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The complexity of the climate-economy nexus: agent-based modelling and policy evaluation

by

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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

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Abstract

While the consensus on the urgency of climate actions has grown in the last decades, what is the pathway to be followed to translate proposal into actions is still argument of debates in the climate change economics literature. Most economists believe that carbon pricing is the main and the most efficient option to reduce GHGs emissions, however a growing number of works point out that this result is highly dependent on the type of model used, claiming the superiority of a policy mix when a more realistic representation of the economy is used.

My research work deals with the study of different climate policies with a complex system science approach, in particular, using the Eurace macroeconomic agent-based model. This work has two main objectives: first, to test the common belief that the carbon tax policy is the main and powerful instrument we have to induce the desired climate transition; second, to study the policy mix problem within the Eurace model economy, in particular, a mix of a carbon tax and a feed-in tariff policy.

I enriched the Eurace model with a new agent, the climate module, to account for the climate-economy feedback. The economy affects the climate through greenhouse gas emissions from fossil fuels use for the energy production while the climate affects the economy damaging physical capital, with damages dependent on the temperature anomaly. Moreover, I introduced heterogeneity in the capital good sector, in order to include energy intensity improvements as a factor of technological change. In order to establish a relation between real world and model quantities, I followed an initialization procedure based on imposing physical constraints on model's quantities.

I have developed an extended multi-criteria analysis method to evaluate policies performance accounting for both multiple objectives and variability of the outcomes of computational experiments.

To pursue the research objectives I performed a set of computational experiments with the Eurace model, in which I analyzed a carbon tax policy, a feed-in tariff policy, and a mix of the two policies. Results of computational experiments show that the carbon tax is not the best performing climate policy when analyzed with the Eurace model, both the feed-in tariff and the policy mix perform better. This result is independent from the presence of climate damages. In absence of climate damages the PM performs better than its components, however, climate damages reduce the positive effects of the interaction between the components leading to higher economic costs for the same emission reduction obtained. According to the extended multi-criteria analysis, in presence of climate damages, the feed-in tariff policy is almost always preferred to the policy mix.

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Introduction

Climate change is one of the major threat to human societies, its negative effects are increasing and some changes are likely to be irreversible in the course of this century. The consensus on the urgency of climate actions has grown in the last decades due to both increased evidence on climate change and its negative consequences and to the rise of recent protest movements such as Fridays For Future or Extinction Rebellion. To respond to the climate change challenges many countries have committed to reach the net zero emissions target by the 2050. According to IEA (2021), these pledges cover about 70% of global GDP and CO_2 emissions. However, what is the pathway to be followed to translate proposal into actions is still argument of debates in the climate change economics literature. The reasons are multiple and connected to each other: there are different opinions on what objectives to pursue, what are the risks and uncertainties associated with climate change and their magnitude, what are the most appropriate tools to evaluate the consequences and benefits of a given transition pathway. The most used tools to evaluate climate policies are the integrated assessment models (IAMs), that represent the evolution of both the climate and the economy (Weyant (2017)). They are grounded in general equilibrium theory and given the strong assumptions on which they are based, they are not considered able to represent the complexity of the climate-economy system (Balint et al. (2017); Farmer et al. (2015)).

My thesis adopt the complex systems approach to the climate change problem, and it has two main objectives related to this choice. The first objective is to test the common belief that the carbon tax policy is the main and powerful instrument we have to induce the desired climate transition (Tol (2017)). The second one is to study the policy mix problem within a complexity perspective, in particular, a mix of a carbon tax and a feed-in tariff policy. This means finding the combinations that outperform their single components and, among these, finding the best performing one (Bouma et al. (2019)).

To pursue the objectives the thesis work relies on the agent-based modeling approach, in particular I performed a set of montecarlo experiments with the macroeconomimc Eurace agent-based model, enriched to account for the climate-economy nexus and for other characteristics of the climate change problem (Nieddu et al. (2022, 2023b)). Moreover, I have developed an extended multi-criteria analysis to evaluate the policy performance and to compare different policies, in a context of uncertainties of the outcomes, and multiple objectives (Nieddu et al. (2023a)).

The rest of the thesis is organized as follows. The first chapter presents the climate change problem, remarking the need for a complex science approach. After recalling the main properties of complex systems relevant to the climate change problem, it is shown why climate and economy can be considered complex systems. Finally, IAMs and their main limitations are described.

Chapter 2 describes the objectives of the thesis and the methodology used. Concerning the first objective, the chapter presents the carbon tax policy and the theoretical grounds of the belief that it is the best climate policy. Then, to explain and motivate the second objective, it is presented the policy mix problem: the main motivations for preferring policy mix to single policies given in the literature are presented, and it is described what are the main steps to study a policy mix.

The third chapter is dedicated to the description of the Eurace model and to the enrichment made to pursue the thesis objectives. In particular, the chapter presents the climate module, implemented to account for the climate-economy feedback, and a detailed description of the procedure adopted to set model parameters and initial conditions, based on imposing a set of physical and economic constraints on the model.

Chapter 4 presents the experiments performed and discusses the results. After a description of the experimental settings, the channels through which emission reductions and economic costs emerge are shown for each of the policies considered. Policies are first compared looking at their average consequences and benefits without expliciting a preference structure. Then, policies are compared accounting for the volatility of their consequences through the extended multi-criteria analysis.

Finally, in the conclusions section, the main results of the thesis are summarized and discussed together with limitations of the work and future research directions.

Chapter 1

Complexity and climate change economics

1.1 The climate change problem

The Earth climate remained relatively stable to allow human life to survive for millions of years. That is, atmospheric temperature, pressure and composition have varied within a limited range during this period. However, large scale changes have continually occurred during Earth history, such as periods of glaciation, widespread and persistent volcanic activity, variations in the Earth's orbit and axial tilt, and changes in the distribution of continents and oceans that affected global ocean currents and atmospheric circulation patterns. In recent years, we are witnessing global warming and other climate changes unprecedented over centuries to millennia. We know from paleoclimate data that current multi-decadal rates of change of global mean surface temperature are the highest observed over the past two thousand years (Pages 2k Consortium (2019)); that the global mean sea level rise in the last century has been faster than the previous three thousand years (IPCC (2021)); and more strikingly that the rate of increase of CO_2 concentrations in the last hundred years is one order of magnitude higher than the highest rate of increase observed over the previous two hundred thousand years (Marcott et al. (2014)).

Although the total greenhouse gases (GHGs) concentration in the atmosphere is about 0.05% (excluding water vapor), a seemingly negligible fraction, it has been shown that the actual increase of global temperatures is correlated with the increase of GHGs concentration (IPCC (2021)). Furthermore, there is high evidence that the actual increase of the GHGs atmospheric stock is caused by human activities: emissions of greenhouse gases in the atmosphere from energy production and use, as well as from industrial processes, agricultural activities and deforestation are among the most important factors.

Human impact on the climate system can be traced back to the industrial revolutions. The use of machines powered by the cheaper fossil energy sources for industrial production and transportation, the increased connectivity, the innovations in the organization of production were essential to create a virtuous circle of increasing supply and demand, as new technologies and innovations led to a decrease of production costs, and then a growth in the demand for goods and creation of new jobs, which in turn stimulated new innovations and development. Nations that underwent industrialization witnessed a sharp surge in their material prosperity, often expressed as a hockey-stick growth of GDP per capita.[1]

The industrial revolutions brought about not only technological innovations, but also radical changes to the economy and to the society: the capitalist economic system, in which the production is undertaken by firms that own the machines and use labor force of employees, and the capitalist society, in which a minority of capitalists own the means of production and has the largest share of wealth and a majority offer its workforce, were born. Individualism, competition, the pursuit of profit, and wealth accumulation were placed at the heart of a new social value system.

Although several changes occurred since the first industrial revolution, some core characteristics have survived till today: the permanent technological progress, the assessment of well-being and living standards by materialistic measures, the more recent belief that economic growth is necessary to increase the general well-being. Therefore, in a capitalist economy the problem of climate change is expressed as finding a way to avoid impacts on environment still maintaining economic growth. Although in this work I will use the economic growth as a measure of policy performance, this is not the only nor the most appropriate criteria through which evaluating policies. GDP does not include important factors contributing to the well-being of people, such as free time or environmental and social quality. However, even if we are willing to give up economic growth, climate change remains an exceptional challenge for our societies: we can not simply turn off all factories to stop global warming. Materialistic needs are unavoidable, for example, food production can not be interrupted. Moreover, materialistic needs depend on the social contest, as for the case of flights. In more general terms, the climate change problem can be formulated as how can we reduce our impact, avoid the worst consequences of climate change while avoiding economic and social crisis.

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[1] See for example https://ourworldindata.org/grapher/historys-hockey-stick-gross-domestic-product-per-capita-using-the-ratio-scale-1990

Climate change involves different physical phenomena such as global warming, sea level rise, rainfall pattern shift, rise of extreme weather events frequency, etc. Climate impacts are not equally distributed among countries, and while the cost of mitigation will be felt on the short and medium term, the benefits will manifest only in the long run. Impacts do not manifest in the same place where GHGs emissions were generated and historically Western nations have contributed the most to the GHGs concentration increase (IPCC (2021)). Therefore, the climate change problem is a global problem that involves coordination among parties with different economic and geopolitical interests, historical responsibilities and geopolitical power.

In order to respond to the climate change threat different international treaty and framework were established. In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) with the tasks of assessing scientific, technical and socio-economic information relevant to understanding the risks of climate change, and to provide advice to policymakers. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was established with the objective of stabilizing greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. In 1997, the Kyoto Protocol was adopted, which aimed to reduce greenhouse gas emissions that cause climate change. The protocol established binding emission reduction targets for developed countries. Finally, in the 2015 the Paris agreement was adopted, with the aims to limit global warming to well below 2 degrees Celsius above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5 degrees Celsius. According to the agreement, parties (the nations signatories of the agreement) have to regularly compile a national greenhouse gas inventories reporting their GHGs emissions, and they have to submit the Nationally Determined Contributions, that is the announced and realized targets and plans to pursue the Paris agreement goals.

To date, many nations have committed to achieve net-zero emissions by 2050, these pledges covering about 70% of the global GHGs emissions (IEA (2021)). Nonetheless, according to the UNEP emission gap report (UNEP (2021)), the current National Determined Contributions of the Paris agreement signatories are not sufficient to avoid a global warming greater than 3°C by 2100.

Policies are judged using knowledge from both empirical studies and theoretical models. It has been argued that the climate change problem calls for a radical change in the approach used to think at the economy: from the general equilibrium theory to complexity economics (see for example Farmer et al. (2015); Lamperti and Roventini (2022); Roos (2023)). I will show in the next section that viewing both the climate and the economy as complex systems has important implications in the formulation of the problem, as well as in the choice of the instruments (models) used to judge and design climate policies.

1.2 The climate and the economy as complex systems

Complex systems

Complex systems are everywhere in our world, from our societies to the atmosphere of the Earth, from the Internet to the cells that constitute our bodies. Due to their transverse nature, the study of complex systems involves many disciplines, each contributing with its own scope, theoretical definitions and methodology. Then, there is not a precise and commonly accepted definition of complex system. Nevertheless, there are common features in almost all definitions that allow to understand the term. A complex system is a system composed by a usually large number of heterogeneous elements that interact, often non-linearly, with each other and with the environment in which they operate. Complex systems are in general difficult to treat with analytical solvable models. Even when it is possible to write down a set of equations for the evolution of the variables representing the state of the system, it is difficult or impossible to solve analytically this system. Complex systems require the use of non-linear models, out-of-equilibrium descriptions and computer simulations.

A non-linear system is one in which the future state is related to previous states and to eventual external forcings by a non-linear transformation involving squares of or product between previous states and external forcings. A more common sense definition, inspired by the properties of non-linear systems, is that in non linear systems, small changes in part of the system or in the external forcing can result in radical changes in the evolution of the system. Non-linear systems are often characterized by high sensitivity to initial conditions, irreversibility, hysteresis, path-dependence and phase transitions. This means that the evolution of the system depends on the previous history, that the system can overcome to abrupt and sudden changes both for internal or external small changes and that it can be difficult or impossible to reverse an occurred change.

An important feature of complex systems is emergence. In these systems, the behavior of the system is not encoded in the properties of the elements, but emerges as a result of the local interaction between elements. Relevant examples are fish school and birds flocking behavior. Fish schools are not formed from the top-down, that is, there is no one fish or group of fishes ordering others how to behave. Each fish simply watches the nearby fish and adjusts its speed to the changes in speed of the neighbours. If there are enough fishes eventually the fish school emerges.

Elements in complex systems are often organized in structures at different levels or scales: elements are divided in groups whithin which individuals behave similarly. Once groups are formed, they influence and are influenced by the global pattern as well as individual behavior. Social communities are examples of such coherent structures. Individuals belonging to a community are similar or behave similarly, have similar representations of the world, and share a system of values and judgments. Communities are further splitted in smaller communities. Community rules regulate the interactions between individuals among the community and with individuals belonging to other communities. However, new ideas from a small group of a community can change radically the whole community. This is the reason why complex systems cannot be effectively studied with purely reductionist or purely holistic approaches. There are not fundamental microscopic laws from which the global behavior can be deduced, since the global pattern emerges from interactions and is not encoded in the components. At the same time, the behavior of the elements is not solely determined by the system, to implement a certain functionality, because the global behavior is continually affected by the adaptation and changing behavior of the elements.

Another important aspect of complex systems is related to power laws distributions or more in general to fat-tailed distributions. Often properties of constituents, like income of economic agents, or the occurrence of certain events are distributed according to power laws distributions. This implies a high degree of heterogeneity in the system, for example, referring to the income distribution in a nation, when the distribution is a power law there are many individuals with an income roughly equal to the average income and a few individuals that have an income orders of magnitude greater than the average income. While the occurrence of extreme events is roughly forbidden with uniform, Gaussians and similar distributions, it is expected with heavy-tailed ones. Power laws distributions are related to another characteristic of complex systems, to talk about which it is useful to use the theory of complex networks. The elements of a system are represented by nodes, while interactions between couple of elements are represented by links connecting the nodes. The number of links of a node is called degree. One of the most important characterization of networks is to understand the degree distribution. It has been shown that in a large number of real system the degree is distributed according to a power law distribution (Albert et al. (1999); Faloutsos et al. (1999); Huberman and Adamic (1999)). That is, in real networks there are many nodes with a degree similar to the average degree and few nodes, termed hubs, with a degree several order of magnitude greater than the average degree. The occurrence of hubs is connected to the organizing principles according to which the network forms. Indeed, if the links between nodes are established at random, the degree is distributed more uniformly and hubs do not occur.[2] The presence of hubs is connected to different properties of real networks. Real networks show enhanced robustness to random removal of nodes with respect to random or lattice networks (Albert et al. (2000)). That is, while lattices or random networks break down in disconnected pieces when a fraction of nodes above a threshold fraction strictly lower than one is removed, to break down a real network it is necessary to remove almost all the components. This is mainly due to the role of hubs: while it is difficult for a hub to be randomly removed because the fraction of hubs is negligible, they guarantee network connection thanks to their high number of links. However, hubs are responsible for the fragility of real network to target attacks. When nodes are removed starting from those having the highest degree, the fraction of removed nodes necessary to break down the network is very low and far from one. In random networks instead, target attacks have roughly the same effect of random attacks since the degree is homogeneously distributed among nodes and there are no hubs. Without explicitly using the language of network theory we can state that, often complex systems exhibit robustness against random fluctuations, but show fragility against events affecting functional parts.

Elements in real complex system live and operate in a physical environment, and interact with it. However, the environment for an individual is not just the physical environment, but it is constituted also for example by structures present in the systems, by the networks of different relations existing between elements, by set of behaviors of the other elements, and so on. Individuals try to adapt to the environment and to its changes, and in doing so, they change the environment. There is a feedback loop connecting the evolution of individuals and that of the environment: elements and environment co-evolve.

Finally, I want to mention another property of complex systems relevant for the climate change problem, that is complex systems are said to be "at the edge of the chaos". Though the notion is not formally defined and it is not precise, it is generally meant that in system at the edge of chaos one (or more parameters) regulating the dynamics of the system is close to a critical value beyond which the system becomes chaotic. Systems at the edge of chaos are in a zone between order and chaos. In response to a change in external conditions they can respond transitioning to a chaotic phase that can result in profound structural changes of the system. Eventually the system return to an orderly phase, adapted to the new environmental conditions.

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[2] Random assignation of links between a fixed number of nodes generate a random network, like the Erdos-Renyi graph, in which the degree follows a Poisson distribution.

The climate as a complex system.

The Earth climate system is usually divided in five main components, termed "spheres": the atmosphere, that is composed by all the gases surrounding the Earth and is held by gravity; the hydrosphere, including all the liquid water of the earth, from oceans to lakes and rivers, to underground water; the lithosphere, that is the solid outermost layer of Earth; the cryosphere, that includes all the ice in the Earth surface, from glaciers to ice caps and sea ice; and finally the biosphere, that is constituted by all the living matter in the Earth.[3]

All of these components can be considered complex systems in their turn, since they share the same characteristics of complex systems cited in the previous section. For example, the atmosphere and the oceans exhibit non linear behavior since they can be described by Navier-Stockes equations, that are non-linear partial differential equations used to describe the motion of fluids. Non-linear behavior characterizes also the other spheres, such as the biosphere: small changes in the population size of a species at the bottom of a food chain can have huge impacts on the whole system through chain reaction effects.

Also the interactions between spheres have non-linear character. Spheres exchange with each other energy, such as heat, radiation and mechanical energy, and matter, for example through biogeochemical cycles or volcanic eruptions. Considering the hydrological cycle, hydrosphere and biosphere give water to the atmosphere during the evaporation, while water goes from the atmosphere to all the other spheres during precipitation. Small changes in atmospheric temperatures can have significant impacts on the hydrological cycle since warming increase the evaporation rate that increase the water vapor atmospheric concentration leading to further warming via greenhouse gas effect. Interactions between spheres are not captured only by the exchange of energy and matter. Each sphere, or part of it, can be considered as a border or environmental condition for the other spheres. The border condition of a sphere is not static and is influenced in its turn by the sphere dynamics. For example, the ocean free surface constitutes a border condition for the atmosphere and it is continually perturbed by winds and more in general affected by the evolution of the atmosphere.

The climate system is forced by the flux of energy that comes from the Sun. The Earth in turn emits energy into space in the form of long-wave radiation. The incoming solar radiation is in part reflected and in part absorbed by the surface of the Earth, while part of the long-wave radiation emitted by the Earth is absorbed by the GHGs of the atmosphere, and

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[3] However, there are other classifications of the Earth climate system that include additional spheres, such as the Sixth Sphere framework, that includes the anthroposphere, or the Earth System Science framework that comprises the five spheres mentioned above as well as other components such as the magnetosphere.

though part is emitted again by GHGs, the net balance is that less radiation is emitted into space. Due to its curvature, the surface of the earth is heated unevenly by the sun: the energy per unit of time and surface area is maximum at the equator and minimum at the poles. The global circulation pattern of the atmosphere and the oceans distributes the heat from the equator to the poles. Circulation patterns are driven by the differential heating of the Earth surface, by the Earth rotation, by pressure and salinity gradients among the main factors, and are influenced by the interactions between spheres. In general, the climate system varies on a large range of spatial and temporal scales. These means that coherent structures of very different size and life time coexist and interact with each other, from the circulation pattern in the Hadley cells, to cyclones and vortexes, to wind patterns in a city. Therefore, the global pattern of circulation is not just the result of external forcing, emerges from the interactions between spheres and it is shaped by the constant emergence and disappearance of coherent structures at all scales and their interactions.

As mentioned in the introduction, although the climate remained relatively stable for millions of years, it has changed dramatically in the past, going from glacial eras in which the temperature was low enough to allow the glaciation of poles, to warming periods in which no ice was present in the Earth. In an ice age, glacial periods, characterized by cold temperatures and the advance of ice from the poles towards the equator, alternate with shorter interglacial periods, during which the ice cover retreats. Changes occurred both for external as well as internal variability, and due to the non-linearity of the climate system, There are different feedback mechanisms, both positives and negatives, that affect climate system evolution, amplifying or reducing external changes as well as internal fluctuations. Examples of positive feedback are the above mentioned water vapor feedback or the ice-albedo feedback: an increase of temperature lead to a decrease of the ice covered surface leading to a decrease of the surface albedo, that results in a further increase of the temperature. The long wave radiation feedback is an example of negative feedback: a warmer Earth will increase emission of long wave radiation that lead to a decrease of the temperature.

