000	0.000	0.000	0.000	0.000	0.000							
CGP Employment	0.807	0.457	0.877	0.257	0.015	0.031	0.000	0.997	0.237	0.937	0.488	0.434	0.032	0.000
$\frac{\Delta C}{C}$ (consumption growth rate)	0.904	0.579	0.073	0.048	0.163	0.000	0.000	0.823	0.218	0.015	0.025	0.003	0.000	0.000
Real consumption	0.056	0.000	0.000	0.000	0.000	0.000	0.000	0.206	0.001	0.001	0.000	0.000	0.000	0.000
p_C (consumption goods price)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.127	0.021	0.009	0.004	0.000	0.000	0.000
i_E (energy intensity)	0.014	0.002	0.125	0.007	0.002	0.102	0.617	0.997	0.269	0.844	0.926	0.904	0.336	0.134
p_E (energy price)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.234	0.959	0.992	0.387	0.410	0.738	0.024
FIT cost/GDP								0.000	0.000	0.000	0.000	0.000	0.000	0.000
GDP	0.167	0.833	0.738	0.171	0.926	0.003	0.000	0.647	0.020	0.067	0.006	0.028	0.000	0.000
Gov. debt/GDP	0.702	0.697	0.430	0.136	0.001	0.091	0.001	0.697	0.127	0.176	0.000	0.006	0.953	0.245
Gov. deficit/GDP	0.350	0.652	0.692	0.293	0.035	0.115	0.000	0.662	0.056	0.035	0.000	0.000	0.102	0.045
General tax rate	0.907	0.975	0.631	0.407	0.266	0.000	0.000	0.097	0.000	0.000	0.000	0.000	0.000	0.000
Inflation rate	0.014	0.015	0.001	0.035	0.002	0.000	0.000	0.383	0.199	0.036	0.229	0.097	0.000	0.000
Real investments	0.975	0.712	0.497	0.964	0.833	0.002	0.000	0.697	0.058	0.196	0.269	0.042	0.000	0.000
KGP Employment	1.000	0.723	0.723	0.677	0.480	0.035	0.000	0.833	0.090	0.383	0.612	0.155	0.003	0.002
$\mathcal{E}$ (GHGs emissions)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Real GDP	0.237	0.034	0.002	0.000	0.000	0.000	0.000	0.343	0.006	0.015	0.001	0.000	0.000	0.000
GDP growth rate	0.376	0.163	0.030	0.034	0.029	0.000	0.000	0.801	0.027	0.002	0.002	0.000	0.000	0.000
Real wage	0.997	0.070	0.004	0.000	0.000	0.000	0.000	0.515	0.003	0.008	0.000	0.000	0.000	0.000
s_R (renewable energy share)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TFC	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.000	0.000	0.000	0.000	0.000
Unemployment	0.406	0.163	0.065	0.005	0.002	0.000	0.000	0.964	0.088	0.042	0.006	0.000	0.000	0.000

Table 7
The table shows the p-Values of the two-sided Wilcoxon rank-sum test, which tests the null hypothesis that the values of one of the relevant variables relative to two different scenarios come from distributions with the same median against the hypothesis that they are not. The test has been performed between the data relative to the policy mix scenarios listed in the column indices and the data relative the BAU. All data are relative to scenarios without physical damage feed-back. When the p-Value is lower than the 5% (1%) the null hypothesis is rejected with a 5% (1%) significance level.

	Policy mix (p_ϵ, p^r_E)						
	(15,60)	(15, 75)	(15, 120)	(30,75)	(30,90)	(60,90)	(60,120)
p_k (capital goods price)	0.000	0.000	0.438	0.000	0.016	0.000	0.020
K (capital stock)	0.860	0.004	0.000	0.044	0.000	0.010	0.000
s_g (green investments share)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CT revenues/GDP	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CGP Employment	0.218	0.158	0.000	0.153	0.051	0.005	0.000
$\frac{\Delta C}{C}$ (consumption growth rate)	0.603	0.218	0.000	0.254	0.003	0.000	0.000
Real consumption	0.035	0.000	0.000	0.000	0.000	0.000	0.000
p_C (consumption goods price)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
i_E (energy intensity)	0.008	0.087	0.866	0.006	0.281	0.020	0.442
p_E (energy price)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
FIT cost/GDP	0.000	0.000	0.000	0.000	0.000	0.000	0.000
GDP	0.143	0.319	0.000	0.484	0.009	0.155	0.001
Gov. debt/GDP	0.414	0.178	0.471	0.077	0.044	0.612	0.132
Gov. deficit/GDP	0.672	0.123	0.189	0.524	0.004	0.828	0.329
General tax rate	0.093	0.000	0.000	0.000	0.000	0.000	0.000
Inflation rate	0.006	0.050	0.003	0.010	0.000	0.000	0.000
Real investments	0.844	0.161	0.001	0.438	0.001	0.018	0.000
KGP Employment	0.450	0.446	0.024	0.959	0.017	0.243	0.003
$\mathcal{E}$ (GHGs emissions)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Real GDP	0.254	0.000	0.000	0.001	0.000	0.000	0.000
GDP growth rate	0.201	0.014	0.000	0.024	0.000	0.000	0.000
Real wage	0.537	0.001	0.000	0.005	0.000	0.000	0.000
s_R (renewable energy share)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TFC	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Unemployment	0.542	0.000	0.000	0.002	0.000	0.000	0.000

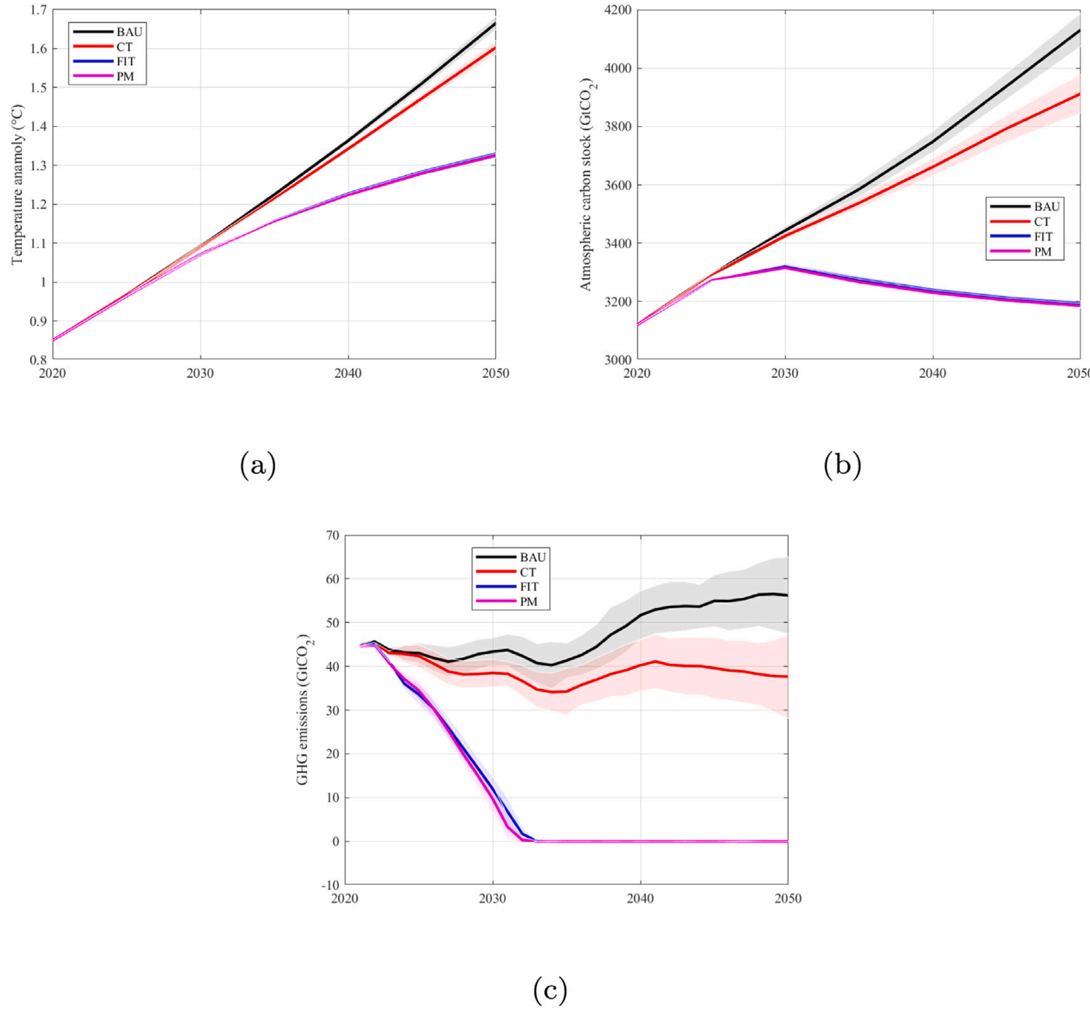

Fig. 9. The figure shows the temporal evolution of the ensemble average (over seeds) of the variables of interest for all the scenarios without physical damage feedback considered. The trajectory of the ensemble average is depicted with shadowing regions representing the standard deviation around the mean. In particular, it shows: (a) the temperature anomaly, (b) the atmospheric carbon stock and (c) the GHGs emissions.