It is therefore difficult to determine the climate response to changes in the GHGs concentration, and even more difficult to determine the impacts of the climate response on human societies. This difficulty is exacerbated by the presence of components with high inertia: even if we stop emitting GHGs now, the accumulated in the ocean will continue to heat the atmosphere for centuries to millennia. Therefore, to reduce uncertainty through data accumulation, it is necessary to observe the climate systems for periods much longer than time span considered useful for climate change mitigation.

The climate system allows to show another type of problem, related to data, that can emerge when analyzing complex systems, that in the context of climate models is known as "the parametrization problem" (see for example Provenzale (2014)). Consider for example the atmosphere. Since models can not include all the details of their target systems, a spatial and temporal scale have to be chosen. The atmosphere is divided in a large number of parallelograms whose size determine the spatial resolutions of the model. Inside each parallelogram the relevant variables, such as temperature, pressure, chemical composition, and so on, are assumed homogeneous. Then, the equation of fluid dynamics are used to evolve the system. The homogeneity assumption implies neglecting the internal dynamics inside each parallelogram, and in particular means assuming that the dynamics of all structures whose typical size is lesser than one of the sides of the parallelogram is dominated by and do not influence the macro dynamics of the parallelogram. Though in climate models the internal dynamics influence is to a some extent taken into account through parametrization, the larger scale dynamics of the parallelogram is supposed to dominate the lower scale, since parametrization is expressed in terms of large scale variables while lower scale variables are excluded from the analysis. Since the climate presents coherent structures at all scales, the parametrization problem does not disappear just improving the resolution of models. Increasing data storage capacity, increasing computational power and the development of knew data processing techniques give hope for an increase in understanding, in a progressive reduction of the uncertainties in understanding the climate, but are not enough. As recognized by the IPCC in its latest assessment report (IPCC (2021)), the progress made by climate models with respect to the time of the previous report was modest, despite the increased spatial resolution of new climate models. The parametrization problem imposes us to understand better the link between elements and system, the link between different scales phenomena and more in general, how the global pattern emerges from the system components behavior.

Adopting a complex system approach to describe the climate system has important implications for the climate change problem. First, it is a problem that involve fundamental uncertainty, that is a problem in which the probabilities distributions of certain variables or events are not known. As we have seen, there are processes affecting climate change, the understanding of which requires future observations over centuries or millennia. Moreover, new and more data, and increasing computational power will not guarantee alone a reduction of uncertainties, we really need a better understanding of complex systems. Furthermore, since complex systems can have uncomputable dynamics, we are faced with the very possibility that uncertainties will be unavoidable at all.

If the climate is seen as a complex system, it is much easier to accept the idea that climate change involves numerous risks of various magnitudes, including catastrophes. The climate system interconnected components contribute to maintain the conditions that support our existence. Our life is based on a fragile system of interconnected meta-stable states. The non-linear behavior of the climate imply that small changes in the climate system can be amplified by numerous feedback mechanisms resulting in a global change in which human life supporting conditions can be severely affected or even destroyed. The climate system is characterized by tipping points, therefore some changes can be irreversible, and there can be a global climate tipping point beyond which the actual global warming will be unstoppable (Lenton et al. (2019)). In a context characterized by high and fundamental uncertainties the existences of such risks leads to a preference for more cautious approaches in dealing with climate change.

The economy as a complex system.

The economy is composed by many heterogeneous agents, usually grouped into institutional sectors such as households, firms, banks, governments, that interact with each other in complex ways, exchanging, among other things, money, goods, services, work, financial products.

As remarked by Arthur (2021), agents in the economy make decisions in a context characterized by fundamental uncertainty. First, they do not know the future states of the world. Second, the result of their actions is influenced by the actions of the others. Therefore, in their decision making process, agents have to account for how the others make decisions. Decisions are based on expectations, not on complete and perfect information, as often assumed in general equilibrium models. The outcome of the decisions of all the agents gives rise to the global pattern, and it determines the success or the failure of a decision strategy in satisfying a certain purpose. Then, agents try to adapt to the others actions changing their expectations and strategies, in a continuous feedback loop of interaction between expectations formation and actions.

An illustrative example is provided by bubbles and crashes occurring in the financial market. A typical bubble can form because of a self-reinforcing process of diffusion of the expectation of an increase in the price of a given asset (see for example, Arthur et al. (2018); Palmer et al. (1994)). When enough people are convinced that the price of an asset will rise, their purchase of assets causes the price of that asset to rise, confirming the initial expectation and causing this belief to spread to other people as well, determining a further growth in purchases, and therefore in the price, of the asset in question. This process leads to a fast growth of the asset price, determining the formation of a bubble. The bubble can eventually burst due to a similar mechanism: a group of people, convinced of a future drop in the price, sell their holdings of the asset, causing a slowdown or decrease in the price. This spreads the expectation of a decrease in the price and triggers further sales, and so on.

The economy shows a non-linear behavior since small changes in part of the system or in the environment can trigger radical changes in the whole economy. A relevant example is the 2007-2008 financial crisis, in which the crisis in the US subprime mortgage market spread to other markets until it affected the entire world economy (Crotty (2009)). Crawford et al. (2009) present a list of the damages that involved the other markets, reporting for example that the US stock market recorded a 1.3 trillion dollars of wealth-loss in a single day.

Another example relevant for the climate change problem is the credit sector. Boss et al. (2004) analyzed the Austrian interbank market, showing that the resulting network, in which links between banks are identified by liabilities directed from the debtor to the creditor, is a scale-free network, with power-laws in- and out-degree distribution with exponent 1.7 and 3.1, respectively. As we have mentioned above, scale-free network are robust against random failure, but fragile against target attacks. Moreover, in scale-free networks the spread of a disease, than can be identified as a bank failure in this context, can occur even if the epidemic start with only one bank failure (Barrat et al. (2008)). However, direct transmission between banks is not the only way through which losses or defaults can propagate in the credit sector; according to Hellwig (2009), losses due to credit constraints in a non financial firm can feedback to the banking system. Crisis in the financial system can emerge endogenously and can feed-back to the real economy, leading to prolonged crisis (Riccetti et al. (2015, 2016, 2018)).

Climate transition risks (Monasterolo (2020)), i.e., risks deriving from the way the transition is realized, are strictly related to financial contagion. Fossil fuel reserves, machines and infrastructures for search, extraction and distribution of fossil fuels are currently evaluated without an assessment of climate risks. According to IEA (2020b) the carbon content of proved fossil fuel reserves is about 3000 $GtCO_2$, much larger than the remaining carbon budgets. If the world is to meet the Paris targets a large fraction of current reserves will be unburnable and will become stranded (Carbon Tracker Initiative (2011)). The sudden introduction of climate policies (Monasterolo et al. (2022a)), such as a global carbon tax (Monasterolo and Raberto (2018)) or a global cap on carbon stocks, as well as a technological shock or a sudden change in climate sentiments (Dunz et al. (2021b); Gourdel et al. (2022)) can lead to an abrupt revaluation of carbon-intensive and low-carbon assets. The consequent losses in the carbon-intensive sector can propagate through the financial networks, undermining the financial stability and can affect the real economy. Moreover, climate transition risks can be exacerbated by events not directly related to the climate policies or even to the climate change, such as the COVID-19 pandemics (Dunz et al. (2021a)).

Viewing the economy as a complex system has important consequences for the climate change problem. First, uncertainty is not confined to the climate systems, but present everywhere in the economy and is an important driver of the economy evolution. Second, since complex systems are rarely in a state of equilibrium, it is better to avoid assuming equilibrium behavior, in order to not neglect the factors that determine the change of economy over time (Arthur et al. (2018); Roos (2023)). As I will discuss in the next section, this require a great change in how policies analysis and future economy projections are made, since the most used models are grounded on general equilibrium theory. As remarked by Kirman (2016), adopting a complex system approach to evaluating policy interventions means abandoning the attempt to restore the economy to a state of equilibrium from which it had temporarily drifted away.

1.3 Limits of the mainstream approach.

Integrated assessment models (IAM), models where both the climate and the economy are represented, are the main tools used to evaluate mitigation and adaptation policies. Although existing IAMs differ for the level of detail used to represent the climate and the economy, all include a representation of the carbon cycle, whose dynamics is influenced by GHGs emissions coming from economic activities; the resulting change in the climate system is used to determine impacts on the economy. The economic module is usually based on equilibrium theory.

There are two fundamental types of IAMs: benefit-cost (BC-IAM) and process-based (PB-IAM) (Weyant, 2017). BC-IAMs (Hope, 2006; Nordhaus, 1993; Tol, 1997) use an aggregated representation of the economy and their main aim is to determine the optimal policy, for example, a carbon tax, that maximizes the discounted social welfare. They have been used to calculate the social cost of carbon (SCC) in USA (Interagency Working Group on Social Cost of Greenhouse Gases, 2016). PB-IAMs (Fricko et al., 2017; Kriegler et al., 2017) offer a more detailed representation of the economic sectors, in particular the energy sector, and of the climate and natural systems. Unlike the BC-IAMs, they are used mainly for cost-effectiveness analysis: they provide and rank (according to the cost) different trajectories of the outputs of all sectors that achieve a given level of emissions and a given temperature target. PB-IAMs are used by IPCC to show trajectories compatible with 1.5 and 2 degrees

(IPCC, 2018), by the central bank and financial regulators (Allen et al., 2020; Vermeulen et al., 2019) and by large investors for climate financial risk analysis (UNEPFI, 2020). They were used also in climate stress test exercises by Battiston et al. (2017) and are used by the network for greening the financial system (NGFS) to develop scenarios for climate stress test (NGFS, 2020).

As remarked in Farmer et al. (2015), IAMs are not able to deal properly with uncertainties, distributional issues, technological change associated with climate change. Based on the representative agent hypothesis, they do not account for agents heterogeneity and their interactions. Information asymmetries, different perceptions, imitation among agents can be crucial to the adoption of new green behavior or to the success of climate policies. Moreover, policies can have distributional impacts on income or wealth that can undermine their efficacy and can result in political unrests. Furthermore, climate mitigation targets require a large-scale transition to a low-carbon economy. Then, it is important to account for the characteristics of technological progress. Interactions between agents, limited information and complementarities between technologies can lead to different lock-in states where one type of technology prevails over the others. Equilibrium theory can not account for path-dependency and multiple equilibria systems. Moreover, most original IAMs assume exogenous technological progress. Their extensions, such as (Dietz e Stern 2015), includes endogenous progress; however, they do not account for the role of interactions. Moreover, they do not represent the financial sector, that is crucial to account for transition risks and evaluate financial climate policie (Battiston et al. (2021); Dunz et al. (2021a); Monasterolo et al. (2022b)). BC-IAMs are not suited to account for uncertainties of climate impacts, in particular with extreme events. since the damage functions used in these models generate aggregated damages and can not account for the role of non uniform distribution of impacts.

Though they have their own drawbacks, agent-based models can overcome the above IAMs limits, since they include the main elements of complex systems. As I will show in the following, agent-based models are the instruments used in this work to study climate mitigation pathways.

Chapter 2

Research purposes and adopted methodology

My research is focused on the analysis of climate mitigation pathways with a complex science approach. My two main objectives are first, to test the common belief that the carbon tax policy is the main and powerful instrument we have to induce the desired climate transition; second, to study the policy mix problem, analyzing the mix between a carbon tax policy and a feed-in tariff policy.

In the following section I will discuss about the theoretical foundation of the carbon pricing and of the policy mix applied to the climate change problem. Section 2.2 presents an extension of the multi-criteria analysis method, that I developed to evaluate policy performances and to compare different policies (see Nieddu et al. (2023a)).

To study the climate policies I chose a complex system approach, and in particular, I used the macroeconomic agent-based EURACE model which is described in the next chapter. The last section of this chapter describes the agent-based modelling approach, as well as its applications to the climate change problem.

2.1 Analyzing mitigation policies for climate change

2.1.1 Carbon tax

Carbon pricing is a fiscal policy measure that sets a price on GHGs emissions in order to move economies toward low or zero carbon regimes. It can be of two forms. One is to put a price on unit emissions through a tax; the other is to set a limit on allowable emissions and allow agents to trade their emission rights. The first carbon tax was introduced by Finland in the 1990. Today, there are 68 national and subnational carbon pricing initiative in place, covering about 23% of global GHGs emissions (World Bank (2022)).

When implementing a carbon tax policy one has to take into account several characteristics. Since there are several greenhouse gases that contribute to global warming (CO_2, CH_4, N_2O etc.) one of the characteristic of a carbon tax is the set of GHGs that it covers. Another important aspect is the set of actors that will pay the tax. Since each fuel has a different distribution system, one has to determine the point at which government could impose the tax. The choice may have serious consequences, as the yellow vests movement showed. Further, price trajectory is to be determined. Finally, one has to determine the use of revenues. Governments may use revenues simply to increase their budget, or they can use revenues to counter carbon tax negative distributional impacts, or to finance other climate policies.

Carbon tax is grounded on externality theory. An exeternality associated to an economic action (the production or consumption of a good) is the effect of that action on parties that do not participate to the action. Under the assumptions that prices carry all the relevant information except that relative to the externality, that there are not other externalities and that the market mechanism lead to efficient allocation of resources, to eliminate a negative externality it is sufficient to set a price (or increase its value) of the good associated to the externality equal to the marginal cost of the externality. Climate change can be viewed as an externality of the production and consumption of carbon intensive goods. Its marginal cost is called the social cost of carbon (SCC) and it is defined as the change in the discounted value of social welfare caused by an additional unit of GHG emissions (Nordhaus (2017)). It is usually calculated through IAMs, although estimates are strongly dependent on the damages function and the discount rate (to evaluate social welfare) used which are object of important debates in the literature, (see for example Stern (2008)).

According to this framework establishing a carbon tax equal to the SCC will solve the problems associated to the climate change, but in presence of other market failures the argument falls down. Real market are characterized by many other externalities and distorsion, for example incomplete and imperfect information in capital market may give rise to credit rationing (Stiglitz and Weiss (1981)); this effect is enhanced for green investments and projects, characterized by higher uncertainties related to technological development and regulations (High-Level Commission on Carbon Prices (2017)). There are also climate change specific market failures such as that related to short-terminism in climate actions: the possible catastrophic consequences of climate change will be felt beyond the time horizon usually considered by economic agents (Carney (2015)).

It is not clear how market failures, beyond that generated by the climate externality, affect the carbon tax performance. Some authors, e.g. Tol (2017), argue that other market failures reduce the efficiency of the carbon tax but it is still the best tool. Eventually, coupling the carbon tax with other instruments that account for the other market failures can lead to recovering the efficiency loss. As described in the next subsection, other authors argue that the effect of the other market failures is more complex and needs further investigation.

2.1.2 Policy mix

As mentioned in the introduction, carbon pricing is considered the most efficient option to reduce GHGs emissions (Nordhaus (2007); Tol (2017); Weitzman (2014)). Using other instruments may lead to sub-optimal outcomes. In line with this argument, most environmental economics works has focused on the analysis of single policies or on the comparison between two or more instruments.

However, an emerging body of works has questioned this argument and claims the superiority of a policy mix. Görlach (2014) points out that what the optimal policy is depends on what 'optimal' is meant for. Carbon pricing may loose its best policy status when multiple objectives and deviations from the models are present. These constitute also motivations for the adoption of multiple instruments; 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 in general of market failures, as well as government and behavioral failures.

Beyond the GHGs emissions or stocks targets, and the economic efficiency or cost-effectiveness targets, climate policies have other objectives, such as the mitigation of distributional consequences of policies, and the political feasibility (IPCC (2014)). Climate policies, such as carbon pricing, increase the cost of energy and fuels independently from the income level, and then hit more the lower income households. Preventing such distributional consequences is relevant both for ethical considerations and for the feasibility of a climate policy, as shown in 2018 by the yellow vests protest against a French carbon tax.

Adopting a multiple instruments analysis is relevant because countries have also other objectives beyond those of climate policies (for example SDGs) that may conflict or align with climate objectives. Furthermore, countries are de facto relying on instruments mix to enact their climate commitments. For example, the EU emission trading system stands besides energy efficiency standards for vehicles and buildings, and interact with national carbon taxes, incentives and other national and sub-national environmental policies.

According to the Tinbergen rule (Tinbergen (1952)), the number of instruments have to be equal to the number of independent goals a policy maker wants to achieve. Then, because of their multiple objectives, climate mitigation interventions can not rely on a single instrument. However, even when there is a single target, the presence of other externalities may need more than a single policy. According to the main result of the second best theory, when multiple market failures are present, targeting only one of them may results in an outcome worse than the do-nothing case (Lipsey and Lancaster (1956)).

Externalities, market power and imperfect information are the classical cause of market failures (Bator (1958); Randall (1983)), and are also used to justify the policy mix to tackle the climate change problem. A well known example of relevant externality is the technological spillover externality, i.e. the benefits that a technological improvement discovered by one gives to the other actors that imitate the new technology. If only a carbon tax is raised to offset the climate externality, the disincentive to R&D due the technological spillover may result in underinvestment in the development of new cleaner technologies and then, in an emission reduction smaller than planned. Then, a combination of subsidies for correcting the technological spillover and a form of carbon pricing is considered a more efficient solution by several authors (Goulder and Schneider (1999); Jaffe et al. (2004); Sorrell and Sijm (2003)).

The superiority of a policy mix is claimed also when imperfect information is considered (Bennear and Stavins (2007); Jaffe et al. (2004); Lehmann (2012)). When agents are not well-informed about the most efficient and cleaner available technologies, unless the relevant information is provided to them, they will be unable to significantly change their behavior, even if a carbon pricing policy is set up. Thought uncertainty can be considered a form of imperfect information, it is cited as another justification for a policy mix (Bouma et al. (2019)). For example, Lecuyer and Quirion (2013) suggest to complement an emission trading system (ETS) with subsidies for renewable energy when there are uncertainties on the abatement cost function.

Similarly to the concept of market failure, behavioral failures are referred to situations in which an unregulated economy do not achieve the maximum welfare state because agents behave differently from what rational choice theory prescribes (Shogren and Taylor (2020)). Therefore, Shogren and Taylor (2020) argue that a single instrument to limit emissions is not necessarily welfare-enhancing in an economy with behavioral failures. Inspired by, among others, the work of Simon (1987) and by prospect theory (Kahneman and Tversky (1979); Tversky and Kahneman (1974)), behavioral economics (Thaler (2016, 2018)) has so far collected numerous anomalies in the behavior of people, and has also proposed alternative solutions to problems in which these anomalies are relevant. Mullainathan and Thaler (2000) found that at least three main categories of divergences from rational behavior occur in real economies: bounded rationality, bounded willpower and bounded self-interest. Agents are bounded rational because of their limited problem solving capabilities and because of the limited time to solve the problems they face. To simplify their problems people use rules-of-thumb, that can led them to make systematic errors, i.e. choices different on average from the rational ones Kahneman and Tversky (1979); Tversky and Kahneman (1974). Even if the computed response is that of rational theory, real agents have difficulties to enact their long term plans (bounded willpower), and self-interest is not the main motivation for every agent. Market-based instruments aimed to correct environmental externalities can fail because agents' response to the same price signal are heterogeneous and there can be people that will not change their behavior for incompetence, ignorance, intransigence (Gunningham and Sinclair (1999)), or because behavior is not based on rational choice but on habit (Twomey et al. (2012)). Similarly, agents' response to information-based policy (policies aimed to tackle market failures due to the lack of information) are heterogeneous and influenced by (real) behavioral factors (Ferraro and Miranda (2013); Weaver (2014)); therefore, it is likely that a policy that neglects behavioral factors will not lead to the desired behavior change.

The characteristics of a real system that diverges from the idealized model can have influence on policy evaluation. Until now, we identified these characteristics with the causes of market and behavioral failures. These notions are based on the equilibrium assumptions. What if real economy evolves out-of-equilibrium?

According to Kirman (2016), one can not consider theorems of the existence of an equilibrium state, like that of Arrow and Debreu (1954), as proofs of the equilibrium assumptions, both because the uniqueness of equilibrium in not granted even under the stringent conditions of the existence theorems (Debreu (1974); Mantel (1974); Sonnenschein (1972)), and because economists have not been able to prove that, starting from an out-of-equilibrium state, an economy of rational agents will necessary converge to an equilibrium state.

Therefore, a policy that results optimal according to an equilibrium model, may be not effective when implemented in real systems because of the out-of-equilibrium dynamics. For example, if a price of GHGs is established in an economy that does not reach an equilibrium state, the quantity of GHGs emitted will be different from (and likely higher than) the equilibrium quantity associated to the GHGs price. Note that this is not an argument for an "equilibrium failure", since the concept of failure makes no sense outside the equilibrium theory. In line with Kirman (2016), we argued that the task of a climate policy analysis is not to find the condition under which, given the multiple failures, the free market condition (perfect competition, perfect information and so on) are restored and the system reaches the desired state; the task is to understand the performance of the policy under analysis, be it a single instrument policy or a policy mix, in a complex economy that continually evolve out-of-equilibrium.

Though so far I enlisted arguments in favor of a policy mix, not all mixes of instruments perform better than their components, and there is not a rule to establish if there is synergy between two or more instruments, or if conflicting interactions prevail. Therefore, one of the two main tasks of the research on policy mix is to understand the interactions of instruments and to characterize the set of mixes that outperforms their components (Bouma et al. (2019)). The second main task is to define and find the best mix among those outperforming their components.

2.2 Developing an extended multi-criteria analysis for policy evaluation

Cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA) are among the most used quantitative methods to compare different climate policies and to establish which is the best one (IPCC (2014)). CBA (Boardman et al. (2017)) compares different policies by evaluating their costs and benefits, and it chooses the alternative that has the greatest net benefit. In addition to the problems concerning the aggregation of individual welfare functions, cost-benefit analysis requires that all the benefits and costs of each policy be expressed in monetary value. CEA (Ekholm (2014)) does not require the evaluation of the benefits, the choice between different alternatives is made first by excluding those that do not reach a predetermined goal, for example a certain level of emission reduction, then by calculating the costs of the remaining alternatives and finally by choosing the policy with the lowest cost. Both methods rely on a single metric to measure policy performance. However, as suggested by Greening and Bernow (2004), a single metric can not represent properly the consequences of climate policies.

Multi-criteria analysis (MCA) allows to use multiple evaluation criteria, without requiring a unique metric to measure policy consequences (Keeney et al. (1993)). The first step of the analysis is to define the objectives , the attributes needed to measure those objectives, and the set of possible alternative policies to choose from. In the second step, the probability distributions of the consequences are determined for each alternative. Third, the preferences on the space of consequences must be made explicit by means of an utility function. Finally, for each policy the average utility is calculated and the policy with the highest average utility is chosen.

Before going on, it is necessary to clarify why I used the expected utility theory in an agent-based model, since the principle of maximization of expected utility is one of the main targets of the criticisms of equilibrium models, and one of the reasons for preferring ABM. The main arguments against this principle are that, combined with other assumptions such as complete and perfect information, unbounded computational power, etc, it is used to describe agent behavior. In contrast, the aim of this work is to rationally evaluate the consequences of different policies, obtained from a model that does not rely on the utility maximization principle, and where the evolution of the system is obtained in a bottom-up fashion. Here the expected utility theory is used as a normative theory, to describe how decision should be made, and not as a descriptive theory. For instance, the preferences and choices of policy makers who deny climate change are excluded from this analysis. Moreover, the expected utility theory is more appropriate than other method to deal with uncertainty because it does not require ad hoc adjustments to deal with extreme cases (see section 4.1.2 of Keeney et al. (1993)), and it is a powerful tool to deal with multi-dimensional consequences because it involves the evaluation of scalar quantities.

As regards the first step of MCA, in this work two objectives are chosen to evaluate policy performance, the first is the maximization of emission reduction and the second is the minimization of economic cost. For future convenience, the level of achievement of the first objective is measured through the negative of the emission reduction with respect to the BAU $\varepsilon = -\frac{\mathscr{E}-\mathscr{E}_{BAU}}{\mathscr{E}_{BAU}}$, where $\mathscr{E}$ and $\mathscr{E}_{BAU}$ are the yearly average emissions relative respectively to the scenario under consideration and to the BAU; the second objective is measured with the consumption loss with respect to the BAU $c = \frac{C-C_{BAU}}{C_{BAU}}$, where C and C_{BAU} are the yearly average consumption relative respectively to the scenario under consideration and to the BAU. Moreover, the set of the existing alternatives is identified with the 22 simulated scenarios. Therefore, the space of consequences is the plane spanned by the negative of emission reduction and by the consumption loss axes. For the second step, the set of the different consequences for each policy is identified with the set of points in the space of consequences relative to the 50 stochastic realizations of each scenario.

To explicit the utility function, a rational and careful policy maker (in the view of the authors) is taken as a reference: the utility should be a monotonic increasing function of both the arguments ε and c (that is, the first partial derivatives are positive), and the policy maker should be risk averse, that is, a lottery between the worst and the best consequence is never preferred to taking the lottery average consequence with certainty. In the following the definitions and theorems relevant for the construction of the utility function are presented without proofs, for a more detailed discussion, the interested reader is referred to Keeney et al. (1993).

Two utility functions u and u' are defined strategically equivalent if and only if they imply the same ranking of preference for any set of lotteries. u and u' are strategically equivalent if and only if they are related through a positive linear transformation, i.e. $u' = au + b$ with a and b non-negative numbers. Therefore, the following normalization conditions can be imposed without loosing generality:

$$u(\varepsilon_m, c_m) = 0 \tag{2.1}$$

$$u(\varepsilon_M, c_M) = 1 \tag{2.2}$$

where the subscripts m and M of ε and c are respectively referred to the lowest and highest values.

To simplify the analysis, a common and reasonable assumption, the mutual utility independence, is made about the preference structure. An attribute ε is utility independent of another c when conditional preferences on ε given c do not depend on the specific value of c. If further c is utility independent of ε, the two attributes are said mutually utility independent. Mutual utility independence condition is satisfied if and only if the utility $u(\varepsilon, c)$ can be written in the linear form

$$u(\varepsilon, c) = k_\varepsilon v(\varepsilon) + k_c w(c) + k_{\varepsilon c} v(\varepsilon) w(c) \tag{2.3}$$

where k_ε and k_c are positive numbers, $k_{\varepsilon c}$ is a real number, and $v(\varepsilon)$ and $w(c)$ are monodimensional utility functions.

Therefore, the task of finding the appropriate function can be decomposed in finding the monodimensional utility functions of emissions reductions and of consumption loss, and then finding the constants k_ε and k_c that regulates the rate of preference between the two attributes.

Both $v(\varepsilon)$ and $w(c)$ have to be monotonically increasing in their argument and decreasingly risk averse, which means that the policy maker is risk averse and that risk aversion decrease as the probability of worst consequences reduces. The functional form chosen for both v and w is $f(x) = a(x - b)^{\alpha_x}$, where $\alpha_x \in [0, 1]$ and x represents ε or c. Imposing normalization conditions $f(x_m) = 0$ and $f(x_M) = 1$ gives a and b, such that:

$$v(\varepsilon) = \left(\frac{\varepsilon - \varepsilon_m}{\varepsilon_M - \varepsilon_m} \right)^{\alpha_\varepsilon} \tag{2.4}$$

$$w(c) = \left(\frac{c - c_m}{c_M - c_m} \right)^{\alpha_c} \tag{2.5}$$

The α's regulate the degree of risk aversion: the higher α_x the lower the risk aversion.

Once the monodimensional utilities are fixed, to determine the global utility three conditions are needed. First, from the normalization conditions it follows that $k_{\varepsilon c} = 1 - k_\varepsilon - k_c$. Note that, since u is monotonically increasing in both its arguments, k_ε and k_c are in the interval $[0,1]$.

To fix k_ε consider the probability π such that the expected utility u_π of the lottery that gives the best consequence (ε_M, c_M) with probability π and the worst (ε_m, c_m) with $1 - \pi$ is equal to the utility of the lottery that gives the best emissions reduction at the worst (highest) cost (ε_M, c_m) with certainty:

$$\pi \cdot u(\varepsilon_M, c_M) + (1 - \pi) \cdot u(\varepsilon_m, c_m) = u(\varepsilon_M, c_m) \tag{2.6}$$

where the right hand side is equal to u_π. Using equations 2.3, 2.4 and 2.5 we obtain $\pi = k_\varepsilon$. Note that, since $u(\varepsilon_m, c_m) = 0$, Eq. 2.6 can be written as $\pi = \frac{u(\varepsilon_M, c_m)}{u(\varepsilon_M, c_M)}$. Therefore, since $k_\varepsilon = \pi$, the parameter k_ε regulates the importance of minimizing emissions relative to both minimizing emissions and cost. Finally, given ε^* such that $u(\varepsilon^*, c_m) = u(\varepsilon_m, c_M)$, from equations 2.3,2.4 and 2.5 it follows that $k_c = k_\varepsilon v(\varepsilon^*)$. To understand the role of $v(\varepsilon^*)$ note that the previous condition can be written as $v(\varepsilon^*) = \frac{u(\varepsilon_m, c_M)}{k_\varepsilon}$ and using the above expression of k_ε and using $u(\varepsilon_M, c_M) = 1$ we find $v(\varepsilon^*) = \frac{u(\varepsilon_m, c_M)}{u(\varepsilon_M, c_m)}$. Therefore, $v(\varepsilon^*)$ regulates the importance of minimizing costs with respect to minimizing the emissions. For future convenience we define $\varepsilon' = \frac{\varepsilon^* - \varepsilon_m}{\varepsilon_M - \varepsilon_m}$. Note that if $\varepsilon' < 1$, reducing the emissions is better than maximizing consumption ($u(\varepsilon_M, c_m) > u(\varepsilon_m, c_M)$), the opposite is true when $\varepsilon' > 1$.

$k_{\varepsilon c}$ determines the importance of reaching both objectives with respect to pursuing only one of them: if is greater than 0, reaching both objectives is more important than reaching only one of the two, that is the lottery that gives (ε_M, c_M) and (ε_m, c_m) with 50% probability is preferred to the lottery that gives (ε_M, c_m) and (ε_m, c_M) with 50% probability. The contrary is true when $k_{\varepsilon c} < 0$, and finally, if $k_{\varepsilon c} = 0$ the policy maker is indifferent between the two lotteries.

To obtain the utility function it is sufficient to specify the values of the parameters α_ε, α_c, π and ε'. However reasonable a given choice of parameters may appear, it is arbitrary and one may ask what happens to the policy ranking when a different set of values is chosen. To reduce arbitrariness to a certain extent, here it is presented a modified MCA method: instead of setting the parameters, these are varied to find the set of utilities that choose the same scenario as the best alternative, that is, an ensemble of policy makers are considered instead of only one. First the parameters that determines the monodimensional utilities (α_ε and α_c) are chosen, and then the optimal policy is determined for all the utility functions obtained varying the parameters π and ε'. This procedure generates a partition of the space of utility functions, represented by the π, ε' plane, in which the utilities belonging to the same region choose the same policy as that with highest expected utility. This allows to study the stability of the choices in a region of interest, specified later (see section 4.4). The same procedure is repeated varying the exponents of monodimensional utilities, to study their impacts on the partitions of the π, ε' plane.

2.3 Agent-based modelling for climate change economics

We have seen that complex systems have characteristics that make difficult the use of traditional analytical tools. There is not a clear relationship between the components and the whole; elements are heterogeneous in characteristics and behavior; there is non-linear feedback (positive and negative) among the elements and between elements and their environment; there is not tendency to equilibrium, instead elements co-evolve with their environment and the final state is strongly path-dependent. The diffusion of computers have relaxed the analytical tractability request. But its use to study complex systems is something more than solving a complicated equation or integration. It has contributed to the birth of a new practical and theoretical modeling paradigm, the Agent Based Modeling.

ABMs are models where agents and their interactions are represented explicitly, that is, agents belonging to the same sector are not aggregated in a single representative agent, instead, the heterogeneous characteristics of agents, as well as the intra-sector interactions are included in the model. Once agents' parameters, interactions rules and initial conditions are specified, the evolution of the system is obtained through computer simulations and usually studied with statistical tools. Therefore, ABMs do not need the assumptions typical of equilibrium models and can overcome the IAMs drawbacks cited above.

While traditional approaches focus on variables and aim to write down a system of equations of motion for those, with ABM the focus of abstraction activity has shifted on the entities that comprise the systems, and on how their characteristics, the interactions among them and with the environment give rise to the global behavior.

In ABMs, macroeconomics variables are obtained summing the corresponding microscopic variables (for e.g. the aggregate household income is given by the sum of the income of all households present in the model) and the relations between macroeconomic variables are not imposed from the top-down but they are constructed from observations. Traditional macroeconomic models, based on the representative agent hypothesis, attribute to the aggregate the same properties of the individual, incurring in the so-called fallacy of composition. In doing so they are not able to reproduce the emergent properties of real systems, that is, properties of the whole not encoded in the individual components. On the contrary, in ABMs the behavior of the system is determined by agents' interactions, therefore, emergent properties, like the thrift paradox, can be naturally observed. For a more extensive discussion about agent-based macroeconomics and its relation to traditional macroeconomics the interested reader is referred to Cincotti et al. (2022).

Macroeconomic ABMs have been used to study the climate change problem and have often led to results complementary to the traditional ones (Balint et al. (2017); Castro et al. (2020)). ABM contributions in the literature differ for the policy (or the set of policies) considered; while a carbon tax is one of the most studied, other fiscal policies such as incentives to low-carbon energy or to efficiency improving investments and other financial interventions are investigated. However, the majority of ABM studies on climate change deals with single instrument analysis or with the comparison of isolated instruments, while only few works (for example Lamperti et al. (2021)) investigate the mix of 2 or more policies. Models differ also for the way the green transition is modelled. We can distinguish between three general cases: models that consider only energy production technologies, those considering only resource efficiency improvements and models that account for both. Moreover, some works assume exogenous innovation or do not consider it at all; they focus on the diffusion of different existent technologies. Agents can influence each other directly, mimicking their neighbors' choices, or indirectly, as choices between different technologies can affect their price or availability. Other models completely endogenize technological progress: agents perform RD investment to improve their products (labor productivity or energy efficiency for productive capital or for reducing installment cost for new energy technology). As regards the distributional consequences of climate policies, only some account it explicitly. The explicit representation of the credit sector is another distinguishing feature of the works considered. Most models do not consider explicitly the economy climate feedback.

The work of Robalino and Lempert (2000) represents one of the first ABM that studies the green transition in the energy sector. They study the effects of carbon taxes and subsidies in an economy where the diffusion of low-carbon technologies depends on the heterogenous preferences and decisions of the agents. Firms choose between three different (high-, medium- and low-carbon intensive) energy production technologies based on their interdependent expectations on the price and productivity of each technology. In contrast to equilibrium models according to which incentives lead to sub-optimal states, they find that the combination of taxes and incentives for low-carbon technologies performs better than carbon price alone. However, the model is too simple since many parts are exogenous and it lacks or have only an implicit representation of relevant sectors, such as the financial one.

The ENGAGE framework (Gerst et al. (2013)), based on Dosi et al. (2010), is an example of a model that completely endogenizes the technological change. Capital good firms can improve the labor productivity and the energy intensity of machines through a RD probabilistic process. The diffusion of the new machines is governed by the investment decisions of consumption good firms. Moreover, they enriched the original model with an energy sector, where different types of production technologies can be used. They use the model to evaluate different revenues recycling schemes of a carbon tax. They find that the transition in the energy sector occurs only when revenues are used to incentivize carbon-free energy RD.

In Monasterolo and Raberto (2018), the authors propose the EIRIN model, able to investigate the effects of incentives to energy efficiency investment as well as for distributional consequences of such policies. The capital good sector produces two types of machines, green and brown, that differ for the energy intensity and for their price (higher for the green). The investment decision of firms, based on net present value calculation, regulates the diffusion of the more efficient capital. The model comprises two household classes, capitalists and workers, that allow to investigate the distributional issues. Moreover, the model includes an explicit representation of the financial sector. They investigate diverse mechanisms of financing a green incentives policy. The results show that the incentives are useful to foster green investments, particularly when the policy is financed by government bond rather than taxes. Compared to the no-policy scenario, the economy performs better in terms of higher consumption and lower unemployment. However, the bond financing scheme implies a wealth concentration in the credit sector that lead to growing inequality, particularly in the long term. The model was further extended in Monasterolo et al. (2022a,b); Monasterolo and Raberto (2019) to account for the energy production technologies dynamics.

The works discussed so far consider only one side of the economy-climate interaction. In this respect, the LAGOM model (Haas and Jaeger (2005)) constitutes the first attempt to model a coupled climate-economy system. A climate module send damages to agents and in turn is influenced by agents actions. The future choices of the agents depend on expectations that evolve with experience through a learning process. One of the main advantage is represented by the different time scales at which the model operates. However, damages are based on emissions not on temperature. The model was further extended, with a resulting framework able to deal with climate change in a multi-country economy.

At our best knowledge, Lamperti et al. (2018) presents the first fully-fledged AB-IAM. The economic module is based on Dosi et al. (2010), which the authors enriched with a climate module, grounded on Sterman et al. (2012). Endogenous technological change with both energy-production technology and resource efficiency progress. Differently from traditional IAMs, the impacts of climate change are modelled as micro-shocks on relevant target variables (such as, stock of capital, labor productivity or energy efficiency). This allows to consider different channels through which climate affects the economy and to deal with non-uniform impacts. The model can also use a DICE-styled damage function affecting aggregate output, which is used as a reference for comparison. The authors showed that the way damages are modelled is crucial in studying the low-carbon transition: while aggregate damages on output do not influence the probability of the transition, this is increased by shocks on labor productivity and decreased by shocks on energy efficiency. The model was further used to study financial policies (Lamperti et al. (2021)) and subsidies (Lamperti et al. (2020)).

Chapter 3

New features of the Eurace model to assess the climate change problem

Introduction

To carry out the policies analysis, the Eurace agent-based model has been used, see Teglio et al. (2019) for a detailed description of the baseline model.

The Eurace model is a stock-flow consistent 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 (see Fig. 3.1). Agents interact in both decentralized and centralized markets, their decisions are based on heuristics, adaptive expectations and limited information. The model comprises the main markets that characterize economic activities. Households and CGPs interact in the consumption goods market in which a uniform consumption good is offered to households at different prices; CGPs and the KGP interactions constitute the capital good market; CGPs and the KGPs compete in the labor market to hire households; CGPs and households ask for loans to the banks in the credit market; furthermore CGPs can sell their shares to households, that together with government bonds constitute the products traded in the financial market; finally banks can ask for loans to the central bank in the money market.