CRediT authorship contribution statement

Marcello Nieddu: Writing – original draft, Software, Investigation, Data curation. **Marco Raberto:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization. **Linda Ponta:** Writing – review & editing, Software, Methodology. **Andrea Teglio:** Writing – review & editing, Validation, Software, Methodology, Conceptualization. **Silvano Cincotti:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix. Model description

In this appendix, we complement the previous section on the model overview with a description of the technical details of the new features of the model introduced for this study. In particular, we begin by introducing the climate module, which has been added to account for climate-economy interactions. Subsequently, we discuss the critical enhancements in the energy sector compared to Ponta et al. (2018). A further subsection describes how the terms in the present value calculations are determined in the investment decision-making. Finally, the last part describes the technological progress.

A.1. Climate module

The economy affects the climate through GHGs emissions from fossil fuels combusted for energy production, while the climate affects the economy by damaging physical capital, with damages that depend on the temperature anomaly. The carbon stock and temperature evolution are grounded on the DICE model (Nordhaus, 1993): the climate is represented as three overlapping layers, namely the atmosphere and the upper and lower oceans, where each layer exchanges GHGs and heat only with adjacent layers. Each layer has its own GHGs stock and

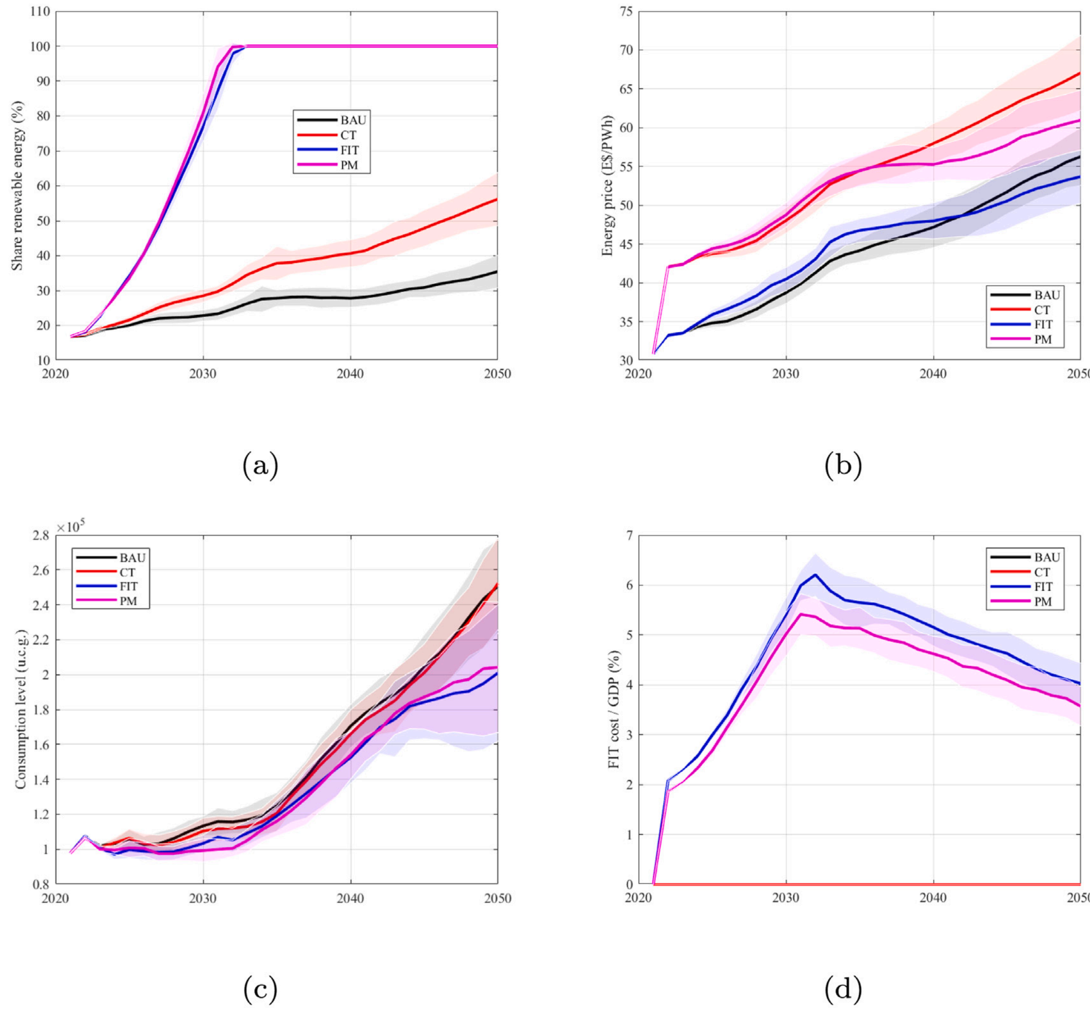

Fig. 10. The figure shows the temporal evolution of the ensemble average (over seeds) of the variables of interest for all the scenarios without physical damage feed-back considered. The trajectory of the ensemble average is depicted with shadowing regions representing the standard deviation around the mean. In particular, it shows: (a) the share of renewable energy, (b) the energy price, (c) the real consumption and (d) the FIT expenditure over GDP.

transfers to the adjacent layers a quantity of GHGs proportional to its stock. Once GHGs are released into the atmosphere from the energy production process, the evolution of stocks is given by:

$$M_{1,t+1} = (1 - A_{21})M_{1,t} + A_{12}M_{2,t} + \mathcal{E}_t \tag{A.1}$$

$$M_{2,t+1} = A_{21}M_{1,t} + (1 - A_{12} - A_{32})M_{2,t} + A_{23}M_{3,t} \tag{A.2}$$

$$M_{3,t+1} = A_{32}M_{2,t} + (1 - A_{23})M_{3,t} \tag{A.3}$$

where M_1, M_2 and M_3 are the GHGs stocks of the atmosphere, the upper ocean and the lower oceans, respectively, the coefficient A_{ij} is the share of GHGs stock in layer j transferred to layer i and it is zero for non-adjacent layers. Note that in the absence of emissions, the total quantity of GHGs, i.e. the sum of all the stocks, is constant. In the absence of emissions, the linear system evolves toward an equilibrium point that can be calculated by imposing $M_{i,t+1} = M_{i,t}$ for each layer and $\mathcal{E}_t = 0$. Therefore, if GHGs are emitted into the atmosphere for a limited period, the quantity of GHGs given by the cumulative emissions is redistributed in the three layers according to the proportions of the equilibrium point.

The accumulation of GHGs in the atmosphere alters the net flux of energy in the climate system and leads to global warming. Following Nordhaus (1993), the influence of GHGs accumulation is captured in the expression for the change in radiative forcing F_t with respect to the pre-industrial levels:

$$F_t = f_{CO_2 2X} log_2 \left(\frac{M_{1,t}}{M_{1,1750}} \right) + F_t^{ex} \tag{A.4}$$

where $f_{CO_2 2X}$ represents the increase due to a doubling of the GHGs atmospheric stock with respect to the 1750 level, and F_t^{ex} is an exogenous forcing component including the influence of aerosols, ozone, albedo changes, and other factors. To describe temperature changes, the atmosphere and the upper ocean layers are aggregated in one layer, which will be called the atmosphere in the following. It is assumed that the atmosphere and the lower oceans exchange a quantity of heat proportional to the difference between the temperature of the two layers. This leads to a change in the temperature of each layer equal to the quantity of heat mentioned above divided by the thermal capacity of each layer. Given that the radiative forcing affects only the atmosphere, the temperature evolution reads:

$$T_{1,t+1} = T_{1,t} + \xi_1 \left[F_{t+1} - \frac{f_{CO_2 2X}}{t_{CO_2 2X}} T_{1,t} - \xi_3 (T_{1,t} - T_{2,t}) \right] \tag{A.5}$$

$$T_{2,t+1} = T_{2,t} + \xi_4 (T_{1,t} - T_{2,t}) \tag{A.6}$$

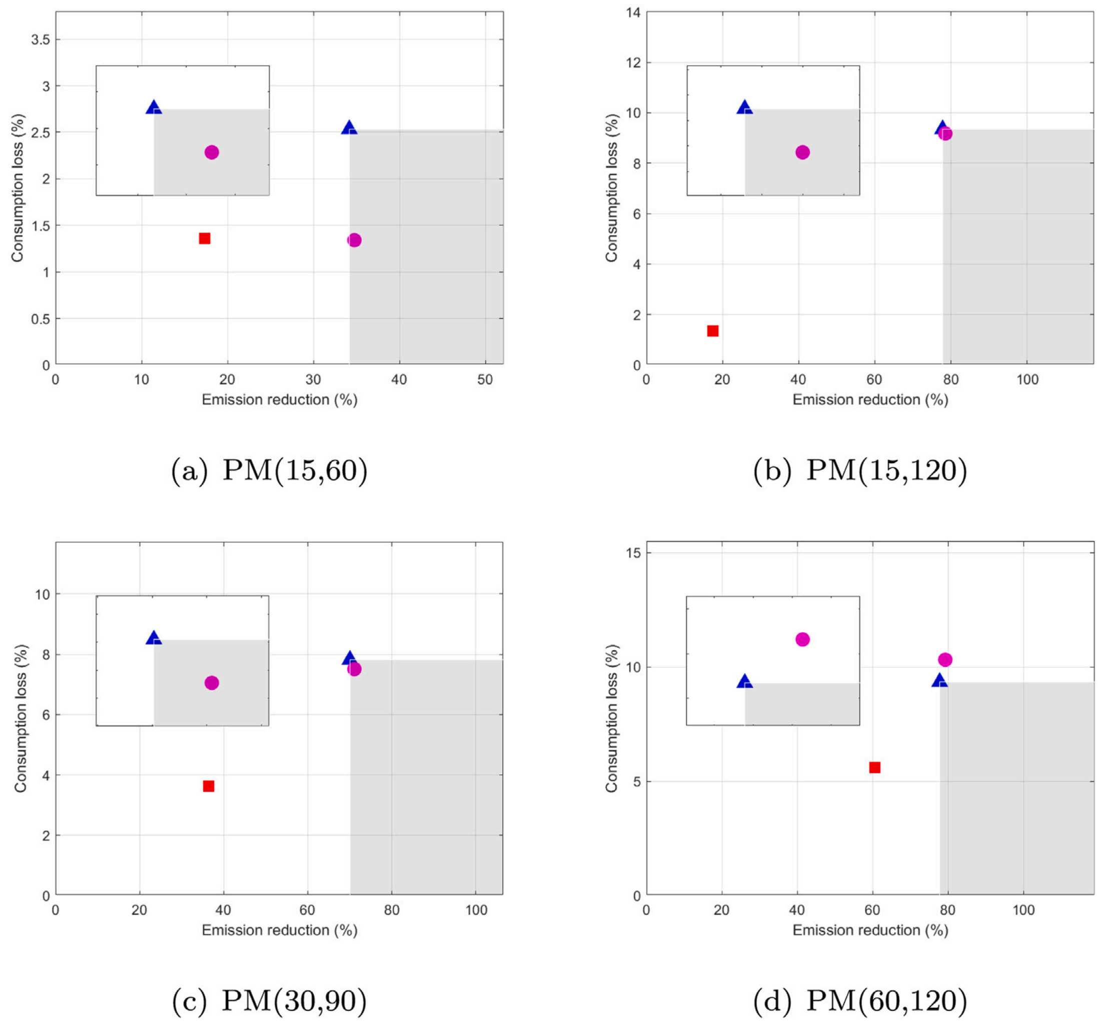

Fig. 11. The figure shows the policy mix performance compared to that of its parent policies in the scenarios without physical damage feedback. In each panel, the *x*-axis represents the negative of emission reduction with respect to the BAU, the *y*-axis represents the negative of the consumption loss with respect to the BAU, as defined in the main text. In each graph, the average values of the emission reduction and consumption loss relative to the policy mix under exam (magenta circles) and to its CT (red squares) and FIT (blue triangles) components are represented. The shaded area represents the region where the policy mix reaches an objective (emission reduction) better than the best reached by the isolated policies at a cost (consumption loss) lower than the highest cost implied by the isolated policies. Each graph shows an enlargement at the top left of the figure that helps to evaluate the performance of the policy mix with respect to the shaded region.

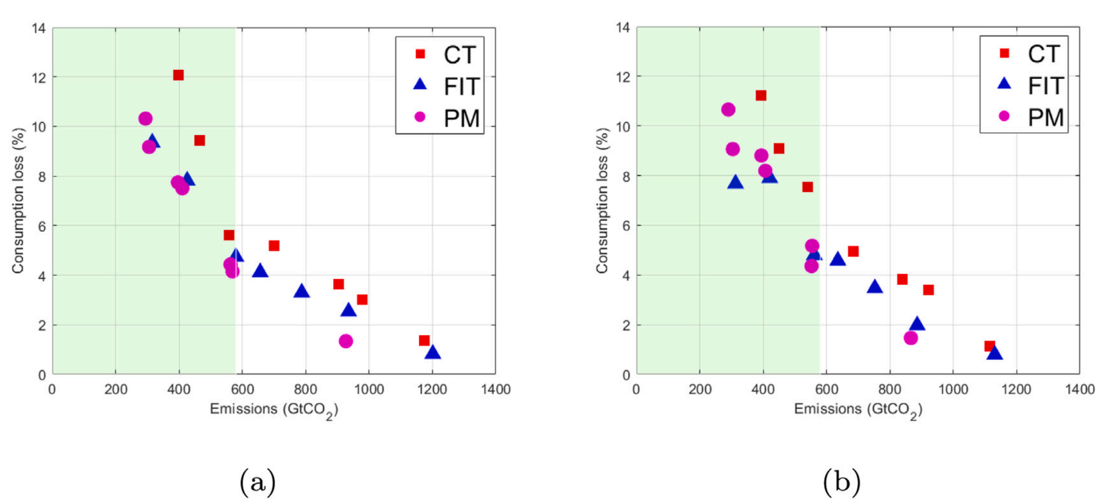

Fig. 12. The figure shows the cost VS objectives graph, where the policies are represented by points in the plane total emission VS consumption reduction with respect to the BAU. The green shaded area represents the policies for which total emissions are lower than the remaining carbon budget of 580 $GtCO_2$.