The Eurace model was developed at the end of a three years European project started in 2006. It was the first attempt at representing a complete economy that comprises all the main markets and mechanisms existing in the real world, and it pioneered the use of stock-flow consistency to build agent-based macroeconomic models, along with the models by Caiani et al. (2018, 2016). Motivated by the need for new tools to understand phenomena not captured by mainstream economics, such as the 2008 global financial crisis, it provides a

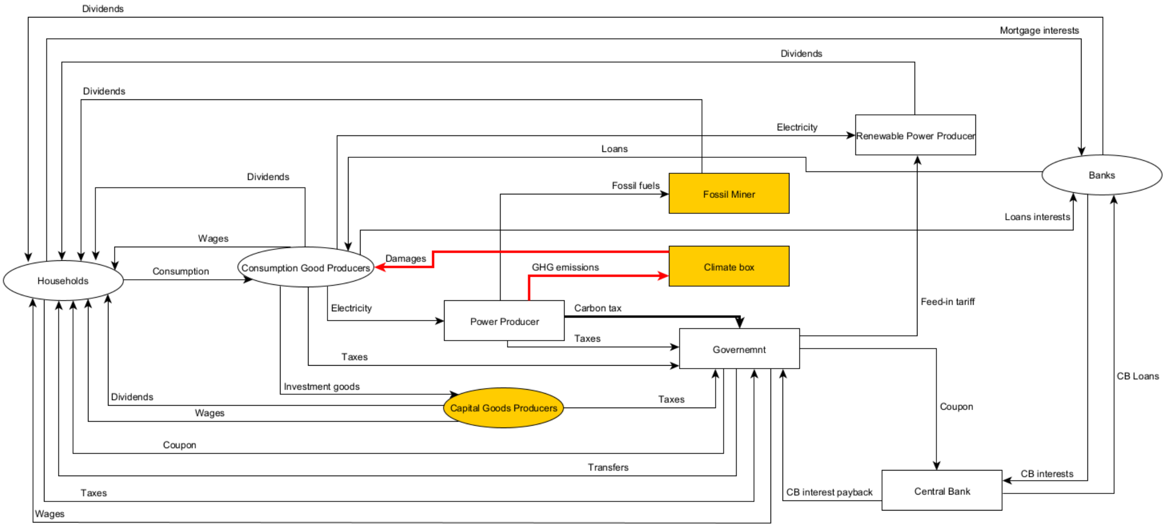

Figure 3.1 The figure shows a graphical representation of Eurace model used in this work. Agents classes are represented by ellipses or rectangles while current account monetary flows are represented by arrows. Rectangles are used for the classes containing only one agent, whereas ellipses represent classes with multiple agents. Yellow boxes refers to newly introduced agents.

suitable environment to study non-equilibrium transitory dynamics triggered by changes in policy parameters. It has been used to study and to give insights about different economic challenging themes such as the relation between the amount of credit money in an economy and its macroeconomic instability (Cincotti et al. (2010) and Raberto et al. (2011)), the relation between different capital adequacy requirements and the main economic indicators (Teglio et al. (2012)), the role of resource efficiency investment in industrial sustainability (Tonelli et al. (2016)), the sustainability transition in the energy sector (Ponta et al. (2018)), the effect of austerity measures in crisis times (Teglio et al. (2019)), the housing market (Ozel et al. (2019)), the effect of loans and mortgages securitization on business cycles (Mazzocchetti et al. (2018)) and the role of discriminating bank regulation policies in fostering green investments (Raberto et al. (2019)).

In Ponta et al. (2018) the model was enriched with an energy sector, and Raberto et al. (2019) further added energy efficiency improvements. This work relies on the previous two works and enriches further the model, coupling the economy with a climate module (Nieddu et al. (2022, 2023b)). Moreover, we introduced another type of KGP in the capital good market, and we substituted the foreign economy agent introduced in Ponta et al. (2018) with a fossil miner agent, in order to deal with a global economy. In the following sections we describe in detail the enrichment discussed above.

3.1 The addition of Climate module and climate-economy interaction

The economy affects the climate through GHGs emissions from fossil fuels use for the energy production while the climate affects the economy damaging physical capital, with damages dependent 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 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

$$M_{AT,t+1} = (1-A_{21})M_{AT,t} + A_{12}M_{UO,t} + \mathscr{E}_t \tag{3.1}$$

$$M_{UO,t+1} = A_{21}M_{AT,t} + (1-A_{12}-A_{32})M_{UO,t} + A_{23}M_{LO,t} \tag{3.2}$$

$$M_{LO,t+1} = A_{32}M_{UO,t} + (1-A_{23})M_{LO,t} \tag{3.3}$$

where the coefficient A_{ij} stands for the quantity of GHGs transferred by the layer j to the layer i per unit of GHGs in the stock of layer j and it is zero for non adiacent layers. Note that in absence of emissions the total quantity of GHGs, i.e. the sum of all the stocks, is constant. In absence of emissions the linear system evolves toward an equilibrium point, that can be calculated imposing $M_{i,t+1} = M_{i,t}$ for each layer and $\mathscr{E}_t = 0$. Therefore, if GHGs are emitted in 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.

As mentioned in the first chapter, 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:

$$F_t = f_{CO_2 2X} log_2(\frac{M_{AT,t}}{M_{AT,1750}}) + F_t^{ex} \tag{3.4}$$

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

Parameter	Symbol	Value	Unit
GHGs Equilibrium concentration in the atmosphere	M_{AT}^{eq}	588	GtC
GHGs Equilibrium concentration in the upper oceans	M_{UO}^{eq}	360	GtC
GHGs Equilibrium concentration in the lower oceans	M_{LO}^{eq}	1720	GtC
Exchange coefficient from upper oceans to the atmosphere	A_{12}	$\frac{M_{AT}^{eq}}{M_{UO}^{eq}}A_{21}$	
Exchange coefficient from lower oceans to upper oceans	A_{23}	$\frac{M_{UO}^{eq}}{M_{LO}^{eq}}A_{32}$	
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 responce for doubling of GHGs	$f_{CO_2 2X}$	3.6813	Wm^{-2}
Equilibrium temperature responce for doubling of GHGs	$t_{CO_2 2X}$	3.1	$^\circ C$
Atmospheric temperature calibration parameter	ξ_1	0.1005	$^\circ CW^{-1}m^2$
Atmospheric transfer coefficient	ξ_3	0.088	$Wm^{-2\circ}C^{-1}$
Lower oceans transfer coefficient	ξ_4	0.025	
Damage function coefficient	Ω	0.00236	

Table 3.1 Calibration of the climate module parameters, values are taken from Nordhaus and Sztorc (2013).

influence of aerosols, ozone, albedo changes, and other factors. To describe temperature changes, the atmosphere and the upper oceans layers are aggregated in one layer, that will be called 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:

$$T_{AT,t+1} = T_{AT,t} + \xi_1 \left[F_{t+1} - \frac{f_{CO_2 2X}}{t_{CO_2 2X}} T_{AT,t} - \xi_3 (T_{AT,t} - T_{LO,t}) \right] \tag{3.5}$$

$$T_{LO,t+1} = T_{LO,t} + \xi_4 (T_{AT,t} - T_{LO,t}) \tag{3.6}$$

where T_{AT} and T_{LO} are the temperature anomalies[1] of the atmosphere and of the lower oceans respectively, ξ 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

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

of atmospheric GHGs stock. In table 3.1 are reported the values of the parameters used to calibrate the climate module.

As regards the damage function, we choose to express damages as capital reduction instead of output reduction used in the DICE model. The destruction of capital, in contrast to that of output, represents permanent damage, the negative consequences of which extend to all the periods following the occurrence of the damage. Neglecting permanent damages can lead to underestimating the climate impacts on economic growth (Bretschger and Pattakou (2019); Stern (2013)), 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 to use 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) I followed the approach outlined in Lamperti et al. (2018), picking damages fractions s_f from a beta distribution function, in Nieddu et al. (2023a) I used an aggregate damages function, derived from that used by Nordhaus (1993), where the fraction of output $(\frac{\Delta Q}{Q})_{damage}$ destroyed by climate change is expressed as a quadratic function of the atmospheric temperature anomaly:

$$\left(\frac{\Delta Q}{Q}\right)_{damage} = \Omega T_{AT}^2 \tag{3.7}$$

where Ω is a calibration coefficient. Note that using the value reported in table 3.1, in an environment with a temperature anomaly equal to $3°C$ the output destroyed by climate change is roughly two percent 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 exponent for the capital factor, we set

$$s = \left(\frac{\Delta K}{K}\right)_{damage} = \frac{1}{\beta}\left(\frac{\Delta Q}{Q}\right)_{damage} \tag{3.8}$$

3.2 Improving the energy sector

Dealing with a global economy, the energy sector has been slightly changed from Ponta et al. (2018), where fossil fuels were produced and supplied by a foreign economy; then a brief description of the sector will follow. The energy demand comes from consumption goods firms (CGPs) that need it as a third input of production, and for each firm it is given by

$$E_f^D = i_{Ef} Q_f \tag{3.9}$$

where E_f^D is the energy demand, i_{Ef} is the energy intensity of the consumption good production and Q_f is the quantity of goods produced in a month, all relative to the firm f. Energy is produced by a non-renewable power producer (PP) that uses fossil fuels and by a renewable power producer (RP). The RP agent has grid priority, meaning that CGPs energy needs are satisfied first with the renewable energy and then through the fossil energy. Therefore, the energy produced by the PP agent is equal to the total energy demand minus the produced renewable energy.

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 their monthly energy production m_s:

$$E_{RP} = n_s m_s \tag{3.10}$$

The RP decides on a monthly basis the quantity of new renewable power stations to buy by evaluating the net present value (NPV) of the additional earnings implied by the investment Δn_s. However, since there are two KGPs, the RP agent has to choose one of the two suppliers. First, the RP computes the two NPVs associated to the two KGPs; if none of them is positive, the RP does not invest; if only one of the NPVs is positive, then the RP chooses the KGPs with the positive NPV. If both the NPVs are positive, instead of making RP choosing deterministically the investment with the greatest NPV we let RP choice determined by a stochastic rule: the investment with the lowest NPV is not excluded but it is chosen with a small probability (10%) in order to account for the uncertainties related to economic quantity relevant for the investment decision, like the energy price, and for the uncertainties related to bounded rationality and bounded computing power (results of computations made by agents may contain errors).

$$NPV_k(\Delta n_s) = -p_k \Delta n_s + \sum_{j=1}^{30} \frac{p_E 12 m_s \Delta n_s}{(1 + r_{CB})^j} \quad k \in \{green, brown\} \tag{3.11}$$

where p_k is the capital price offered by the KGP k, that can be green or brown, p_E is the energy price and r_{CB} is the central bank yearly interest rate. The first term on the right hand side represents the cost of the investment, while in the second term, the quantity $12 m_s \Delta n_s$ is the additional yearly production implied by the new renewable stations and $(1+r_{CB})^{-1}$ is the discounting factor. Since we are not modeling explicitly renewable station depreciation but we want to capture the finite life-time of the technology, the sum of discounted future additional revenues is truncated at 30 years, that roughly match lifetimes of renewable energy production technologies[2]. Taking out from the summation symbol all the terms that do not depend on the index j and using the known results on power series [3] we obtain from Eq. 3.11

$$NPV_k(\Delta n_s) = \Delta n_s \left(-p_k + \frac{p_E m_s}{\frac{r_{CB}}{12}} \xi \right) \tag{3.13}$$

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 exam is greater than the discounted expected revenues generated by the investment. Note that the correction term ξ is positive and lower than one, and it determines a more stringent condition for the NPV to be positive with respect to dealing with infinite summation in Eq. 3.11, as done in Ponta et al. (2018). Therefore, truncating the sum allows to account for renewable stations depreciation, thought we have not explicitly modelled it. When the NPVs associated to the two KGPs are both positive, what is relevant is the sign of the difference $\Delta NPV = NPV_{green} - NPV_{brown}$ that tells which is the greatest one; using Eq. 3.13 one finds:

$$\Delta NPV = -(p_{green} - p_{brown})\Delta n_s \tag{3.14}$$

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

The PP energy production function reads:

$$E_{PP} = \gamma_{en} F \tag{3.15}$$

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

$$\mathscr{E} = i_{\varepsilon} F \tag{3.16}$$

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[2] See for example https://www.nrel.gov/analysis/tech-footprint.html

[3]

$$\sum_{j=1}^{T} x^j = x \frac{1-x^T}{1-x} \tag{3.12}$$

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 supplied by a fossil fuel miner agent (FM). To link the fuel price to the price level of the economy, the FM agent is endowed with a capital stock whose depreciation rate depends on the level of production, in particular, we assume that the number of machines deteriorated in the production process ΔK_{FM} is proportional to the production level:

$$\Delta K_{FM} = \eta F \tag{3.17}$$

where η is the number of machines consumed in the production of a unit of fossil fuel and F is the fuel quantity produced in a month equal to that demanded by the PP agent, see Eq. 3.15. In order to restore its capital stock the FM buys new capital choosing among the two KGPs: the FM assign a 90% probability of being chosen to the KGP offering the lowest capital price. The fuels price p_F is a mark-up on the costs:

$$p_F = (1+\mu_F)\,\eta \cdot p_k \tag{3.18}$$

where μ_F and p_k are respectively the mark-up used by the FM agent and the capital price of the chosen KGP.

Note that for the emissions we can write a modified Kaya identity:

$$\mathscr{E} = \frac{\mathscr{E}}{E} \cdot \frac{E}{Q} \cdot Q \tag{3.19}$$

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 determined using Eq. 3.16, multiplying and dividing by E_{PP}, and further using Eq. 3.15, as

$$\frac{\mathscr{E}}{E} = \frac{i_\varepsilon}{\gamma_{en}} \frac{E_{PP}}{E} \tag{3.20}$$

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

$$\frac{\mathscr{E}}{E} = \frac{i_\varepsilon}{\gamma_{en}}(1 - s_{RP}) \tag{3.21}$$

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

$$\mathscr{E} = \frac{i_{\varepsilon}(1 - s_{RP})}{\gamma_{en}} \cdot \hat{i}_E \cdot Q \tag{3.22}$$

3.3 Heterogeneity of capital goods producers

As regards the energy intensity improvements, the capital good sector is composed by two capital good producers (KGP), labelled green and brown KGP. KGPs use labor force as the only production input. The energy intensity of the new machines produced by the green KGP decreases every month with a constant rate whereas brown KGP machines are produced with the energy intensity equal to the initial value. The green KGP devotes a fraction of its workers to improve the intensity of the new machines and then only a fraction of workers is used for production. The production function of the KGPs reads:

$$Q_k = \gamma_k N_k (1 - d_k) \tag{3.23}$$

where Q_k is the quantity of new capital produced in a month by the k-th KGP, γ_k is the total factor productivity, N_k is the number of employees and d_k is the fraction of workers used in the energy intensity improvement process, and it is equal to 0 for the brown KGP. KGPs set the capital price putting a mark-up on unitary cost:

$$p_k = (1 + \mu_k) \frac{w_k}{\gamma_k (1 - d_k)} \tag{3.24}$$

where p_k, w_k and μ_k are respectively the price established, the average wage offered and the mark-up put by the k-th KGP. Note that for the same average wage and mark-up, the green capital price is higher than the brown one because of the factor $(1 - d_k)^{-1}$, greater than 1. Every quarter, CGPs can choose to buy new capital goods in order to meet the new production plans, determined by expected demand evaluation. The new investment made by a CGP changes the *average* energy intensity i_{Ef} dependening on its previous intensity and on the intensity of the new machines:

$$\Delta i_{Ef} = -\frac{\Delta K}{K + \Delta K} (i_{Ef} - i_{E,k}) \tag{3.25}$$

where K is the capital stock of the firm before the investment, ΔK is the new capital bought and $i_{E,k}$ is the energy intensity of the capital bought from the chosen KGP. Note that the energy intensity decreases only if the green KGP is chosen. CGPs randomly select KGPs assigning 90% probability to the type of capital that has the highest NPV of the investment that reads:

$$NPV_k(\Delta K_f) = -p_k \Delta K_f + PV^{old} + PV_k^{en} \tag{3.26}$$

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. The PV^{old} is expressed as

$$PV^{old} = \sum_j \frac{p_C(1+\pi^e)^j \Delta Q_{fj}}{(1+\tau_C)(1+\frac{\bar{r}}{12})^j} \tag{3.27}$$

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 whithout the investment, and $\bar{r}$ is the yearly average cost of capital. Given that CGPs use a Cobb-Douglass production function, if no investment is done, the production Q_{fj} after j months from the investment decision is given by

$$Q_{fj} = \gamma_f N_f^\alpha K_f^\beta (1-\delta)^{\beta \cdot j} \tag{3.28}$$

where γ_f is the total factor productivity, N is the number of employees, K is the capital of the firm under exam, δ is the capital depreciation rate and α and $\beta = 1-\alpha$ are the Cobb-Douglass exponents; note that the decrease of 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 $Q'_{fj} = \gamma_f N_f^\alpha (K_f + \Delta K_f)^\beta (1-\delta)^{\beta j}$. Note that $\Delta Q_{fj} = Q'_{fj} - Q_{fj}$. 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:

$$PV^{old} = \frac{p_C}{1+\tau_C} Q_{f0} \left[\left(1 + \frac{\Delta K_f}{K_f}\right)^\beta - 1 \right] s^{old} \tag{3.29}$$

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. 3.28 for $j=0$.

As regards the PV^{en} term, if the firm invests, the energy cost payed 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, the energy cost is reduced due to the lower energy intensity with respect to the no investment case; however, the energy cost is increased by the higher production level due to the expanded capital stock[4]. The difference $p_E(i_{Ef}Q_{fj} - i'_{Ef}Q'_{fj})$ represents the savings of energy cost, if positive, or the additional energy cost, if negative implied by the investment. The PV^{en} term is obtained discounting this difference with the same discounting factor used in the PV^{old} definition, and summing over months:

$$PV^{en} = \sum \frac{p_E(i_{Ef}Q_{fj} - i'_{Ef}Q'_{fj})}{(1+\bar{r})^j} \tag{3.30}$$

taking out the sum all the terms independent on the index j and reordering we obtain:

$$PV^{en} = p_E Q_{f0} \left[i_{Ef} - i'_{Ef} \left(1 + \frac{\Delta K_f}{K_f} \right)^{\beta} \right] s^{en} \tag{3.31}$$

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

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

$$\Delta NPV = -(p_{green} - p_{brown})\Delta K_f + p_E Q_{f0} s^{en} \left(1 + \frac{\Delta K_f}{K_f} \right)^{\beta} \frac{\Delta K_f}{K_f} (i_{E,brown} - i_{E,green}) \tag{3.32}$$

That is, the difference of NPVs depends on the negative difference of prices as for the RP investment decision (see Eq. 3.14), but also on investment quantity and on the difference between the energy intensity of the two type of capital.

In summary, concerning the energy intensity, the technological innovation is exogenous while the diffusion of new technologies is endogenous.

3.4 Technological progress

The baseline Eurace model includes also a more general technological progress affecting the total factor productivity (TFP) of firms. Differently from Ponta et al. (2018), this feature of the model is active in this study. The TFP of a firm is determined by the technical productivity of its capital stock and by the skills of its employees. The productivity of new machines

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[4] 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

produced by the KGPs grows with 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

$$\Delta\gamma_f^{tech} = \frac{\Delta K}{K + \Delta K}(\gamma^{new} - \gamma_f^{tech}) \tag{3.33}$$

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 the firm capital, multiplied by a parameter lower than 1. The TFP of each firm is given by the minimum of the average specific level of its employees and the technical productivity of the capital stock.

3.5 Climate policies

As mentioned in the previous chapter, my research is focused on the analysis of three policies: a carbon tax (CT), a feed-in tariff (FIT) and the mix of the two policies.

In the FIT scheme, the government sets a guaranteed price p_E^r for renewable energy, and finances through its budget the difference between p_E^r and the market energy price p_E, if positive, for every unit of energy sold by the RP. Then, the FIT policy cost for the government reads $\max(0, (p_E^r - p_E)E_{RP})$. See Ponta et al. (2018) for further details.

In the CT policy scenario, the government sets a price p_ε on the unit of GHGs emission and collects the corresponding revenues $p_\varepsilon\mathscr{E}$. 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

$$p_E = \frac{(1 + \mu_{PP})}{\gamma_{en}}(p_F + i_\varepsilon p_\varepsilon) \tag{3.34}$$

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_E^r, the FIT cost for the government in the policy mix scenario is lower than that in the corresponding isolated FIT scenario.

3.6 Physical dimensioning of the model

As said above, the one main purpose of this work is to study different climate policies, and in particular, to study the policy mix problem applied to climate policy in a model of the climate-economy system that, contrary to mainstream economic models, does not leave out real world characteristics, such as agents heterogeneity or incomplete and imperfect information, that are crucial for the policy mix performance evaluation. Since the climate change problem can be studied mainly through scenario analysis, we have chosen parameters values and initial conditions of the model to match the order of magnitude of the corresponding real world counterparts. To relate parameters and variables of the model to real world quantities we first identify the target system, that is a simplified description of the real world that is relevant for our exercise, and then we impose a set of physical and economic constraints that tie the model to the target system; note that the constraints give meaning to model quantities.