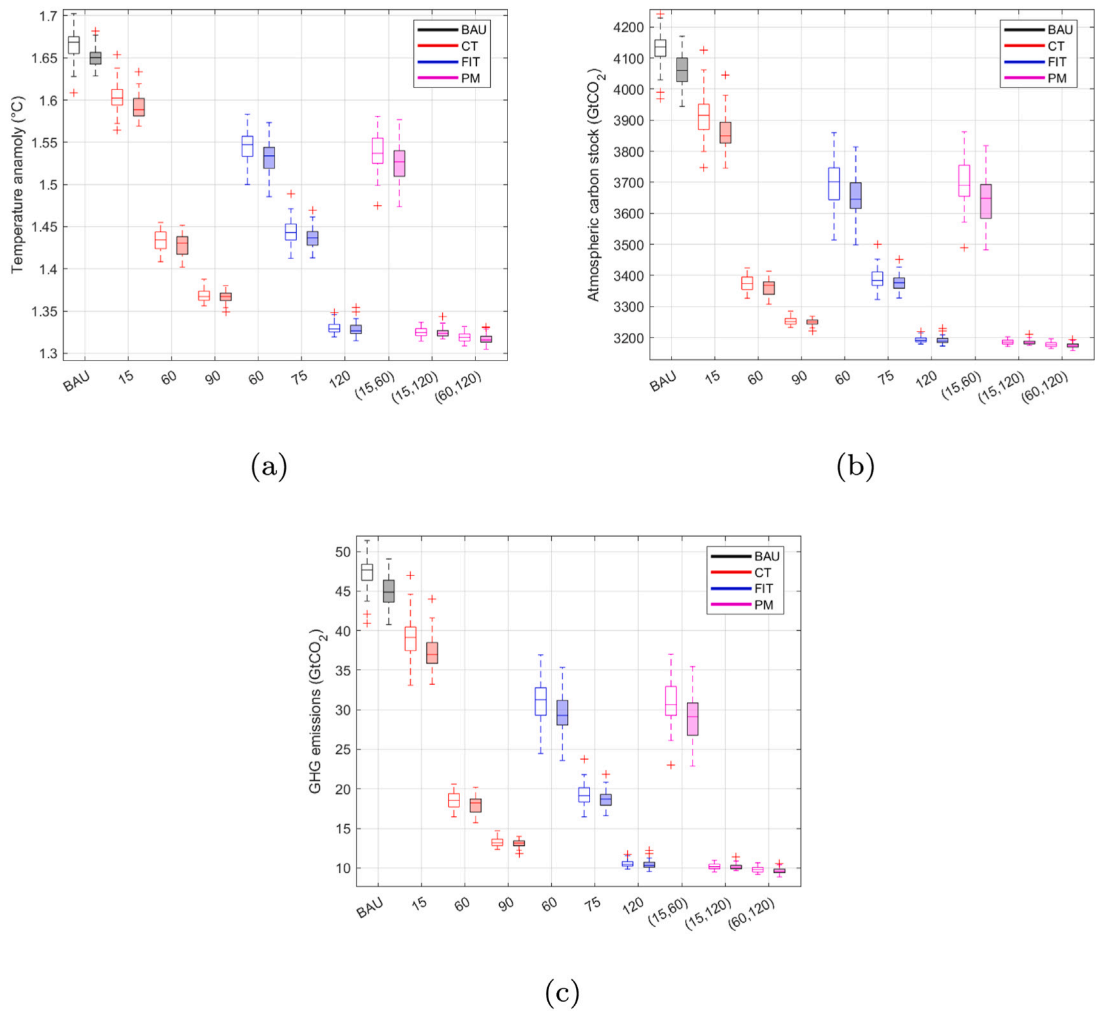

Fig. 13. The figure shows the boxplots of the final value or the temporal mean of the variables of interest for the ten most representative scenarios considered. Empty boxes refer to scenarios without physical damage feedback, while filled boxes refer to scenarios with physical damage feedback. In particular, it shows: (a) the final value of the temperature anomaly, (b) the final value of the atmospheric carbon stock and (c) the mean value of yearly GHGs emissions.

where T_1 and T_2 are the temperature anomalies[17] of the atmosphere and of the lower oceans respectively, ξ_1 is a calibration parameter regulating the time of convergence to equilibrium, ξ_3 and ξ_4 are coefficients related to the thermal capacity of the two layers, and $t_{CO_2 2X}$ is a parameter representing the equilibrium temperature change due to a doubling of atmospheric GHGs stock. In Table A.10 are reported the values of the parameters used to calibrate the climate module.

We express damages as capital reduction instead of output reduction, as used in the DICE model. Unlike output reduction, the destruction of capital represents permanent damage with negative consequences extending to all subsequent periods after the damage occurs. Neglecting permanent damages can lead to underestimating the climate impacts on economic growth (Stern, 2013; Bretschger and Pattakou, 2019); moreover, as pointed out by Lamperti et al. (2018), damages on output do not change the likelihood of the green transition. Every year, the climate module causes damages to every firm, destroying a fraction s_f of its capital (the index f runs over all the firms). The model allows the use of both an aggregate damages function, where $s_f = s \quad \forall f$, and a disaggregate damages function in which fractions s_f are different and are picked up from a probability density function whose properties are dependent on the temperature. While in Nieddu et al. (2022) the authors followed the approach outlined in Lamperti et al. (2018), picking damages fractions s_f from a beta distribution function, here we use an aggregate damages function, derived from that used by Nordhaus (1993), where the fraction of output $\left(\frac{\Delta Q}{Q}\right)_{damage}$ destroyed by climate change is expressed as a quadratic function of the atmospheric temperature anomaly:

$$\left(\frac{\Delta Q}{Q}\right)_{damage} = \Omega T_{AT}^2 \tag{A.7}$$

where Ω is a calibration coefficient.

Using the value from Table A.10, in an environment with a 3 ° C temperature anomaly, climate change destroys approximately two per cent of the total output. Since damages in the Eurace model affect firms' capital stock and since the production function used by firms in the Eurace model is a Cobb–Douglas with β as the exponent for the capital factor, we set:

$$s = \left(\frac{\Delta K}{K}\right)_{damage} = \frac{1}{\beta}\left(\frac{\Delta Q}{Q}\right)_{damage} \tag{A.8}$$

A.2. The energy sector

CGPs demand for energy is given by:

$$E_f^D = i_{Ef} Q_f \tag{A.9}$$

[17] That is the difference between the actual and preindustrial level of the temperature, the latter assumed to be that of the year 1750.

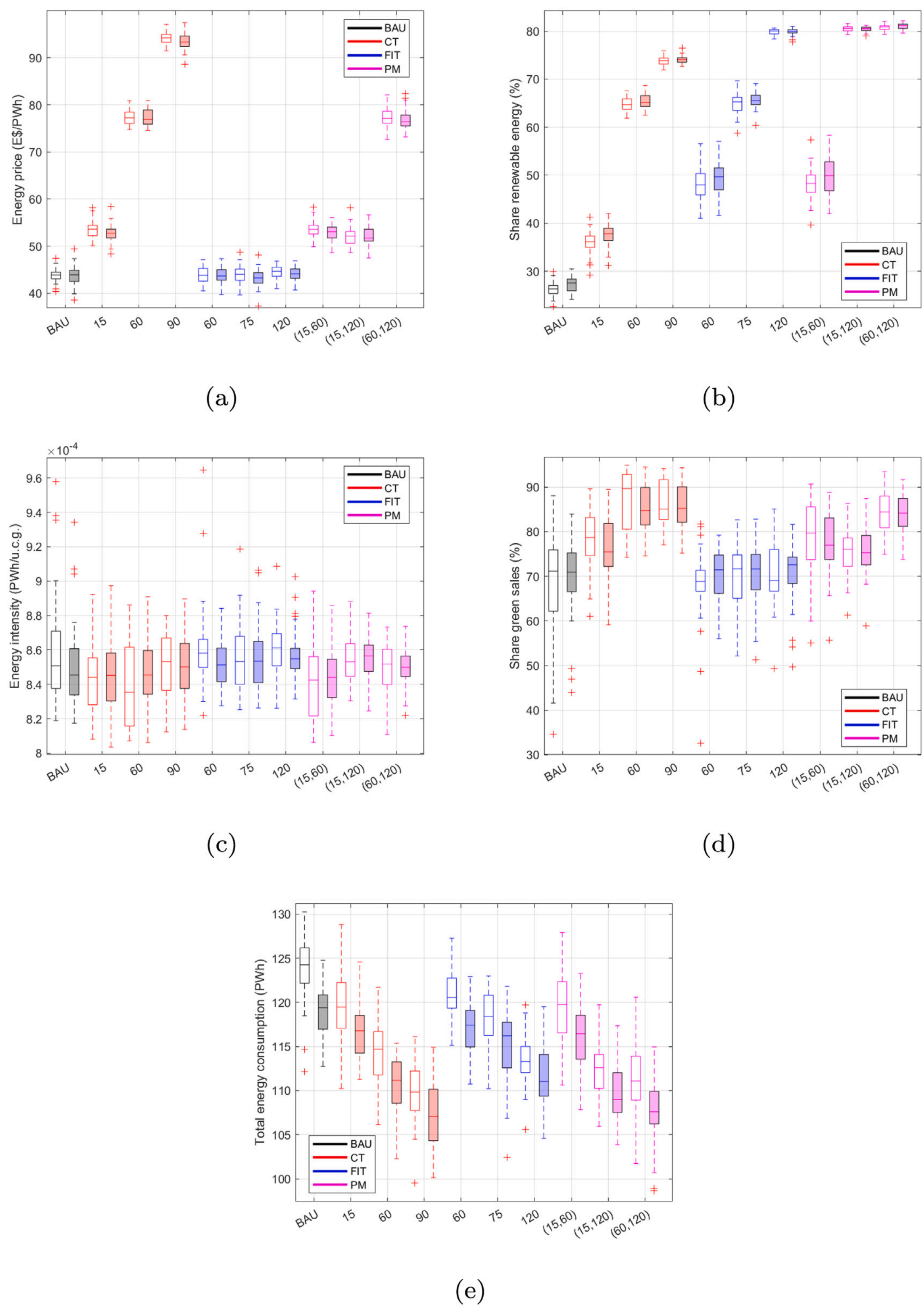

Fig. 14. The figure shows the boxplots of the temporal mean of the variables of interest for the ten most representative scenarios considered. Empty boxes refer to scenarios without physical damage feedback, while filled boxes refer to scenarios with physical damage feedback. In particular, it shows: (a) the energy price, (b) the share of renewable energy, (c) the energy intensity, (d) the share of green investments and (e) the total final consumption of energy.