The target system is an economy in which agents' activities cause emissions of GHGs in the environment. Since three quarters of actual anthropogenic GHGs emissions come from the production and use of energy, we assume that in the target system there are only energy-related emissions. The energy is produced from two types of sources, namely non renewable sources, whose combustion generates GHGs emissions, and renewable ones, that we assume do not generate emissions. To proceed further, it is useful to recall the difference between the total energy supply (TES) or the primary energy production, and the total final consumption (TFC) of energy. The TFC is defined as the global energy consumption by end-users, while the TES also includes the energy used by the energy sector to produce, transform and distribute the energy. The ratio between the two gives the energy sector efficiency of transformation and distribution of energy, since the TES is the input necessary to produce TFC as output. TES is given by the sum of the energy produced from different sources. To measure the input amount of fossil fuels (coal, oil and natural gas) needed to generate the TFC it is commonly practice to convert mass unit to the energetic content of the fossil fuel considered (the energy that can be obtained burning a unit of fuel); this allows us to aggregate different source to build a unique fossil fuel equivalent. Examples of such units are the barrel of oil equivalent, the british thermal unit, the tonne of oil equivalent. In this writing, we express all the energy involved in watt-hour and its multiples.

Emissions alter the climate state that in turn cause damages to economic activities. In order to assess the performances of different policies, the analysis needs to consider the evolution of the climate-economy system in the future. Our target system is one with initial emissions, real GDP, TES and TFC of the same order of magnitude of the corresponding

Symbol	Description	Value
GDP_W	World yearly real GDP	$10^{14}\$$
GDP_M	Model yearly real GDP	$10^5 E\$$
$\mathscr{E}_{\mathscr{W}}$	World yearly GHG emissions	50 $GtCO_2e$
s_{RP}	World share of renewable energy (TES)	20%
Q_y	Yearly CGPs output	10^5 u.c.g.
p_{K0}	Initial model capital good price	1 E$

Table 3.2 Data used for the dimensioning procedure.

actual quantities, and whose future evolution is in accordance with the share socioeconomic pathway SSP5 description (Van Vuuren et al. (2014)); that is, in absence of climate policies, the evolution of the economy is characterized by a strong GDP growth, and although there is progress in both energy efficiency and renewable energy development, by a growing energy demand and growing or constant emissions.

In order to set parameters values and initial condition we impose a set of constraints relating the target system described above to the model. First, initial model (M) emissions have been set to actual (W, as world) emissions $\mathscr{E}_{M0} = \mathscr{E}_W = \mathscr{E}$.

Second, since emissions are associated to the production and consumption of goods, we assumed that the carbon intensity of GDP of the model (the emissions generated by the unit of real GDP) is equal to the actual carbon intensity when measured in actual currency ($). This condition can be expressed as

$$\frac{\mathscr{E}}{GDP_M} = \frac{\mathscr{E}}{GDP_W} \tag{3.35}$$

where $\mathscr{E}$ are the yearly global GHGs emissions, GDP_W is the actual real GDP expressed in $ and GDP_M is the first year real GDP of the model, measured in Eurace dollar $E\$$, the currency of the model. From the above equation we obtain a currency exchange rate equation

$$E\$ = \frac{GDP_W}{GDP_M}\$ \tag{3.36}$$

Substituting for the values given in table 3.2 we obtain:

$$1E\$ = 10^9\$ \tag{3.37}$$

Note that this condition tells how to interpret the goods of the Eurace model: a unit of real GDP of the model corresponds with a billion of actual real GDP units, since it generates the same GHGs emissions amount.

The third constraint consists in setting the initial TES and TFC of the model equal to the actual ones. Since CGPs are the only energy end-users, the initial energy intensity of production $i_{E0,f}$ (set equal for all firms) is determined by

$$i_{E0,f} = \frac{TFC}{Q_{y0}} \quad \forall f \tag{3.38}$$

where TFC is the actual energy consumption, Q_{y0} is the total production of consumption goods in the first year of the model (estimated through preliminary simulations) and f is an index that runs over the firms.

The fourth constraint imposes that the efficiency of energy transformation, that is the ratio between TFC and TES, of the model to the actual one, and its constancy during simulation. For the sake of simplicity, it is assumed that all the energy sources (renewable and non-renewable) are characterized by the same efficiency of energy transformation. Therefore, the efficiency of transformation of fossil energy in the model, that is the ratio between the fossil fuels component of TFC and the fossil fuels component of TES, is equal to the ratio between actual TFC (that is TFC from renewables and fossil fuels) and TES. From Eq. 3.15 it follows that the γ_{en} parameter of the PP production function is determined by the fourth constraint and it reads:

$$\gamma_{en} = \frac{TFC}{TES} \tag{3.39}$$

According to IEA (2020a), TES in 2018 was 166 Petawatt-hour ($10^{15}Wh$) while TFC was 115 Petawatt-hour. Inserting these values in Eq. 3.39, γ_{en} is roughly equal to 0.7.

As fifth condition we assume that the actual and model initial renewable energy share are equal:

$$\frac{E_{RP0}}{E_0} = \frac{TFC^R}{TFC} \tag{3.40}$$

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

$$i_{\varepsilon} = \frac{\mathscr{E}}{TFC^F} \tag{3.41}$$

where TFC^F is the TFC of fossil fuels and $TFC^R + TFC^F = TFC$.

Differently from fossil fuels, the unit cost of production of renewables is mainly determined by the fixed cost of installation. According to Our World in Data[5], the annual investment on renewables is about 250 billion \$ for an average increase the TES that can be generated in a year of 750 TWh. Using the same conversion factor of fossil energy to derive the renewable TFC^R, the cost of increasing yearly TFC by 1 TWh is given by $\frac{250}{0.7\cdot750}\frac{10^9\$}{TWh}$. Since we identified in the model renewable power stations with capital goods, the initial price of a renewable station is given by the initial capital price of the model, set to 1E\$. To obtain the TFC produced in a year by one renewable station in the model, suppose that 1E\$ has been invested in a year to increase the TFC generated in a year by x TWh, that is, the cost of increasing yearly TFC by 1 TWh in the model is given by $\frac{1E\$}{xTWh}$. According to the sixth constraints, the ratio has to be equal to the actual cost of increasing yearly TFC, that is:

$$\frac{E\$}{xTWh} = \frac{250}{0.7\cdot750}\frac{10^9\$}{TWh} \tag{3.42}$$

Using the Eq. 3.37 and dividing by 12 gives the monthly supply of one renewable station, that is roughly $1.75\cdot10^{-4}PWh$. We assumed that the monthly supply of a renewable power station is $1.5\cdot10^{-4}PWh$, in order to account for the variability of renewable sources. Inserting this value in Eq. 3.10 and using the actual share of total renewable energy consumption as set by Eq. 3.40 we get the initial number of renewable power stations n_s.

The seventh constraints imposes that the model fossil fuels initial price p_{F0} is equal to the actual one p_F. Since there are different fossil fuel sources, here it is defined a single fossil fuel equivalent whose price p_F is expressed as a weighted average:

$$p_F = \frac{\sum_f p_f TES_f}{TES^F} \tag{3.43}$$

where the sum runs over the 3 main fuels, i.e. coal, oil and natural gas, and p_f and TES_f are the corresponding price and TES (note $\sum_f TES_f = TES^F$). The p_F is determined using the values reported in table 3.3. Rearranging the terms in Eq. 3.18, one obtains for the number η of machines depleted by the FM agent to produce one unit of fossil energy.

$$\eta = \frac{1}{(1+\mu_F)}\frac{p_{F0}}{p_{K0}} \tag{3.44}$$

where p_{K0} is the initial capital price, equal for the two KGPs. Substituting the value computed for p_F and using Eq. 3.37 gives the value of η reported in table 3.4.

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

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

Table 3.3 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. Data are referred to the year 2018 and are taken from IEA (2020a).

Parameter	Description	Value	Unit
i_{PP}	Carbon intensity of fossil energy	$3.7 \cdot 10^{-1}$	$\frac{GtCO_2}{PWh}$
i_{E0}	Initial energy intensity	10^{-3}	$\frac{PWh}{ucg}$
γ_{en}	Efficiency of fossil energy transformation	0.7	-
p_F	Initial fossil fuel price	18.64	$\frac{E\$}{PWh}$
n_{s0}	Initial number of renewable stations	$\cdot 10^4$	-
m_s	Monthly energy supply of a renewable station	$1.5 \cdot 10^{-4}$	$\frac{PWh}{month}$
η	Consumed capital per PWh	17	$\frac{1}{Pwh}$

Table 3.4 The table presents the values of the parameters that results from the dimensioning procedure.

Finally, the exogenous capital productivity growth rate, as well as the parameters regulating the production 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) are set in order to produced an economy characterized by a strong growth of GDP (growth rate of real GDP in the range from 2% to 4%), a decreasing energy intensity and an increasing energy consumption and GHGs emissions, as requested in the beginning of this section.

Table 3.4 summarizes the values of the model parameters determined through the calibration procedure.

3.7 Stylized facts reproduced by the Eurace model

The Eurace model can reproduce the main macroeconomic stylized facts that can be found in the literature, e.g. in Napoletano et al. (2006); Uribe and Schmitt-Grohé (2017). For instance, the economy of the Eurace model shows:

- endogenous self-sustained growth with persistent fluctuations
- positive correlation between GDP and loans to firms
- negative correlation of GDP with unemployment rate and firms defaults
- positive correlation between the central bank interest rate and bond yelds
- investments volatility higher than consumption volatility

For a more detailed discussion of the stylized facts reproduced by the Eurace model the interested reader is refferred to Ponta et al. (2018); Teglio et al. (2019).

Chapter 4

Computational experiments

4.1 Experimental setting

As mentioned above, the purposes of this work are to study the carbon tax (CT) policy, comparing the tax with a feed-in tariff policy (FIT), and to analyze the policy mix that results from the combination of the two single policies, to check if the mix is superior to both its parent policies when implemented in isolation, and if it can be found the optimal or best mix among those considered.

The Eurace model has been used as a laboratory to test policies and to separate the effects of the single policies in the mix by looking at their behavior when implemented in isolation. In particular, the multiple channels that lead to the desired emissions reduction and to the costs (negative economic or social effects) are identified for each single policy. Then, synergistic and conflicting effects between the two policies in their mix are studied. To this end, a series of Monte Carlo experiments have been performed: each of the 22 scenarios considered was simulated ceteris paribus (with identical parameters and initial conditions) 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 years time span of each simulation.

Table 4.1 presents the values of the two different policy parameters characterizing each of the 22 scenarios. In the first scenario, the so-called business as usual (BAU), no climate policy is implemented. Scenarios from 2 to 8 are characterized by a carbon tax p_ε of increasing value, in scenarios from 9 to 15 a feed-in tariff is implemented, and finally, in the last seven scenarios both policies are active so to implement a policy mix (PM). All scenarios are simulated with and without the climate damages feed-back.

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

Table 4.1 Scenarios definition

Both the values of the carbon tax and the feed-in-tariff are chosen to produce from moderate to extreme emission reduction. In particular, the carbon tax values are chosen in the range [15, 90] $\frac{\$}{tCO_2e}$ 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, the feed-in-tariff values are chosen to produce emissions reduction similar to the one obtained with the carbon taxes considered, compatibly with the constraint $p^r_E > p_E$.

Policy mix values are selected first 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.

4.2 Results and comparison of climate policies

The results of the simulations are presented below through boxplots, other graphs and statistical tables.

Figures 4.1-4.6 show the boxplots representing the distribution for all scenarios of the relevant variables considered without climate damages. In particular, for all variables but temperature and atmospheric carbon stock, each box shows the distribution of the time average over the entire 30 years time span of the simulations. Temperature and carbon stocks are analyzed looking at the distribution of their final year values. The lowest and highest extremes of each box represent respectively the 25th and 75th percentile of the distribution, the dashed line extends from the minimum to the maximum value not considered outliers, and the horizontal line dividing the box represents the median of the distribution. Finally, the + symbol represents any outliers. Boxes have different colors to distinguish policies, in particular, black boxes refer to the BAU scenario, the red ones refer to the CT scenarios, whereas the blue and the magenta boxes are related to the FIT and PM scenarios, respectively.

Figures 4.10-4.13 show the boxplots of relevant variables for both scenarios with and without climate damages. To keep the figures legible, the 10 (out of 22) most representative scenarios are represented in the figures: the 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 damages.

Tables from 4.2 to 4.5 report the results of the two-sided Wilcoxon ranksum test, which for each variable 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. The tables report the p-values of the test; when the p-value is lower than the 5% (1%) the null hypothesis is rejected with a 5% (1%) significance level.

Carbon tax

As shown in Fig. 4.1, both the CT, the FIT and their mix are effective in reducing the impacts of the economic activities on the climate. However, the emissions reduction comes at the cost of a slower growth of the economy as shown in figures from 4.2 to 4.5. As regards the carbon tax, both economic costs and climate benefits (emission reduction) come from the impact on the energy price; as shown in Fig. 4.2(a), the higher the carbon price the higher the energy price. A higher energy price fosters energy intensity improvements (Fig. 4.2(c)), because it increases the net present value of green capital (see Eq. 3.28) and then the share of the less energy intensive capital (Fig. 4.2(d)). Furthermore, a higher energy price increases also the share of renewable energy, as shown in panel (b) of Fig. 4.2, because it increases the net present value of investments in new renewable power stations (see Eq. 3.11).

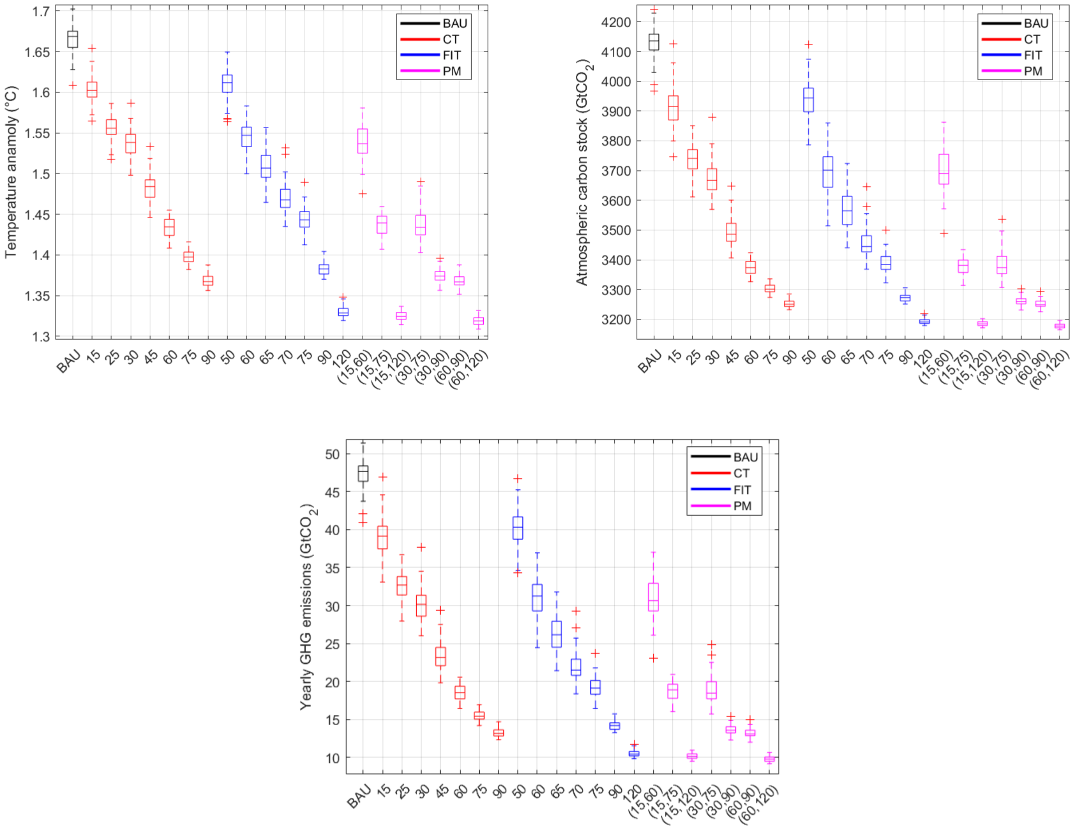

Figure 4.1 The figure shows the boxplots of the final value or the temporal mean of the variables of interest for all the scenarios without climate damages considered. In particular it shows: (a) the final value of the temperature anomaly, (b) the final value of the atmospheric carbon stock and (c) the mean value of yearly GHGs emissions.

In summary, the environmental performance of the CT policy is determined by three causes: lower energy intensity, higher share of renewables and, last but not least, by the slower growth rate of the economy (see Eq. 3.22). However, energy intensity improvements have a minor impact on emission reduction with respect to the other two causes, although the statistical tests indicate a significant difference between the majority of CT policies and the BAU scenario. Indeed comparing figures 4.3(c), 4.3(b) and 4.3(d) it can be seen that the percentage difference of energy intensity relative to a CT scenario and to the BAU are much smaller than the percentages differences of the share of renewable energy and of the consumption level, taken as a proxy for the CGPs production quantity.

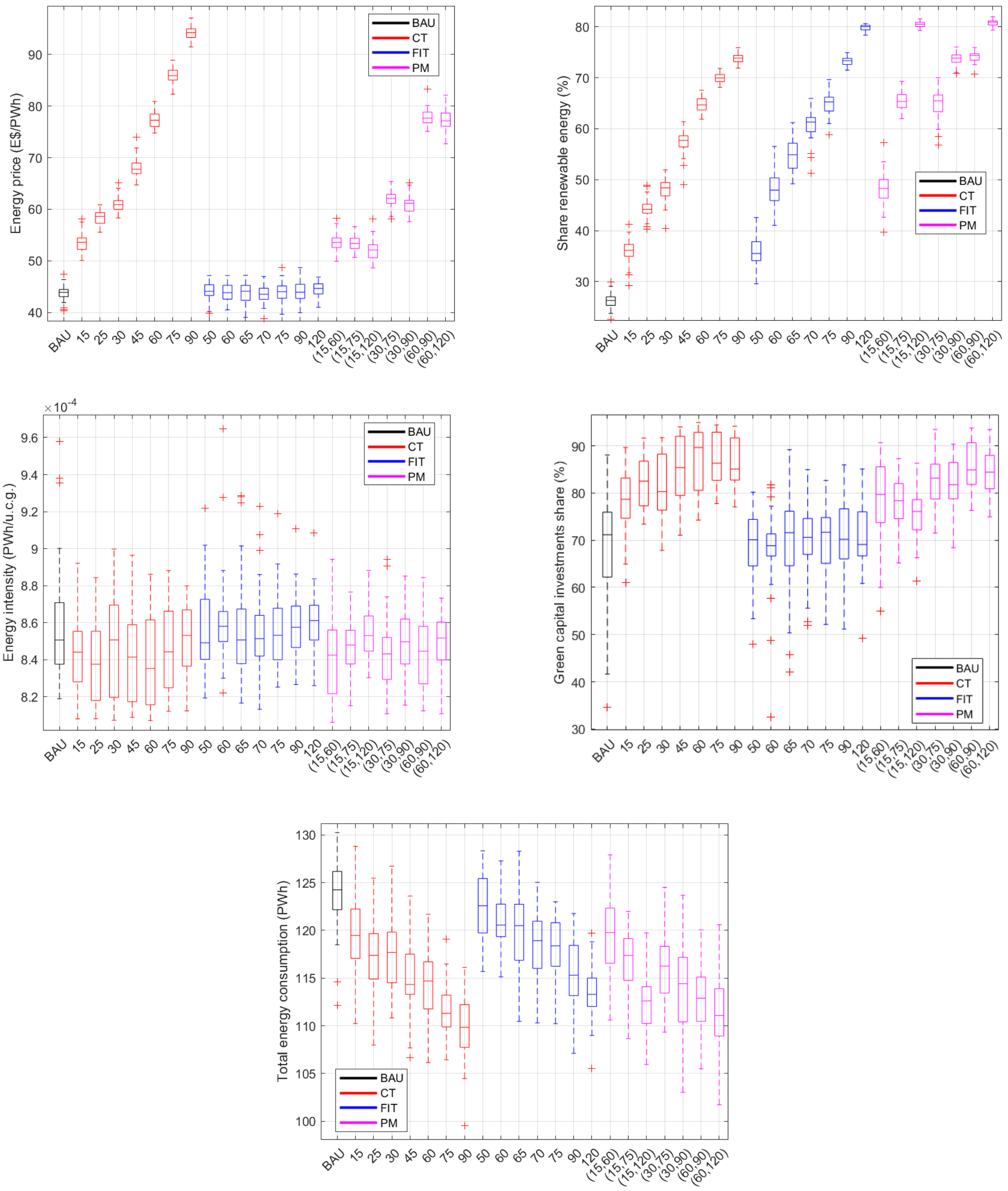

Figure 4.2 The figure shows the boxplots of the temporal mean of the variables of interest for all the scenarios without climate damages considered. In particular it shows: (a) the energy price, (b) the share of renewable energy, (c) the energy intensity, (d) the share of green investments and (e) the total final consumption of energy.

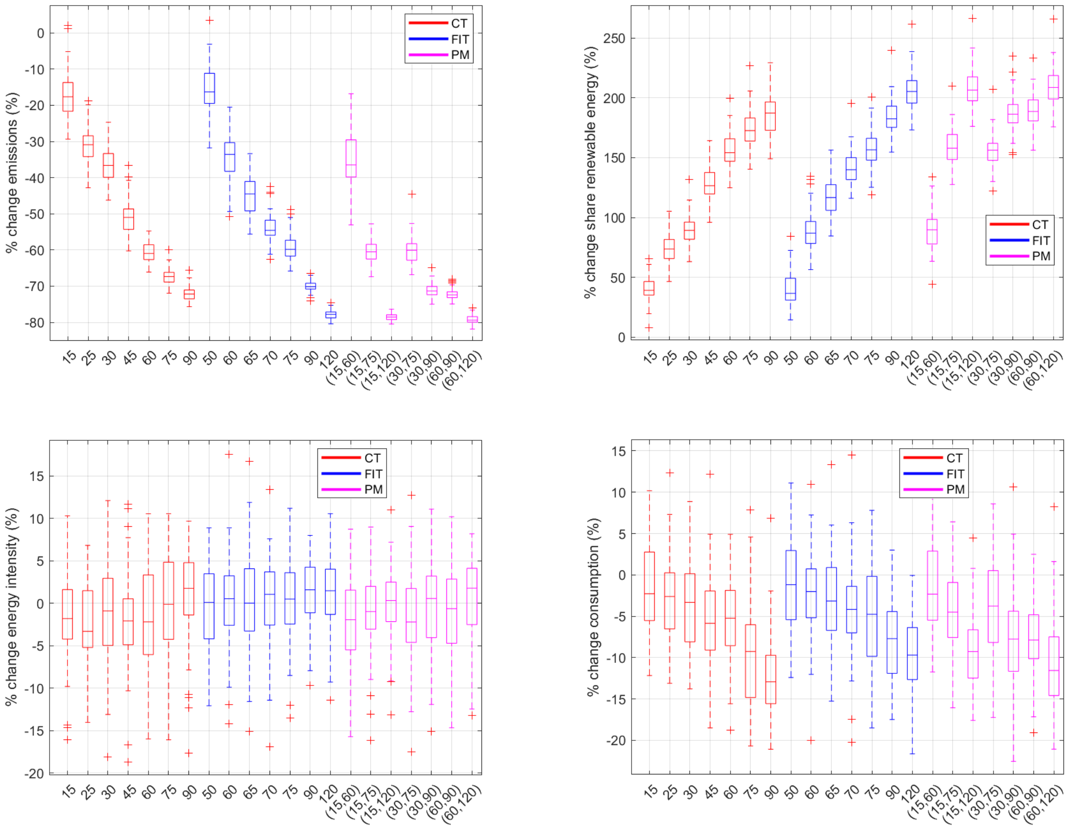

Figure 4.3 The figure shows the boxplots of the percentage difference with respect to the BAU of: (a) total emissions, (b) share of renewable energy, (c) energy intensity and (d) real consumption.

The consumption loss with respect 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. 4.4(a)). This determines a reduction of real consumption (Fig. 4.4(b)) and then, in particular with the highest CTs, a reduction of the employment rate in the private sector and a reduction of household purchasing power (Fig. 4.5(d)). The reduction of the demand of consumption goods leads also to a reduced capital goods demand as shown in (Fig. 4.4(d)). Instead, there is not a recognizable trend in capital prices (Fig. 4.4(c)), meaning that their dynamics is governed by other factors, such as the reduced demand from CGPs and the competition in the labor market between the two KGPs and the CGPs. Indeed, both KGPs set the capital price as a mark-up on the unitary costs, given by the average wage divided by the TFP, and therefore, the price increases when KGPs have to rise 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 affect 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 deficit, the government sets a higher general tax rate (Fig. 4.6) that exacerbates the economic slowdown, determining a further reduction of consumption and an increase of the unemployment, despite the reduction of the interest rate set by the central bank (Fig. 4.6)[1]. We observe also a higher inflation rate for the highest CT values. We argue that this depends both on higher energey prices and a lower total factor productivity determined by lower investments with respect to the BAU scenario.

Feed-in tariff

Concerning the FIT, emission reduction is determined by the higher share of renewables and by the reduced energy demand determined by the lower consumption level. Since the RP is remunerated with the guaranteed price, the FIT increases the NPV of investments in new renewable power stations and then, ceteris paribus, it determines a higher share of renewables. However, the FIT policy has no effect on energy intensity, as shown by Fig. 4.2 and by table 4.2.

The economic cost (consumption loss with respect 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, similarly for the highest CT values, leads to higher consumption prices, lower real demand of consumption goods and then of production inputs, i.e. labor (Fig. 4.5) and capital. Note that we do not observe the shift of workers form the CGPs to the KGPs observed in Ponta et al. (2018). This is because in Ponta et al. (2018) the total factor productivity (TFP) is fixed during all simulations while the economy considered here is characterized by TFP growth; indeed, 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 behavior of the labor market: in the economy represented by the EURACE model there can be unemployment even when all the workforce is required for the production needs). Furthermore, similarly to the CT, the FIT policy leads

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[1] In the Eurace model, the government check the deficit to GDP ratio to update tax rates: if the deficit is higher than 3% of GDP the government increases the all tax rates by 5%, if the deficit is lower than zero the government decreases all tax rates by 5%, while in the other cases tax rates are unchanged. There are different tax rates in the model (e.g., labor taxes, VAT, corporate income taxes), however, for the experiments presented here and reported in Nieddu et al. (2022, 2023b) all the tax rates are equal, since they have the same initial value and the same evolution rule

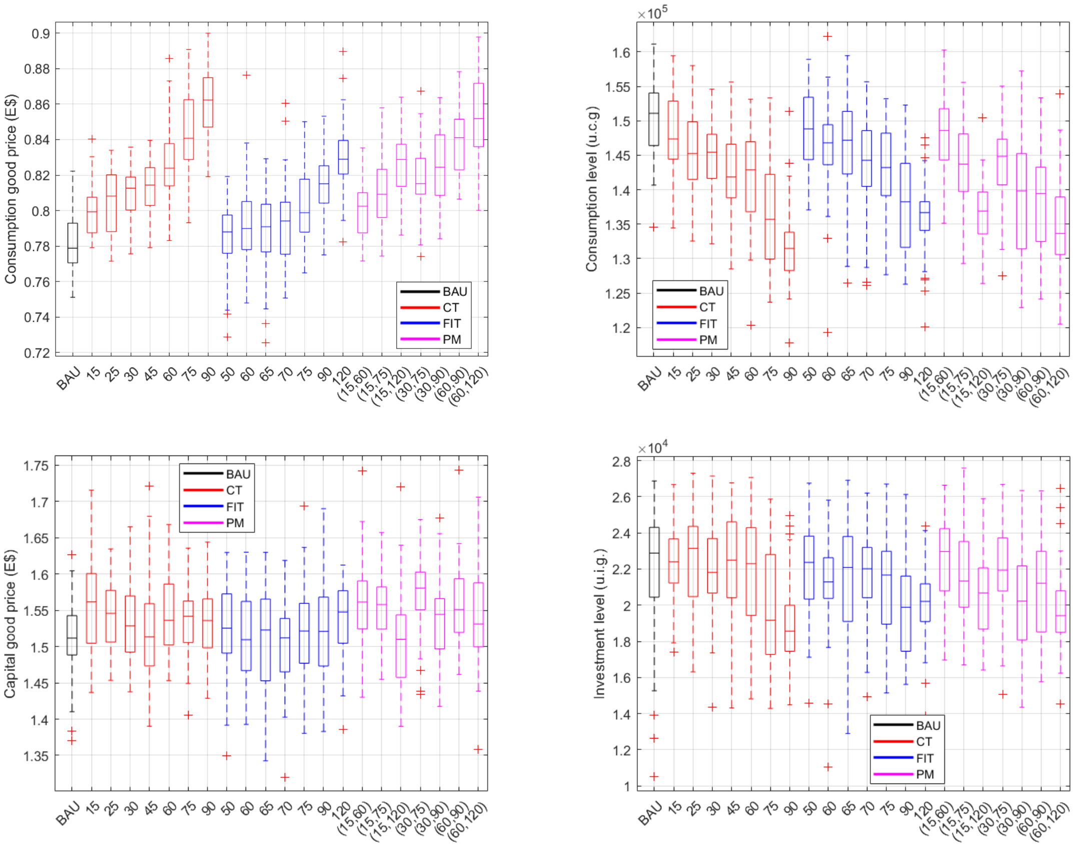

Figure 4.4 The figure shows the boxplots of the temporal mean of the variables of interest for all the scenarios without climate damages considered. In particular it shows: (a) the consumption price, (b) the real consumption, (c) the capital price and (d) the real investments.

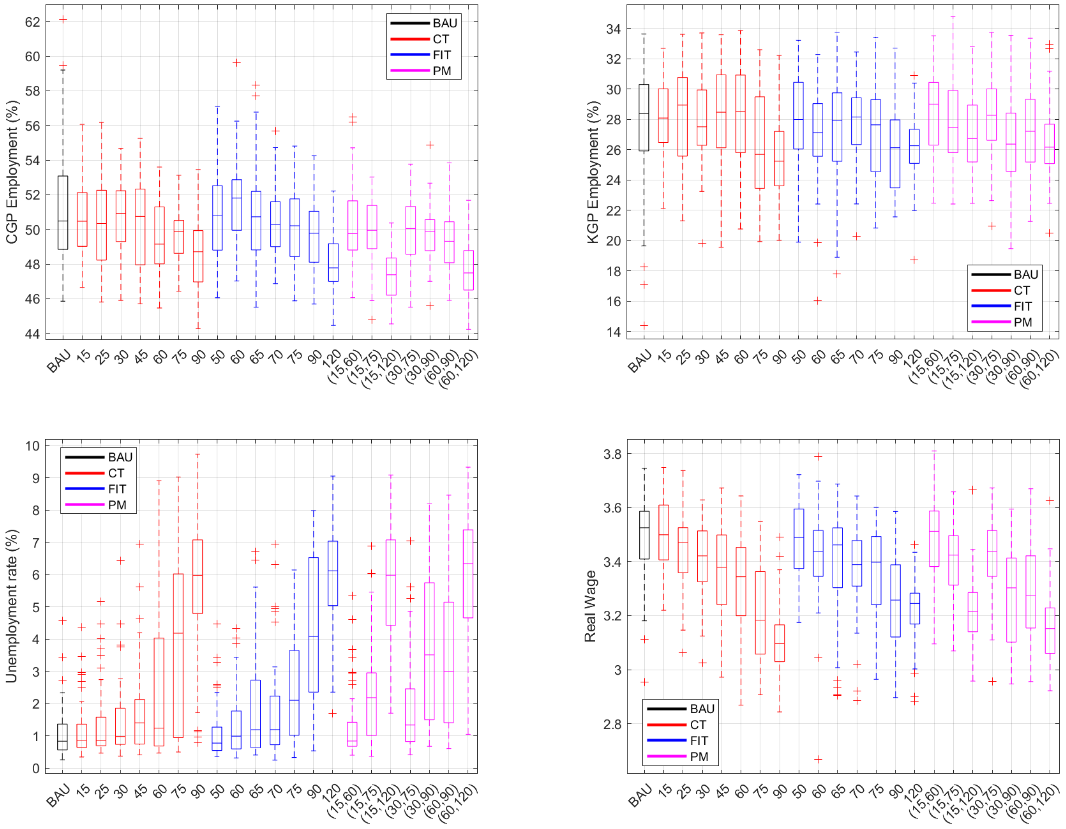

Figure 4.5 The figure shows the boxplots of the temporal mean of the variables of interest for all the scenarios without climate damages considered. In particular it shows: (a) the employment rate of the consumption goods sector, (b) the employment rate of the capital goods sector, (c) the unemployment rate and (d) the mean real wage.

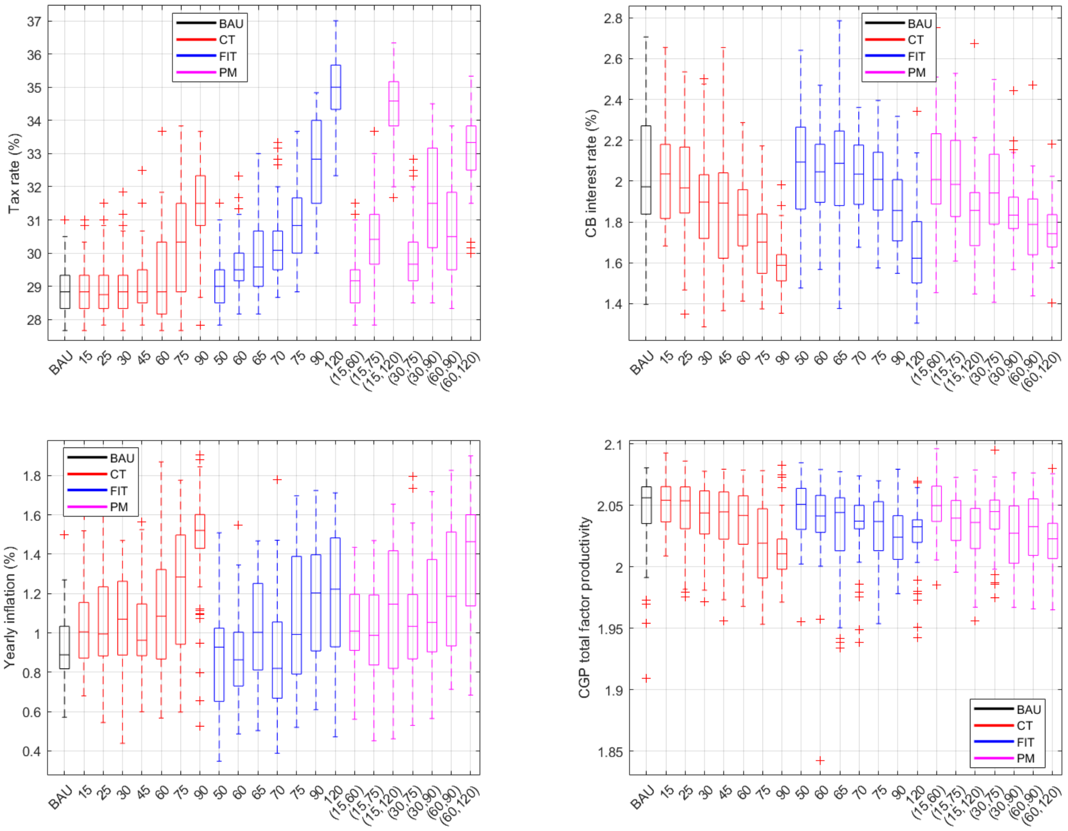

Figure 4.6 The figure shows the boxplots of the temporal mean of the variables of interest for all the scenarios without climate damages considered. In particular it shows: (a) the general tax rate, (b) the central bank interest rate, (c) the inflation rate and (d) the mean TFP of the CGPs.

to higher inflation rate (determined both by higher prices and lower TFP) and to lower policy rate, as shown in Fig. 4.6.

Comparison between single policies

Given that both the CT and the FIT policies are effective in reducing GHGs emissions, which of the two is better? To compare the policies, first their objectives and costs have to be identified. Here we assume a target emission level, or a target emission reduction as the objective and emission or emission reduction as the quantity to measures the level of target achievement. There are different metrics used to assess the cost of a climate policy, most of which are based on measuring the relative difference between the value of a variable (e.g. consumption or GDP, see IPCC (2014)) when the policy is implemented and the value of the same variable in a BAU scenario. In this work, the metric adopted is the consumption loss with respect to the BAU.

Taking the average values of total emission and consumption loss as the certain results of the policies, we can compare the two policies by representing their performances in a graph as in Fig. 4.9, where the left panel is relative to the no-damage scenarios, while the right one refers to scenarios with climate damages. In each panel, the x-axis represents the average of total 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, which will be included in the analysis later, represent the PMs. The green shaded region represents all the policies that lead to emissions lower than the 580 $GtCO_2$ remaining carbon budget cited in the Introduction. A policy is dominated if there is at least another one policy characterized by lower emissions and lower consumption loss, that is, if there are points in region at the south-west with respect to the point representing the policy under examination. Focusing only on CT and FIT, from Fig. 4.9(a) we can conclude that, first, there is not a CT that is dominated by the other CTs; second, the same is true for the FIT; 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 expliciting further the preference structure of the choice between reducing emissions more or pay less. Furthermore, since there are many possible consequences of every single policy, the analysis has to consider the variability of emissions reductions and consumption loss. Next section presents a method based on multi-criteria analysis (Keeney et al. (1993)) to establish the best policy.

	Carbon tax							Feed-in tariff						
	15	25	30	45	60	75	90	50	60	65	70	75	90	120
p_k	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	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	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 2 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
$\frac{\Delta C}{C}$	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	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	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	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 2GDP								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 2GDP	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. debt	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
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	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
$\mathscr{E}$	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	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	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
U	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 4.2 The table shows the p-Values of the two-sided Wilcoxon rank-sum test, that 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 climate damages. When the p-Value is lower than the 5% (1%) the null hypothesis is rejected with a 5% (1%) significance level.

	Policy mix						
	(15,60)	(15, 75)	(15, 120)	(30,75)	(30,90)	(60,90)	(60,120)
p_k	0.000	0.000	0.438	0.000	0.016	0.000	0.020
K	0.860	0.004	0.000	0.044	0.000	0.010	0.000
s_g	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
CGPEmployment	0.218	0.158	0.000	0.153	0.051	0.005	0.000
$\frac{\Delta C}{C}$	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	0.000	0.000	0.000	0.000	0.000	0.000	0.000
i_E	0.008	0.087	0.866	0.006	0.281	0.020	0.442
p_E	0.000	0.000	0.000	0.000	0.000	0.000	0.000
FIT cost 2 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
Public debt 2 GDP	0.414	0.178	0.471	0.077	0.044	0.612	0.132
Public deficit 2 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
$\mathscr{E}$	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
$\frac{\Delta GDP}{GDP}$	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	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

Table 4.3 The table shows the p-Values of the two-sided Wilcoxon rank-sum test, that 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 climate damages. When the p-Value is lower than the 5% (1%) the null hypothesis is rejected with a 5% (1%) significance level.

Policy mix

The channels through which the costs and benefits of individual policies arise form the ground for analyzing their mix. As said in Section 3, the values of the CT and FIT in the PM have to be such that 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. 3.11), and the government would not subsidize the renewable energy, being the difference $p_E^r - p_E$ negative. Therefore, investments in renewable power stations are determined by the FIT value, while the consumption loss arise from the increase in the consumption good price due to the increased energy price via CT and from the increase in the general tax rate due to the need of financing FIT expenditures. However, the CT can mitigate the consumption loss due to the FIT cost because CT revenues can in part compensate the FIT cost and because the higher market energy price decreases the cost $(p^r_E - p_E)$ of each unit of renewable energy paid by the government.