where E_f^D is the energy demand, i_{Ef} is the energy intensity of the consumption good production process, and Q_f is the number of goods produced in a month, all relative to the firm f. Energy is produced by a non-renewable energy producer (PP), which uses fossil fuels, and by a renewable energy producer (RP). The RP agent has grid priority, which means that the energy needs of the CGPs are initially fulfilled with

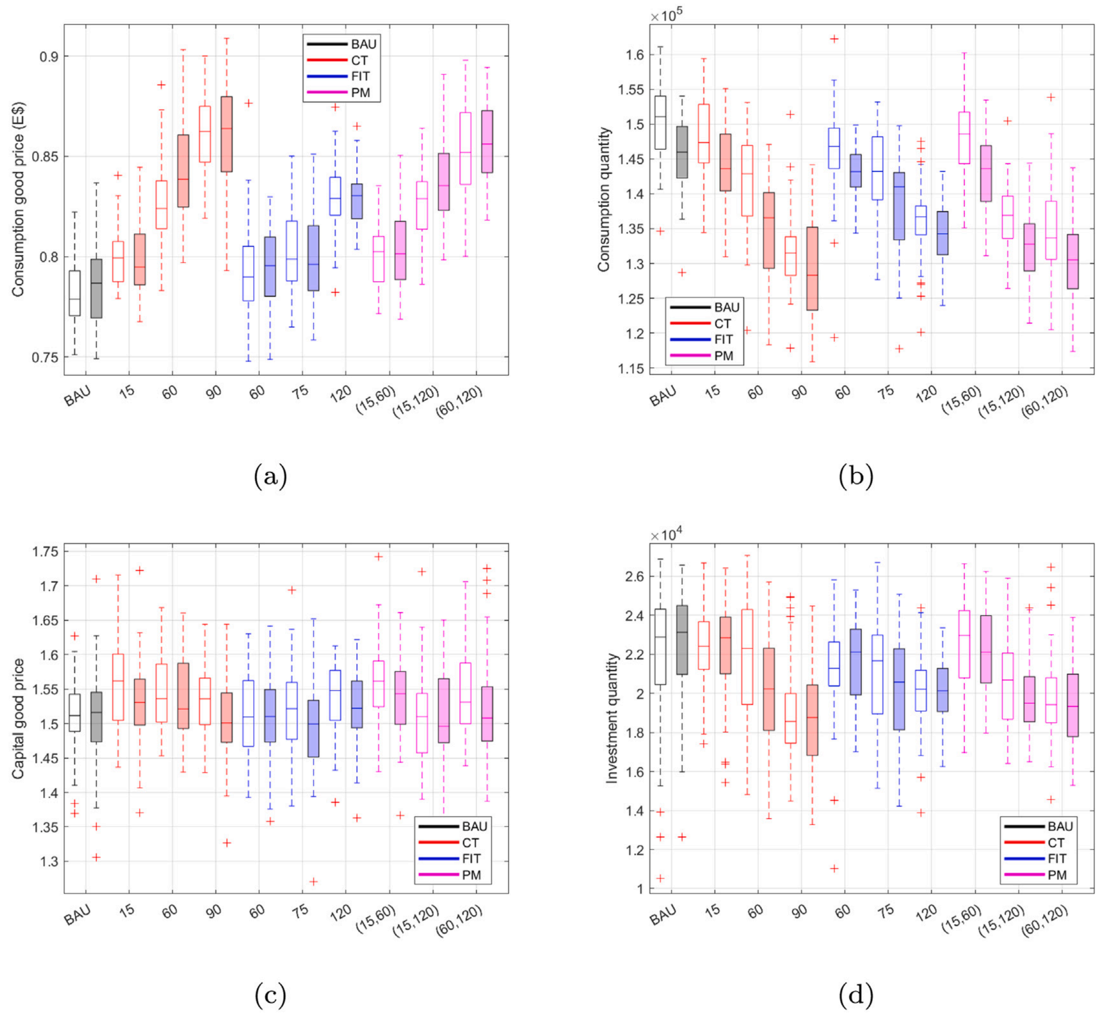

Fig. 15. The figure shows the boxplots of the temporal mean of the variables of interest for the ten most representative scenarios considered. Empty boxes refer to the scenarios without physical damage feed-back, while filled boxes refer to scenarios with physical damage feed-back. In particular, it shows: (a) the consumption price, (b) the real consumption, (c) the capital price and (d) the real investments.

renewable energy before resorting to fossil energy. Thus, the energy produced by the PP agent equals the total energy demand minus the renewable energy produced.

The energy produced by the RP is given by the product of the number of renewable power stations installed n_s (identified in the model as the capital goods) and the monthly energy production m_s of each power station, i.e.:

$$E_{RP} = n_s m_s \tag{A.10}$$

The RP decides on a monthly basis the quantity of additional renewable power plants Δn_s to purchase from the producers of capital goods (KGPs). The decision is taken by evaluating the net present value (NPV) of the expected additional earnings related to the investment Δn_s. Furthermore, since there are two suppliers (KGPs) in the capital goods market, the RP agent must make a selection. To this purpose, the RP calculates the NPV of the investment associated with each of the two KGPs; if none is positive, the RP does not invest; if only one NPV is positive, then the RP chooses the corresponding KGP. If both NPVs are positive, the choice of the RP is determined by a stochastic rule: the supplier associated with the lowest but positive NPV is not excluded but is chosen with a low probability (10%) to take into account the uncertainties related to the economic quantities relevant for the investment decision, such as the expected future price of energy, and for the uncertainties related to limited rationality and limited computing power of the agents. In particular, the NPV is determined by the following formula:

$$NPV_k(\Delta n_s) = -p_k \Delta n_s + \sum_{j=1}^{30} \frac{p_E\, 12\, m_s\, \Delta n_s}{(1+r_{CB})^j} \quad k \in \{green, brown\} \tag{A.11}$$

where p_k is the price of capital set by the green or brown KGP, depending on flag k, p_E is the energy price and r_{CB} is the annual central bank interest rate. The first term on the right is the present cost of the investment, while in the second term, the quantity $12\, m_s\, \Delta n_s$ is the annual additional energy supplied by the new renewable stations and $(1+r_{CB})^{-1}$ is the discount factor. Since we are not explicitly modelling the depreciation of renewable stations, but we want to capture the finite lifetime of the technology, the sum of discounted future additional revenues is truncated to 30 years, which roughly corresponds to the lifetime of renewable energy production technologies. After removing from the summation symbol all terms that do not depend on index j