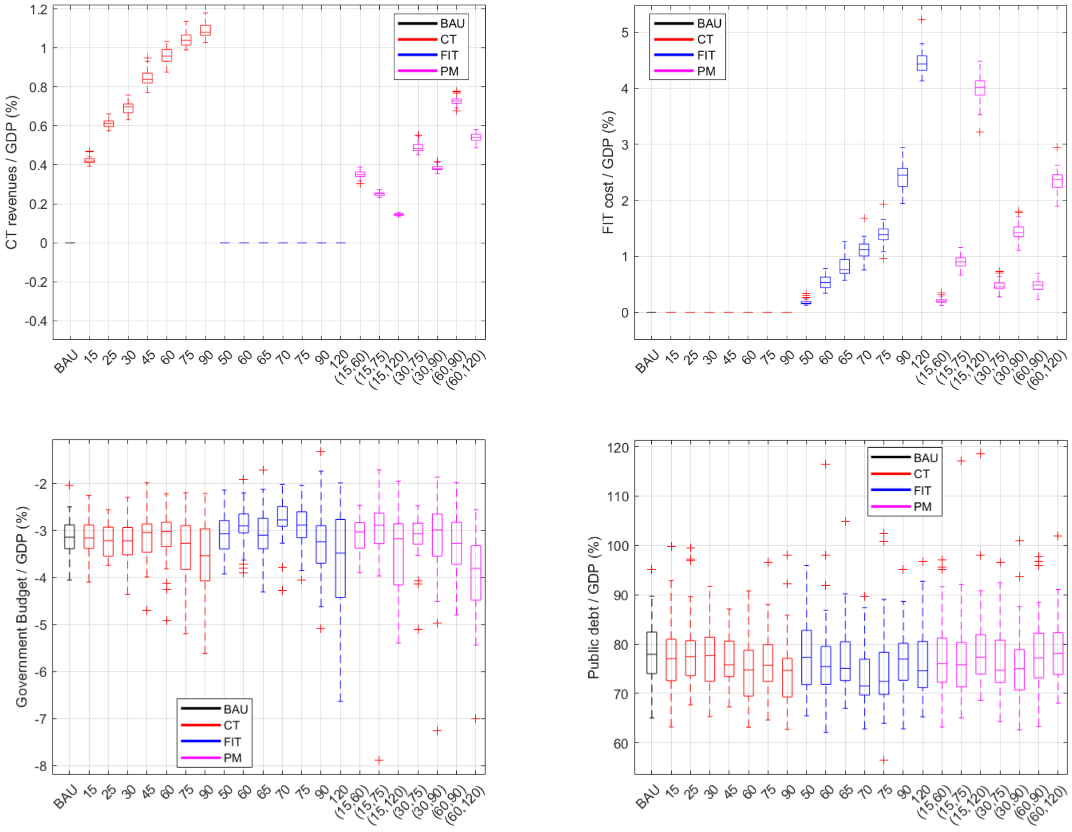

Figure 4.7 The figure shows the boxplots of the temporal mean of the variables of interest for all the scenarios without climate damages considered. In particular it shows: (a) the CT revenues over GDP, (b) the FIT expenditure over GDP, (c) the government budget over GDP and (d) the government debt over GDP.

Figure 4.1 shows that the PM environmental performances are equal to, or better than those of the corresponding FITs. This is mainly due to the impact on the renewable share (Fig. 4.2(b)). Due to the energy price increase (Fig. 4.2(a)), the PM influences also the share of green investments in less energy intensive machines (Fig. 4.2(d)) and therefore it leads to higher energy intensity improvements with respect to the BAU (Fig. 4.2(c)); however, this progress has minor effect on emissions reduction. Fig. 4.2(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. 4.7(b) shows that the higher the carbon price the lower the FIT policy cost. Therefore, the increase in the general tax rate due to the FIT policy cost is milder in the PM than in the isolated corresponding FIT, see Fig. 4.6(a).

Drews et al. (2020) provide a method to check if there is interaction between two policies or if they are independent from each other. In the context of climate policies, according to Drews et al. (2020), two policies are independent if the emission reduction achieved by their mix is the sum of the emission reduction achieved by each of the policies implemented in isolation, otherwise the two policies are said interacting. The interaction gives benefits (that is, the policy mix is advantageous) when the emission reduction of the mix is strictly greater than the greatest of the emission reduction achieved by the parent policies.

We claim that this is not the only situation in which a policy mix is preferable to its components, and that the argument above need to include costs. Therefore, we redefine two policies independent if their mix achieves an emission reduction equal to the sum of reductions of the single policies at a cost that is the sum of the costs of the isolated parents policies. The interaction is advantageous when the emission reduction of the mix is **equal to** or higher than the greatest of the emission reduction achieved by the parent policies, provided that the cost of the mix is lower than the highest of the single policies costs[2]. First, note that according to the argument of Drews et al. (2020), if the emission reduction achieved by the mix is equal to the greatest of the reductions achieved by the components, the policy mix is considered redundant and the single policy achieving the highest emission reduction is preferred, while according to our argument the mix is preferred, provided its cost is lower than the highest of the single policy costs. Second, if emission reduction of the mix is higher than the highest reduction but also the cost of the mix is higher than the costs of the single policies, it can not be stated that the mix is better or not without making explicit a preference structure. The same is true when both the emission reduction of the mix are between the two emission reduction of the isolated policies and the cost of the mix is lower than the highest cost of the components.

Using this criterion to evaluate PM performance and dealing with mean values as they were certain outcomes, we found that all the PM but one is preferred to its components. The results of the analysis are shown in Fig. 4.8. In each panel, the x-axis represents the negative of emission reduction with respect to the BAU ($\frac{\mathscr{E}_{BAU}-\mathscr{E}}{\mathscr{E}_{BAU}}$), the y-axis represents the negative of the consumption loss with respect to the BAU ($\frac{C_{BAU}-C}{C_{BAU}}$). In each graph the average values of the emission reduction and consumption loss relative to the PM under exam (magenta circles) and to its CT (red squares) and FIT (blue triangles) components are represented. The shaded

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[2] 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.

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 to evaluate the performance of the policy mix with respect to the shaded region. Only the PM(60, 120) is out of the shaded region, however, it is necessary to explicit a preference structure to ascertain if the 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. 4.9(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. 4.1 and in Fig. 4.4.

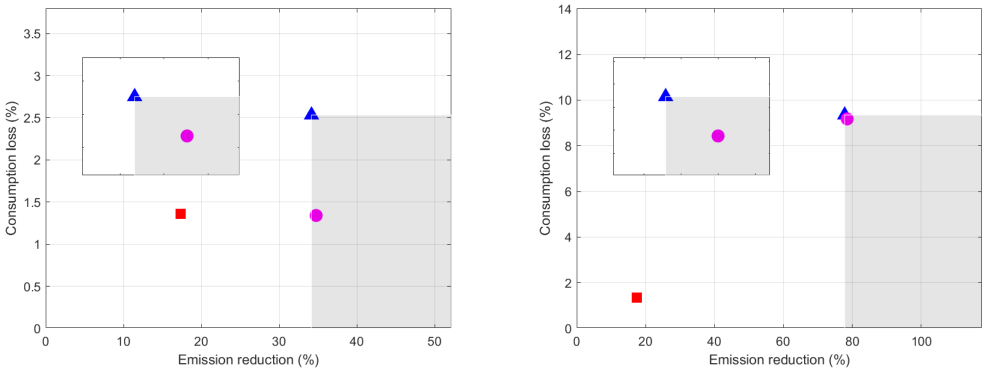
As for the parents policies, to choose among the non dominated policies and to deal with the uncertainty of the outcomes, the analysis cannot be restricted to mean values and therefore, we use the expected utility analysis.

4.3 Results and comparison of climate policies under climate damages

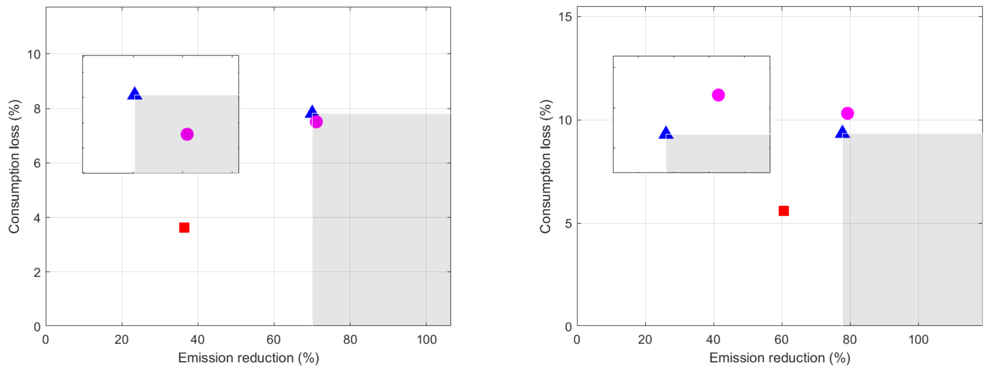
Policies have better performance under damages, because they lead on average to lower total emissions (Fig. 4.1(c)) at similar costs.

The main effect of the damages to capital stock is the reduction of the productive capacity that leads to consumption levels lower than what is demanded by households. Since firms' production plans are based on past sales, the input demand (labor and capital) decreases and scenarios with climate damages are characterized by higher unemployment rates (Fig. 4.13(c)) with respect to the no damages scenarios. The lower the consumption (Fig. 4.12(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 figures 4.10(c). This is because lower emissions lead to lower climate damages and then, given the damages function used, the most effective policies are able to reduce the negative consequences of the damages. However, this is not granted if a function that leads to higher damages for every value of the temperature anomaly is used, because higher damages require higher reduction and eventually if, damages are higher enough, no emission reduction will succeed in avoiding damages consequences. A similar reasoning holds if the time span of simulations is changed from 30 to 80 years.



(a) PM(15,60) (b) PM(15,120)



(c) PM(30,90) (d) PM(60,120)

Figure 4.8 The figure shows the policy mix performance compared to that of its parent policies in the scenarios without climate damages. 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.

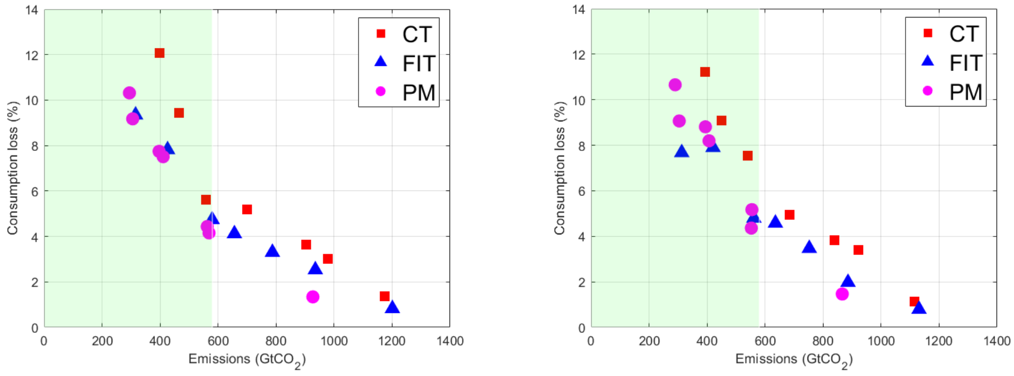


Figure 4.9 The figure shows the cost VS objectives graph, where the policies are represented by points in the plane total emission VS consumption reduction with repsect to the BAU. The green shaded area represents the policies for which total emissions are lower than the remaining carbon budget of 580 $GtCO_2$.

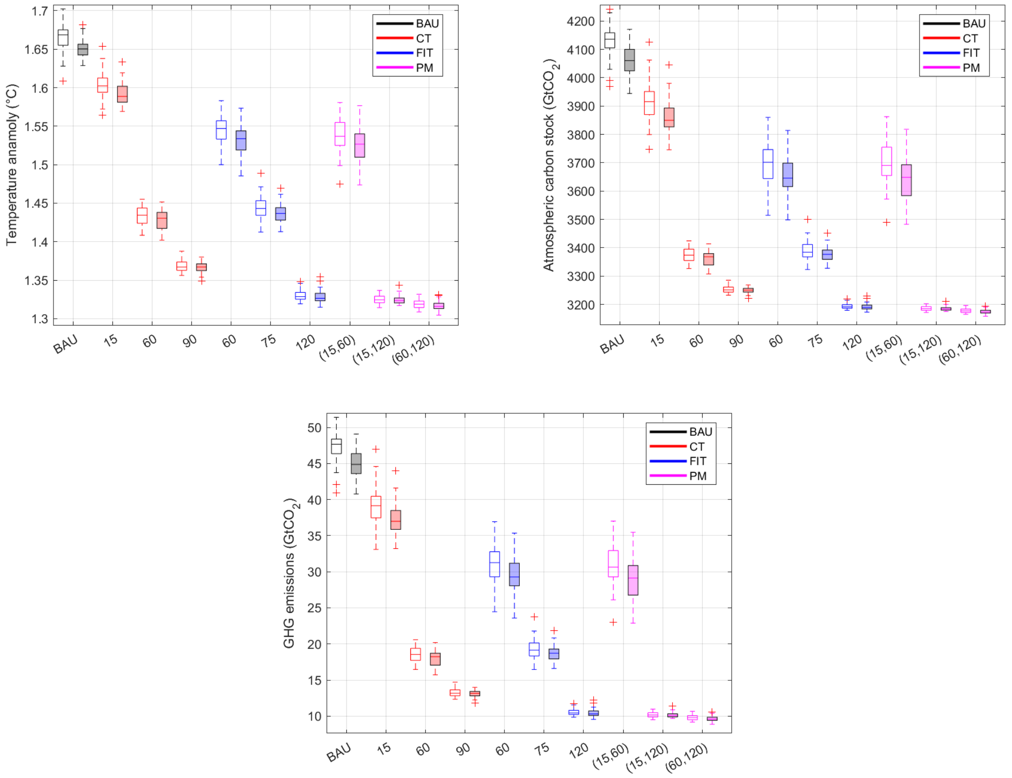


Figure 4.10 The figure shows the boxplots of the final value or the temporal mean of the variables of interest for the ten most representative scenarios considered. Empty boxes refer to the scenarios without climate damages while filled boxes refer to scenarios with climate damages. In particular it 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.

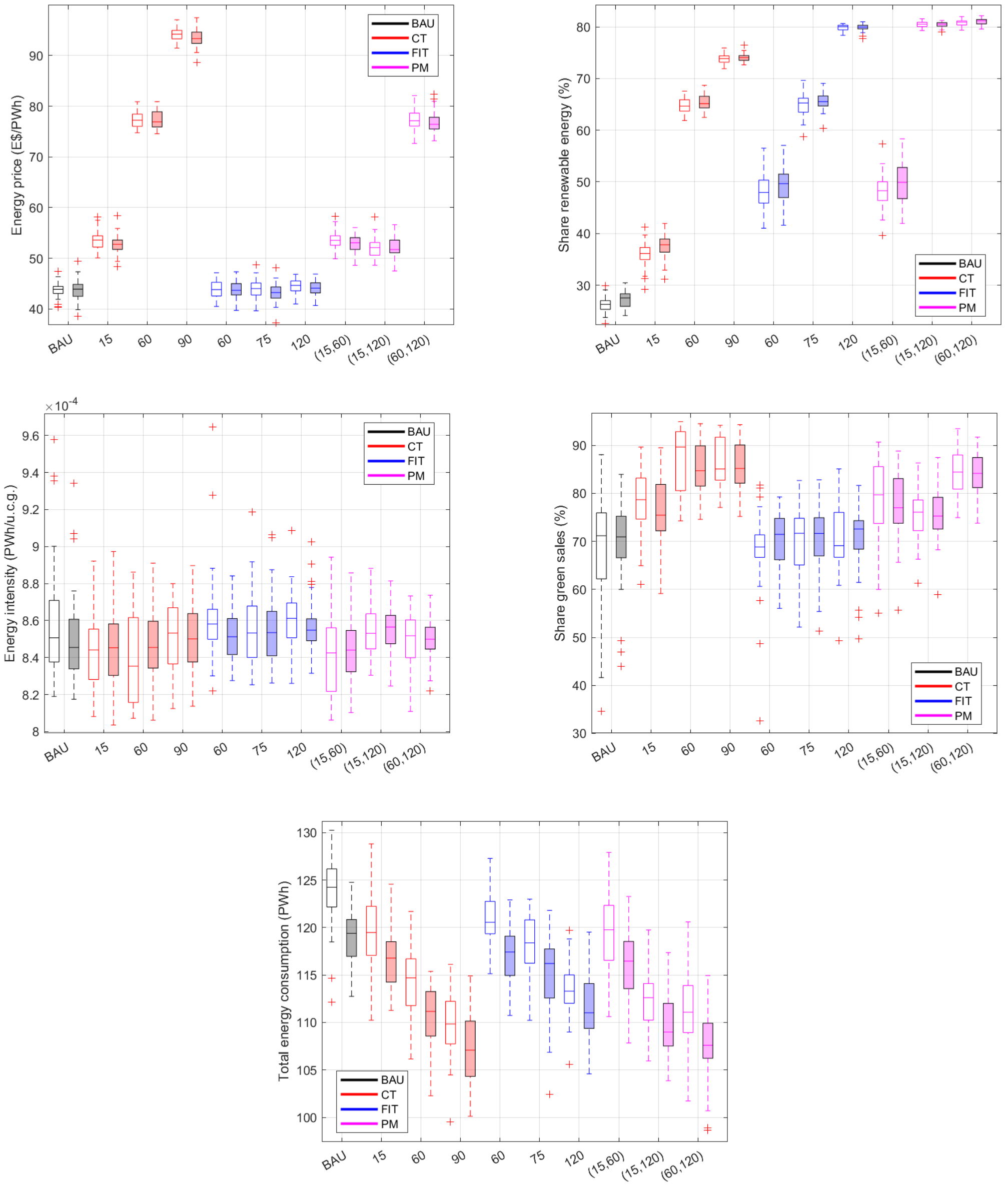


Figure 4.11 The figure shows the boxplots of the temporal mean of the variables of interest for the ten most representative scenarios considered. Empty boxes refer to the scenarios without climate damages while filled boxes refer to scenarios with climate damages. In particular it shows: (a) the energy 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.

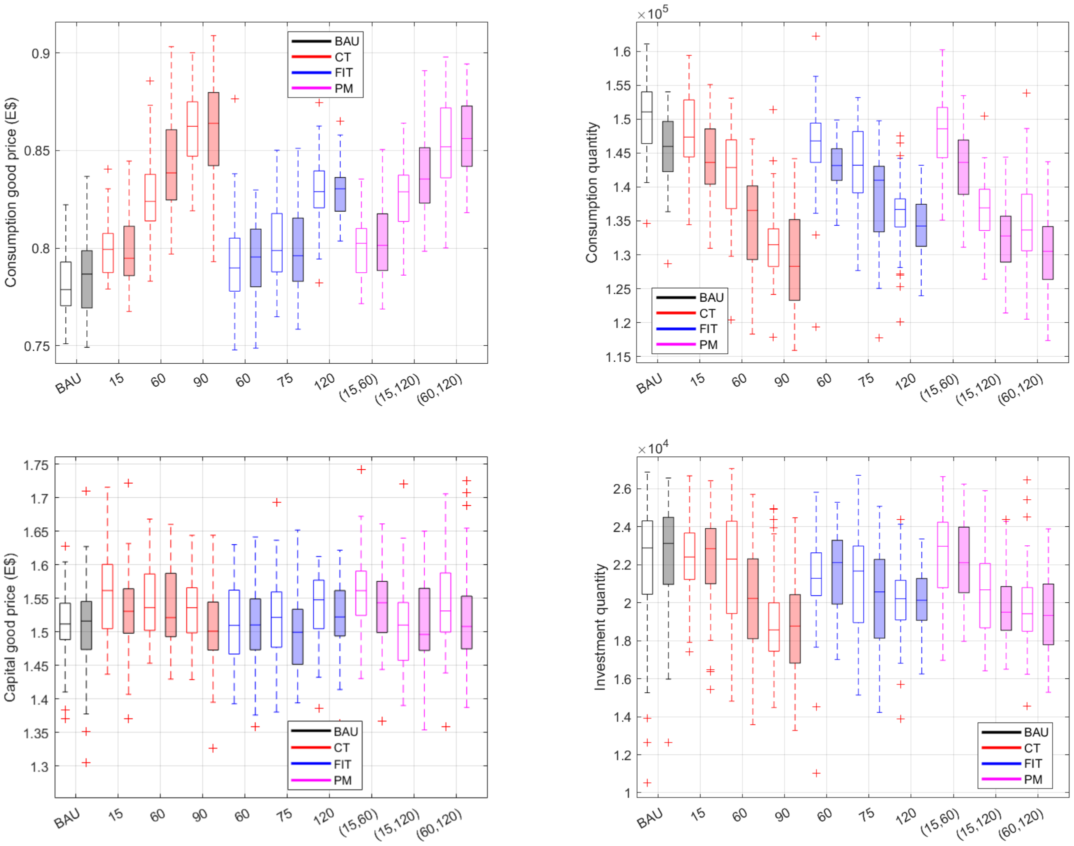


Figure 4.12 The figure shows the boxplots of the temporal mean of the variables of interest for the ten most representative scenarios considered. Empty boxes refer to the scenarios without climate damages while filled boxes refer to scenarios with climate damages. In particular it shows: (a) the consumption price, (b) the real consumption, (c) the capital price and (d) the real investments.