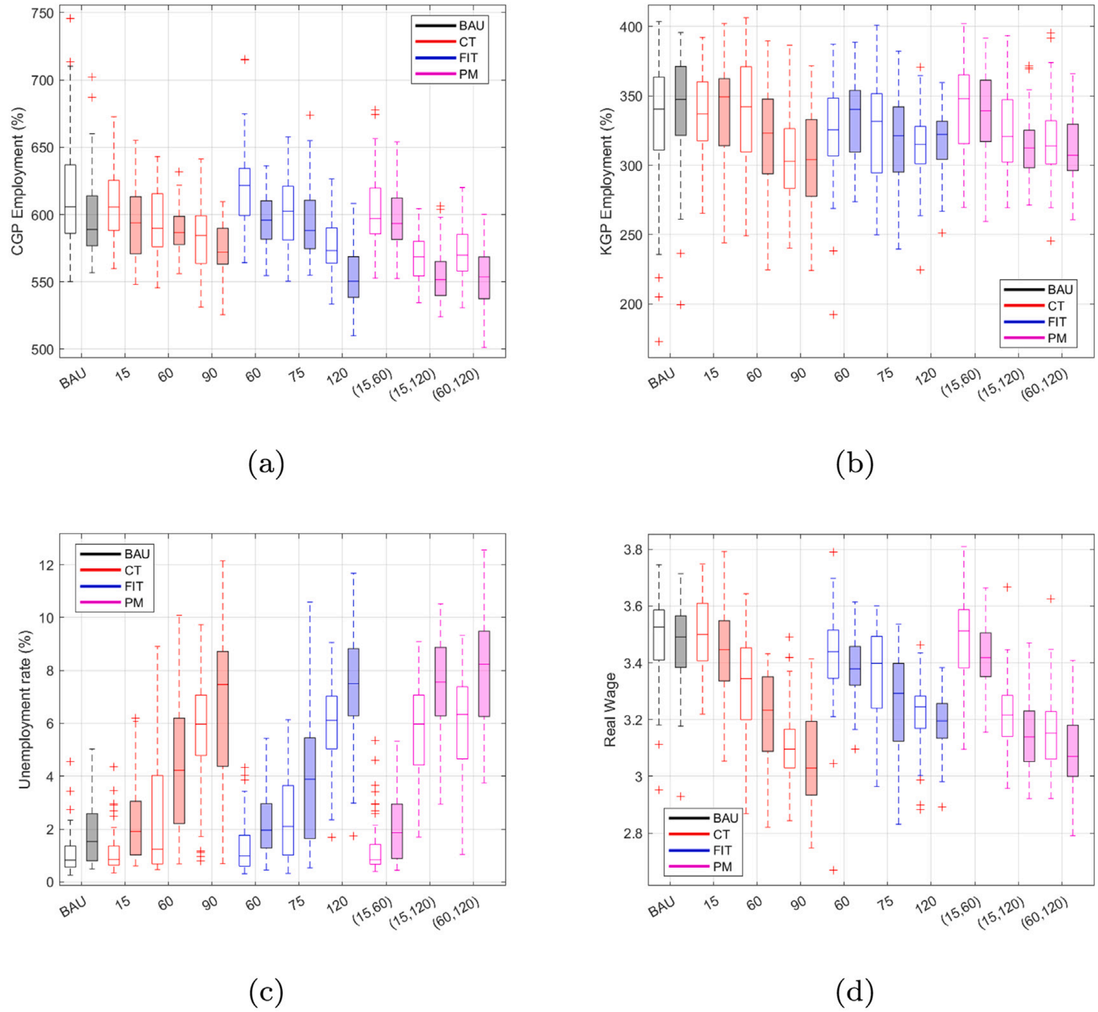

Fig. 16. The figure shows the boxplots of the temporal mean of the variables of interest for the ten most representative scenarios considered. Empty boxes refer to the scenarios without physical damage feedback, while filled boxes refer to scenarios with physical damage feedback. In particular, it shows: (a) the employment rate of the consumption goods sector, (b) the employment rate of the capital goods sector, (c) the unemployment rate and (d) the mean real wage.

and, based on well-known results from power series[18] we get:

$$NPV_k(\Delta n_s) = \Delta n_s \left(-p_k + \frac{p_E m_s}{\frac{r_{CB}}{12}} \xi \right) \tag{A.12}$$

where $\xi = 1 - \left(\frac{1}{1+r_{CB}}\right)^{30}$ is the correction term arising from the finite summation. The NPV is positive if the capital price of the KGP under consideration is greater than the discounted expected revenues generated by the purchase of one additional unit of renewable power stations. Note that the correction term ξ is positive and less than one, and it determines a more stringent condition for the NPV to be positive with respect to handling infinite summation in Eq. (A.11), as done in Ponta et al. (2018). Therefore, the truncation of the sum allows the depreciation of renewable stations to be taken into account, even if we have not modelled it explicitly.

When the NPVs associated with the two KGPs are both positive, what is relevant is the sign of the difference $\Delta NPV = NPV_{green} - NPV_{brown}$ that indicates which is greater; using Eq. (A.12) one finds:

$$\Delta NPV = -(p_{green} - p_{brown})\Delta n_s \tag{A.13}$$

that is, the sign of the NPV difference depends only on the negative difference between the prices set by the two KGPs.

Concerning emissions, note that we can write a modified Kaya identity:

$$\mathcal{E} = \frac{\mathcal{E}}{E} \cdot \frac{E}{Q} \cdot Q \tag{A.14}$$

where $E = \sum_f i_{Ef} Q_f$ is the total energy consumed in a period and $Q = \sum_f Q_f$ is the total CGPs output of the same period. The first ratio can be re-written using Eq. (2), multiplying and dividing by E_{PP}, and further using Eq. (1), as:

$$\frac{\mathcal{E}}{E} = \frac{i_\epsilon}{\gamma_{en}} \frac{E_{PP}}{E} \tag{A.15}$$

Defining the share of renewable energy as $s_{RP} = \frac{E_{RP}}{E}$, and using the relation $E_{RP} + E_{PP} = E$, we get:

$$\frac{\mathcal{E}}{E} = \frac{i_\epsilon}{\gamma_{en}}(1 - s_{RP}) \tag{A.16}$$

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$$\sum_{j=1}^{T} x^j = x\frac{1-x^T}{1-x},.$$

Table 8
The table shows the p-Values of the two-sided Wilcoxon rank-sum test, which tests the null hypothesis that the values of one of the relevant variables relative to two different scenarios come from distributions with the same median against the hypothesis that they are not. The test has been performed for each policy considered between the data relative to scenarios with and without climate damage. When the p-Value is lower than the 5% (1%) the null hypothesis is rejected with a 5% (1%) significance level.

	BAU	Carbon tax (p_ϵ)							Feed-in tariff (p^r_E)						
		15	25	30	45	60	75	90	50	60	65	70	75	90	120
p_k (capital goods price)	0.975	0.039	0.770	0.888	0.537	0.501	0.178	0.014	0.076	0.953	0.899	0.850	0.010	1.000	0.234
K (capital stock)	0.063	0.020	0.004	0.087	0.018	0.000	0.089	0.008	0.047	0.533	0.001	0.000	0.018	0.020	0.114
s_g (green investments share)	0.697	0.067	0.510	0.114	0.251	0.082	0.556	0.817	0.506	0.076	0.203	0.785	0.637	0.712	0.406
CT revenues/GDP		0.001	0.000	0.000	0.010	0.015	0.001	0.221							
CGPEmployment	0.026	0.007	0.123	0.004	0.163	0.354	0.000	0.044	0.056	0.000	0.143	0.430	0.030	0.013	0.000
$\frac{\Delta C}{C}$ (consumption growth rate)	0.000	0.007	0.002	0.025	0.003	0.001	0.208	0.189	0.000	0.011	0.077	0.001	0.019	0.232	0.785
Real consumption	0.000	0.002	0.000	0.000	0.004	0.000	0.032	0.045	0.000	0.000	0.000	0.000	0.004	0.002	0.041
p_C (consumption goods price)	0.281	0.379	0.012	0.211	0.189	0.004	0.398	0.948	0.926	0.163	0.040	0.016	0.598	0.011	0.931
i_E (energy intensity)	0.120	0.796	0.992	0.115	0.807	0.106	0.426	0.584	0.326	0.031	0.446	0.218	0.909	0.565	0.112
p_E (energy price)	0.926	0.040	0.438	0.672	0.603	0.467	0.266	0.016	0.064	0.942	0.992	0.882	0.012	0.931	0.203
FIT cost/GDP									0.387	0.791	0.828	0.574	0.014	0.899	0.817
GDP	0.182	0.021	0.028	0.051	0.143	0.000	0.134	0.015	0.018	0.426	0.089	0.002	0.002	0.043	0.024
$\frac{\Delta GDP}{GDP}$	0.007	0.000	0.001	0.001	0.004	0.000	0.100	0.662	0.000	0.002	0.019	0.001	0.004	0.033	0.019
Gov. debt/GDP	0.379	0.697	0.723	0.871	0.139	0.226	0.888	0.009	0.672	0.336	0.893	0.001	0.096	0.097	0.232
Gov. deficit/GDP	0.226	0.042	0.100	0.313	0.035	0.723	0.471	0.091	0.095	0.272	0.488	0.020	0.603	0.145	0.570
General tax rate	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.021	0.001	0.000	0.000	0.000	0.002	0.000	0.001
Inflation rate	0.882	0.035	0.278	0.622	0.092	0.118	0.275	0.002	0.855	0.430	0.463	0.024	0.717	0.071	0.434
Real investments	0.570	0.915	0.245	0.632	0.430	0.005	0.850	0.888	0.672	0.284	0.176	0.015	0.180	0.109	0.904
KGP Employment	0.361	0.524	0.422	0.948	0.584	0.012	0.915	0.904	0.855	0.120	0.319	0.033	0.422	0.278	0.323
$\mathcal{E}$ (GHGs emissions)	0.000	0.000	0.000	0.000	0.014	0.026	0.006	0.357	0.000	0.003	0.028	0.087	0.035	0.206	0.163
Real GDP	0.043	0.050	0.005	0.009	0.042	0.000	0.122	0.191	0.020	0.073	0.006	0.001	0.013	0.008	0.189
Real wage	0.226	0.047	0.017	0.046	0.103	0.000	0.132	0.040	0.017	0.056	0.033	0.003	0.008	0.024	0.112
s_R (renewable energy share)	0.001	0.000	0.000	0.000	0.009	0.029	0.012	0.410	0.004	0.051	0.083	0.100	0.132	0.560	0.812
TFC	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.002
Unemployment	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.055	0.000	0.000	0.002	0.000	0.002	0.000	0.000

Table 9
The table shows the p-Values of the two-sided Wilcoxon rank-sum test, which tests the null hypothesis that the values of one of the relevant variables relative to two different scenarios come from distributions with the same median against the hypothesis that they are not. The test has been performed for each policy considered between the data relative to scenarios with and without climate damage. When the p-Value is lower than the 5% (1%) the null hypothesis is rejected with a 5% (1%) significance level.

	Policy mix (p_ϵ, p^r_E)						
	(15, 60)	(15, 75)	(15, 120)	(30, 75)	(30, 90)	(60, 90)	(60, 120)
p_k (capital goods price)	0.096	0.033	0.216	0.006	0.060	0.039	0.040
K (capital stock)	0.000	0.015	0.015	0.000	0.000	0.000	0.000
s_g (green investments share)	0.430	0.697	0.882	0.290	0.132	0.855	0.860
CT revenues/GDP	0.008	0.130	0.237	0.546	0.012	0.488	0.125
CGP Employment	0.357	0.064	0.001	0.723	0.000	0.002	0.000
$\frac{\Delta C}{C}$ (consumption growth rate)	0.026	0.001	0.476	0.001	0.051	0.044	0.574
Real consumption	0.000	0.004	0.000	0.000	0.002	0.000	0.001
p_C (consumption goods price)	0.759	0.817	0.017	0.120	0.087	0.208	0.391
i_E (energy intensity)	0.754	0.687	0.637	0.027	0.442	0.652	0.775
p_E (energy price)	0.201	0.038	0.224	0.007	0.084	0.010	0.028
FIT cost/GDP	0.387	0.074	0.051	0.006	0.120	0.019	0.111
GDP	0.002	0.002	0.065	0.000	0.003	0.000	0.001
Gov. debt/GDP	0.002	0.000	0.226	0.000	0.013	0.004	0.306
Gov. deficit/GDP	0.488	0.844	0.055	0.343	0.542	0.153	0.002
General tax rate	0.020	0.434	0.145	0.251	0.964	0.931	0.071
Inflation rate	0.000	0.012	0.000	0.000	0.000	0.000	0.000
Real investments	0.045	0.111	0.510	0.037	0.528	0.931	0.100
KGP Employment	0.414	0.143	0.099	0.001	0.103	0.041	0.476
$\mathcal{E}$ (GHGs emissions)	0.528	0.537	0.213	0.002	0.201	0.077	0.383
Real GDP	0.002	0.155	0.450	0.251	0.184	0.467	0.044
$\frac{\Delta GDP}{GDP}$	0.004	0.033	0.002	0.000	0.009	0.001	0.015
Real wage	0.015	0.007	0.009	0.000	0.004	0.001	0.005
s_R (renewable energy share)	0.019	0.232	0.915	0.248	0.617	0.493	0.022
TFC	0.000	0.001	0.000	0.003	0.001	0.000	0.000
Unemployment	0.001	0.004	0.000	0.000	0.000	0.000	0.000

Finally, defining the (weighted) average energy intensity as $\hat{i}_E = \frac{E}{Q}$, the Kaya identity can be rewritten as:

$$\mathcal{E} = \frac{i_\epsilon(1 - s_{RP})}{\gamma_{en}} \cdot \hat{i}_E \cdot Q \tag{A.17}$$

Using the continuous approximation, we can write emissions relative change as:

$$\frac{\Delta\mathcal{E}}{\mathcal{E}} = -\frac{s_{RP}}{1 - s_{RP}}\frac{\Delta s_{RP}}{s_{RP}} + \frac{\Delta\hat{i}_E}{\hat{i}_E} + \frac{\Delta Q}{Q} \tag{A.18}$$

A.3. Net present value calculation in investment decisions by CGPs

The PV^{old} is expressed as:

$$PV^{old} = \sum_j \frac{p_C(1+\pi^e)^j \Delta Q_{fj}}{(1+\tau_C)(1+\frac{\bar{r}}{12})^j} \tag{A.19}$$

where p_C is the consumption goods price level, π^e is the expected inflation rate, ΔQ_{fj} is the difference between the production levels in the month j relative to a scenario where the firm buys the new capital and to a scenario without the investment, and $\bar{r}$ is the yearly

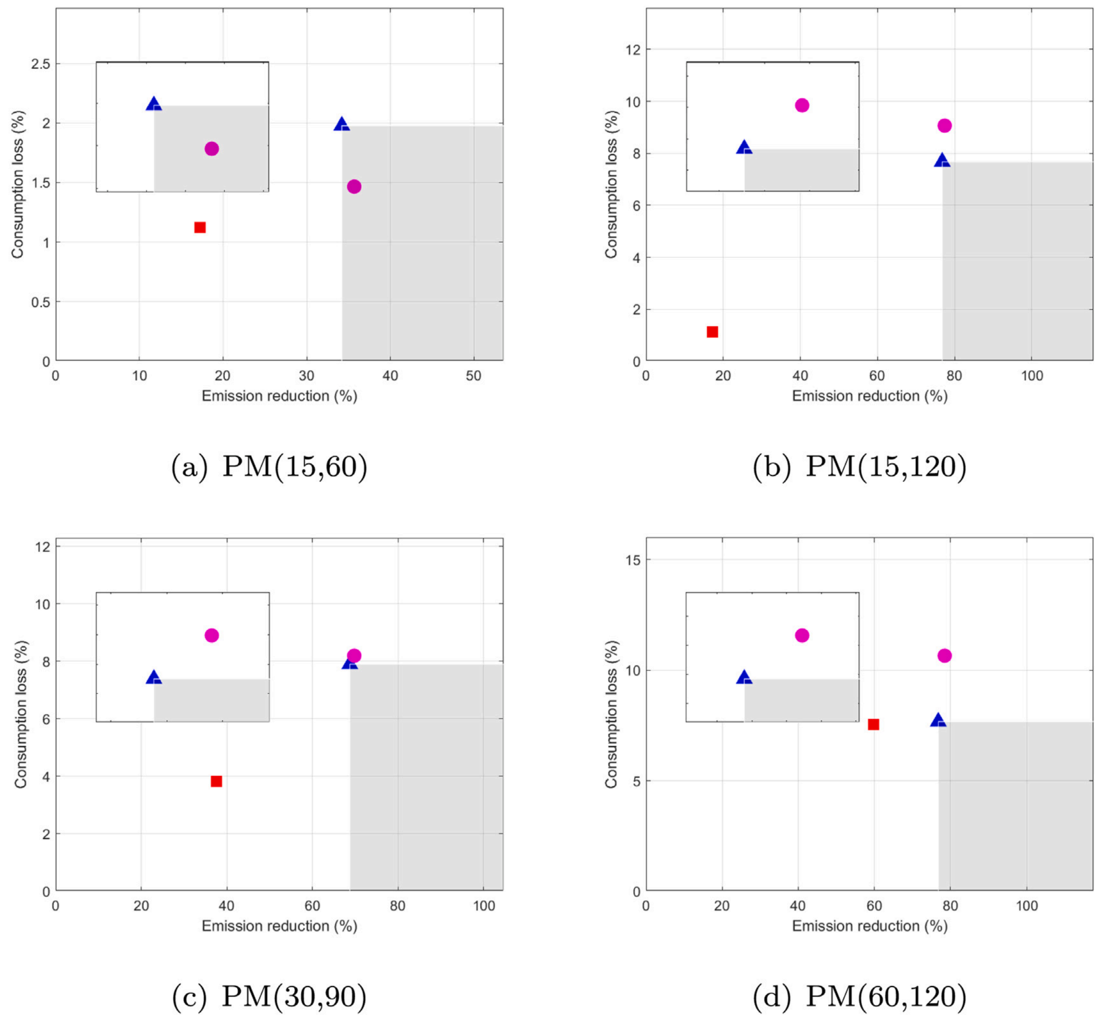

Fig. 17. The figure shows the policy mix performance compared to that of its parent policies in the scenarios with physical damage feed-back. In each panel, the *x*-axis the negative of emission reduction with respect to the BAU, the *y*-axis represents the negative of the consumption loss with respect to the BAU, as defined in the main text. In each graph, the average values of the emission reduction and consumption loss relative to the policy mix under exam (magenta circles) and to its CT (red squares) and FIT (blue triangles) components are represented. The shaded area represents the region where the policy mix reaches an objective (emission reduction) better than the best reached by the isolated policies, at a cost (consumption loss) lower than the highest cost implied by the isolated policies. Each graph shows an enlargement at the top left of the figure that helps to evaluate the performance of the policy mix with respect to the shaded region.

Table A.10
Calibration of the climate module parameters, values are taken from Nordhaus and Sztorc (2013).

Parameter	Symbol	Value	Unit
GHGs Equilibrium concentration in the atmosphere	M_1^{eq}	588	GtC
GHGs Equilibrium concentration in the upper oceans	M_2^{eq}	360	GtC
GHGs Equilibrium concentration in the lower oceans	M_3^{eq}	1720	GtC
Exchange coefficient from upper oceans to the atmosphere	A_{12}	$\left(M_1^{eq}/M_2^{eq}\right) A_{21}$	
Exchange coefficient from lower oceans to upper oceans	A_{23}	$\left(M_2^{eq}/M_3^{eq}\right) A_{32}$	
Exchange coefficient from atmosphere to upper oceans	A_{21}	0.12	
Exchange coefficient from upper oceans to lower oceans	A_{32}	0.007	
Equilibrium forcings response for doubling of GHGs	$f_{CO_2 2X}$	3.6813	W m^{-2}
Equilibrium temperature response for doubling of GHGs	$t_{CO_2 2X}$	3.1	°C
Atmospheric temperature calibration parameter	ξ_1	0.1005	°C W^{-1} m^2
Atmospheric transfer coefficient	ξ_3	0.088	°C^{-1} W m^{-2}
Lower oceans transfer coefficient	ξ_4	0.025	
Damage function coefficient	Ω	0.00236	

average cost of capital. Considering the Cobb–Douglass production technology employed by CGPs, in case of no investment (both NPVs brown and green are negative), production Q_{fj} after j months from the (no)-investment decision is given by:

$$Q_{fj} = \gamma_f N_f^{\alpha} K_f^{\beta} (1-\delta)^{\beta \cdot j}, \tag{A.20}$$

where γ_f is the total factor productivity, N_f is the number of employees, assumed constant in the calculation, K_f is the capital stock subject to the depreciation rate δ, and α and $\beta = 1-\alpha$ are the Cobb–Douglass exponents. Note that the decrease in the production level due to capital depreciation is accounted for by the j exponent of the term $(1-\delta)$. If the firm buys new capital, the production Q'_{fj} at month j reads $Q'_{fj} = \gamma_f N_f^{\alpha}(K_f + \Delta K_f)^{\beta}(1-\delta)^{\beta j}$. Finally, $\Delta Q_{fj} = Q'_{fj} - Q_{fj}$.

Taking out of the sum all the terms that do not depend on the index j and again using results on power series, one obtains:

$$PV^{old} = \frac{p_C}{1+\tau_C} Q_{f0} \left[\left(1 + \frac{\Delta K_f}{K_f}\right)^{\beta} - 1 \right] s^{old} \tag{A.21}$$

where $s^{old} = \sum_{j=1} \left(\frac{(1+\pi^e)(1-\delta)^{\beta}}{1+\frac{r}{12}} \right)^j$, and Q_{f0} is obtained from Eq. (A.20) for $j = 0$.

As regards the PV^{en} term, if the firm invests, the energy cost paid at month j will be $p_E i'_{Ef} Q'_{fj}$, where p_E is the energy price and $i'_{Ef} = i_{Ef} + \Delta i_{Ef}$ is the energy intensity in the investment case. If otherwise the firm does not buy new capital, the energy cost will be $p_E i_{Ef} Q_{fj}$. If the green capital is chosen, two opposite effects emerge, i.e., the energy cost is reduced due to the lower energy intensity compared to the case of no investment; however, the energy cost is also increased by the higher production level due to the expanded capital stock.[19] The difference $p_E(i_{Ef}Q_{fj} - i'_{Ef}Q'_{fj})$ represents the total savings of energy cost, if positive, or the additional energy cost, if negative because the increase of energy cost due to the higher production implied prevails on the savings. The PV^{en} term is obtained by discounting this difference with the same discounting factor used in the PV^{old} definition, and summing over months:

$$PV^{en} = \sum_j \frac{p_E(i_{Ef}Q_{fj} - i'_{Ef}Q'_{fj})}{(1+\bar{r})^j} \tag{A.22}$$

Taking out the sum of all the terms independent of the index j and reordering we obtain:

$$PV^{en} = p_E Q_{f0} \left[i_{Ef} - i'_{Ef} \left(1 + \frac{\Delta K_f}{K_f}\right)^{\beta} \right] s^{en} \tag{A.23}$$

where $s^{en} = \sum \left(\frac{(1-\delta)^{\beta}}{1+\hat{r}} \right)^j$.

When the NPVs associated with the two KGPs are both positive, the choice between the two capital goods suppliers depends on the sign of the difference $\Delta NPV = NPV_{green} - NPV_{brown}$; using the results above, after some algebra we find:

$$\begin{aligned} \Delta NPV = &-(p_{green} - p_{brown})\Delta K_f + \cdots \\ &+ p_E Q_{f0} s^{en} \left(1 + \frac{\Delta K_f}{K_f}\right)^{\beta} \frac{\Delta K_f}{K_f} (i_{E,brown} - i_{E,green}) \end{aligned} \tag{A.24}$$

That is, the difference of NPVs depends on the negative difference of prices as for the RP investment decision (see Eq. (A.13)), but also on investment quantity and on the difference between the energy intensity of the two type of capital.

In summary, technological innovation in energy intensity is exogenous while its diffusion is endogenous.

[19] If the brown KGP is chosen, there is no energy intensity improvement, therefore the investment determines an increase of energy cost because of the higher production level determined by the increased capital stock.

A.4. Technological progress

Differently from Ponta et al. (2018), where the total factor productivity (TFP) of firms was held constant, in this study the TFP of firms increases over time. TFP is determined by the technical productivity of its capital stock and by the skills of its employees. The productivity of new machines produced by KGPs grows at an exogenous rate every month; when a CGP buys new capital, the increase $\Delta\gamma_f^{tech}$ of the productivity of its stock is determined by:

$$\Delta\gamma_f^{tech} = \frac{\Delta K}{K + \Delta K}(\gamma^{new} - \gamma_f^{tech}) \tag{A.25}$$

where γ_f^{tech} is the productivity of the firm capital before and after the investment, γ^{new} is the productivity of the new machines. Every household is characterized by a specific skill level, that evolves according to the experience accumulated during its working activities: the monthly growth rate of the skill level is given by the difference between the skill level and the technical productivity of firm capital, multiplied by a parameter lower than 1. The TFP of each firm is given by the minimum between the average specific level of its employees and the technical productivity of the capital stock.

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