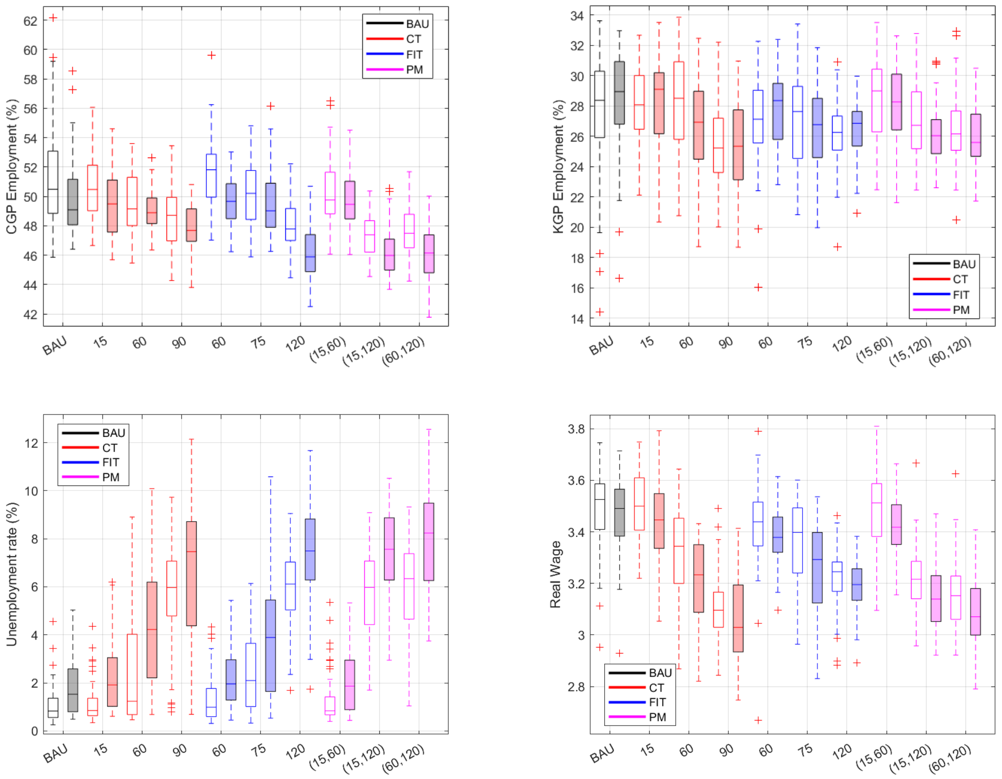


Figure 4.13 The figure shows the boxplots of the temporal mean of the variables of interest for the ten most representative scenarios considered. Empty boxes refer to the scenarios without climate damages while filled boxes refer to scenarios with climate damages. In particular it shows: (a) the employment 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.

The effects of the damages are different for each of the 3 types of policies considered. Comparing again the two individual policies lead to similar results with respect to the no-damage case (see Fig. 4.9(b)): only two of the CTs are not dominated by the FITs. Including PMs, we can see that damages affects negatively their performances relative to those of the FITs: there are two PMs dominated by a FIT.

This result is confirmed by the analysis of the interactions between the components of the mix. Fig. 4.14, the analogous of Fig. 4.8 for the scenarios with climate damages, shows that most of the PMs lie outside the shaded region, and since both emission reduction and costs of the PMs are higher than those of their components, it can not be concluded that PMs are better or worse without defining a preference structure.

Damages affects the PM more negatively than the FIT. This can be explained looking at the effects of damages on the interaction between the two single policies. As shown in the previous section, consumption losses with respect to the BAU scenario in the PM scenario are determined by two potential causes each related to one of its components and a third 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 to hold the deficit below 3% of GDP and this leads to:
    - higher consumption prices (prices are proportional to $1+\tau_C$)
    - lower **nominal** demand[3] because the disposable income is proportional to $1-\tau_L$
- (Interaction) Since the carbon tax increases the energy price p_E, the cost of the FIT, given by $(p_E^r - p_E)E_R$, is reduced for every unit of renewable energy sold with respect to the scenario in which only the FIT policy is implemented. Then, the government deficit is lower in the policy mix scenario than that in the FIT scenario, and the average tax rate is lower. Therefore, consumption losses due to the previous cause are mitigated by the interaction between the two policies.

With a non rigorous reasoning, the consumption loss of the policy mix can be thought as 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

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[3] if $\tau_L \geq 0.3$ 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

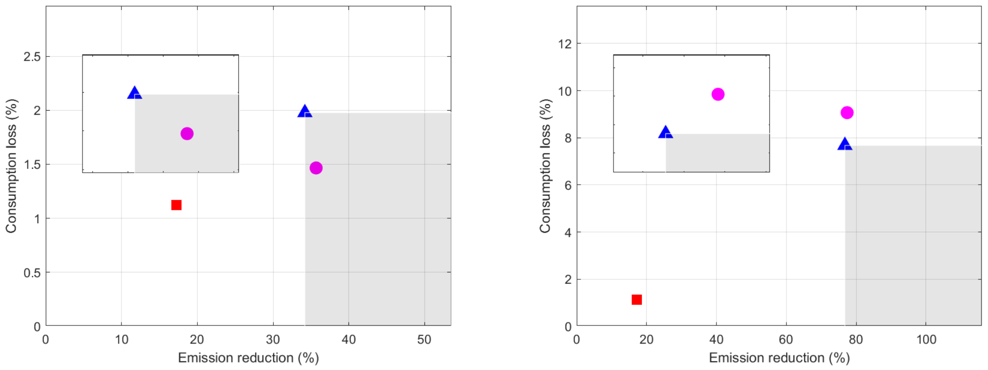
lower than the sum of the consumption losses of the other two policies. With climate damages the unemployment level is higher for all the policies. Therefore the shift of the deficit to GDP ratio under the 3% threshold is countered by an increase of the deficit due to an increase of the unemployment benefits that the government has to pay. This results in a lower contribution of the interaction term in reducing the constumption loss of the PM.

4.4 Extended multi-criteria evaluation

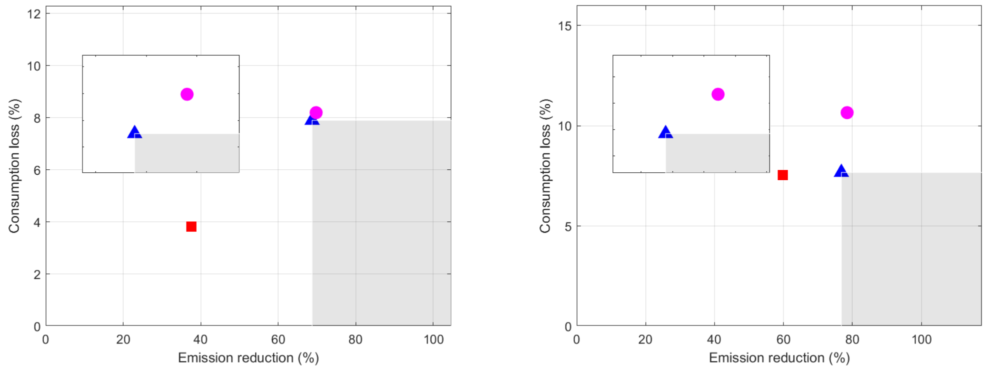
The results of the analysis conducted on scenarios without climate damages are depicted in Fig. 4.15, that is referred to the comparison of only the single-instrument scenarios and in Fig. 4.16, that includes the PMs. Figures 4.17 and 4.18 are the corresponding figures referred to the scenarios with climate damages. Each panel shows the partitions of a bidimensional projection of the utility space generated by the set of policies considered. The projection is obtained fixing α_ε and α_c, so that each panel shows a different projection corresponding to different values of the α's: α_ε increases from the top to the bottom panels, while α_c increases toward the right. The values considered are intended to model from extreme (0.3) to moderate (0.7) risk-aversion policy makers. Note that while $\pi \in [0,1]$ because of utility definition, ε' is not limited in principle, but it has been limited to $[0,1]$ because the reference policy maker has been assumed to prefer reducing emissions to the maximization of consumption. The dashed line represents the points for which the $k_{\varepsilon c} = 0$, that is when $\varepsilon' = \left(\frac{1-\pi}{\pi}\right)^{\frac{1}{\alpha_\varepsilon}}$. Since it is important to avoid both environmental and economic catastrophes, $k_{\varepsilon c}$ has to be greater than 0; the latter condition is satisfied in the region to the left of the dashed line. To further define the region of interest, it is imposed $\pi > 0.2$, that guarantees that the utility of the maximum emission reduction and minimum consumption loss (highest cost) is the 20% of the utility of the best consequence. As regards ε', given the emissions of the BAU and the carbon budget mentioned in the introduction, if $\varepsilon' > 0.75$ the BAU is preferred to reaching the 1.5°C target at the worst consumption loss (about -15%). Therefore, the region of interest is restricted to $\varepsilon' <= 0.75$. It is assumed risk-aversion of emission reduction greater than that of consumption loss, i.e. $\alpha_\varepsilon < \alpha_c$. To restrict α_ε note that the monodimensional utility of the reduction satisfying the 1.5°C target is given by 0.92, 0.87 and 0.82 for α_ε equal respectively to 0.3, 0.5 and 0.7. The higher this utility the lower is the value attributed to reduce more. Therefore, it is better to chose α_ε between 0.5 and 0.7, because, as mentioned in the introduction, emitting all but not more than the 580 $GtCO_2$ carbon budget gives a 50% of staying below the 1.5°C warming. Reducing total emissions increases that probability and

	BAU	Carbon tax							Feed-in tariff						
		15	25	30	45	60	75	90	50	60	65	70	75	90	120
p_k	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	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	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	NaN	0.001	0.000	0.000	0.010	0.015	0.001	0.221	NaN	NaN	NaN	NaN	NaN	NaN	NaN
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
$\frac{\Delta C}{C}$	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 (C)	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	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	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	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 2 GDP	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	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
Public debt 2 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
Public deficit 2 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
$\mathscr{E}$	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	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 4.4 The table shows the p-Values of the two-sided Wilcoxon rank-sum test, that 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 damages. When the p-Value is lower than the 5% (1%) the null hypothesis is rejected with a 5% (1%) significance level.



(a) PM(15,60) (b) PM(15,120)



(c) PM(30,90) (d) PM(60,120)

Figure 4.14 The figure shows the policy mix performance compared to that of its parent policies in the scenarios with climate damages. 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.

	Policy mix						
	(15,60)	(15, 75)	(15, 120)	(30,75)	(30,90)	(60,90)	(60,120)
p_k	0.096	0.033	0.216	0.006	0.060	0.039	0.040
K	0.000	0.015	0.015	0.000	0.000	0.000	0.000
s_g	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
CGPEmployment	0.357	0.064	0.001	0.723	0.000	0.002	0.000
$\frac{\Delta C}{C}$	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	0.759	0.817	0.017	0.120	0.087	0.208	0.391
i_E	0.754	0.687	0.637	0.027	0.442	0.652	0.775
p_E	0.201	0.038	0.224	0.007	0.084	0.010	0.028
FIT cost 2 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
Public debt 2 GDP	0.002	0.000	0.226	0.000	0.013	0.004	0.306
Public deficit 2 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
$\mathscr{E}$	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	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

Table 4.5 The table shows the p-Values of the two-sided Wilcoxon rank-sum test, that 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 damages. When the p-Value is lower than the 5% (1%) the null hypothesis is rejected with a 5% (1%) significance level.

then it is important to guarantee appreciable utility gains for further emission reduction. The restrictions on the α's lead to focusing on the (e), (f) and (i) panels.

Figure 4.15 reveals that all the policy makers considered prefer the FIT to the CT when the PMs are escluded from the set of the alternatives. Although there are small regions where FIT 90 is preferred, only two policies compete for dominance: FIT 75 and FIT 120. The former is characterized by lower emission reduction (Fig. 4.1(c)) but lower cost (4.12(b)). Focusing on a panel of Fig. 4.15, for example panel (e), it can be seen that FIT 75 dominates in the region with lower π and higher ε', that is the region where the utility of achieving only one objectives is far lower than the utility of achieving both, and where the utility of reducing emissions is similar to that of reducing losses. Indeed, regions with π near 0 corresponds to utility functions that assign a value to the consequence (ε_M, c_m) very similar the worst consequence (ε_m, c_m), and when $\varepsilon' \simeq 1$ the monodimensional utilities $v(\varepsilon)$ and $w(c)$ have similar weights in $u(\varepsilon, c)$. Since the time span of simulations is only 30 years, it is important to reduce emissions, even if this is achieved at a high economic cost. This justify further the definition of the region of interest given above.

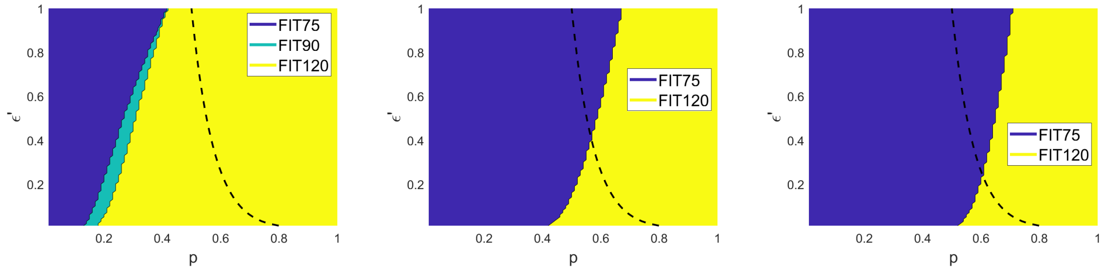
Decreasing α_ε, i.e. increasing risk-aversion of emission reduction, expands the FIT 75 dominance region towards the right, as confirmed looking the panels from the bottom to the top. This happens because increasing risk aversion towards reducing emissions increases the gap between the utility of reducing emissions even slightly and the utility of not reducing them at all, while the difference between the utility of high reductions and the utility of the maximum reduction decreases. Therefore, for fixed π, ε' the expected utility difference between the FIT 120 and FIT 75 reduces as α_ε is decreased from the highest to the lowest value, and eventually it reverses.

Decreasing α_c, i.e. increasing risk-aversion toward consumption losses, contracts the FIT 75 dominance region towards the left, as confirmed looking the panels from the right to the left. This is because the risk aversion increase reduces the utility difference of the two alternatives due to the consumption losses, and eventually differences in emission reduction prevail over consumption differences.

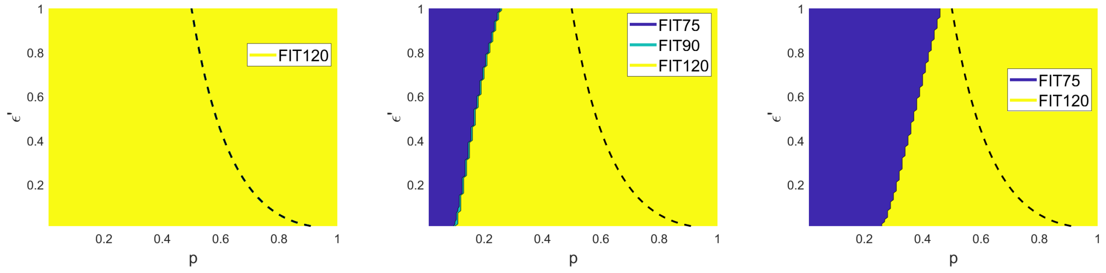
Restricting the choice on the region of interest lead to conclude that FIT 120 dominates in a region greater than that of FIT 75. The latter dominates only for the lowest values of π and the highest for ε'.

Figure 4.16 shows that there are not regions where a single policy dominates, the dominance is contended only by different PMs. PM(60, 120) dominates only in the top right regions, where $k_{\varepsilon c} < 0$ and therefore it is out of the region of interest. PM(60, 90) appears in the set of dominant policies, however, regions of dominance are negligible respect to the others and they are not detectable in the figure. The main competition for dominance is between PM(15,75), PM(15, 120) and PM(30, 75). The latter dominates only when there is high risk aversion towards emissions and a moderate risk aversion toward consumption losses (Fig. 4.16(c)). Although it is desirable to have policy makers more risk averse toward emissions than toward consumption, the difference between the two α's that fix the utility space projection of panel (c) of Fig. 4.16 is too high. Therefore, the best policy is the PM(15,75) or the PM(15, 120). As for the FIT, The former is characterized by lower emission reduction (Fig. 4.1(c)) but lower cost (4.12(b)). It dominates in the top left regions, where reducing emissions is equivalent to increasing consumption and where pursuing only one of the objectives is vary similar to doing nothing.

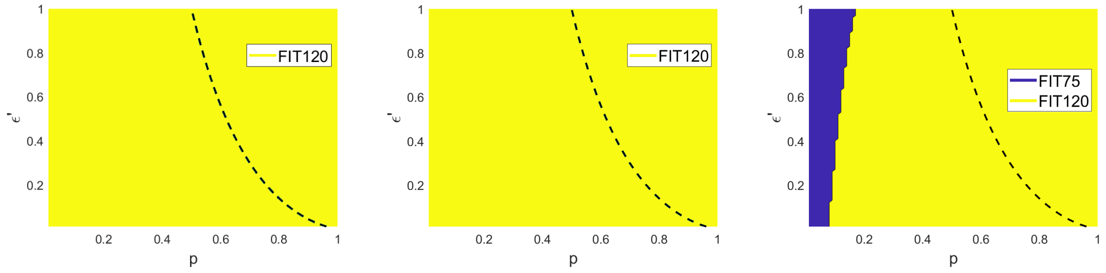
Decreasing α_ε moves the partition lines to the right expanding PM(15, 75) dominance regions, while decreasing α_c, does the opposite. Restricting the attention to the region of



(a) $\alpha_\varepsilon = 0.3$, $\alpha_c = 0.3$ (b) $\alpha_\varepsilon = 0.3$, $\alpha_c = 0.5$ (c) $\alpha_\varepsilon = 0.3$, $\alpha_c = 0.7$



(d) $\alpha_\varepsilon = 0.5$, $\alpha_c = 0.3$ (e) $\alpha_\varepsilon = 0.5$, $\alpha_c = 0.5$ (f) $\alpha_\varepsilon = 0.5$, $\alpha_c = 0.7$



(g) $\alpha_\varepsilon = 0.7$, $\alpha_c = 0.3$ (h) $\alpha_\varepsilon = 0.7$, $\alpha_c = 0.5$ (i) $\alpha_\varepsilon = 0.7$, $\alpha_c = 0.7$

Figure 4.15 The figure shows the results of the extended MCA used to evaluate the performances of only the single policies, without climate damages. Each panel represents a bidimensional projection of the space of utility functions obtained fixing α_ε and α_c. Each bidimensional projection is partitioned in different regions such that the utility functions belonging to the same region choose the same policy as that with the highest expected utility. The dashed line represents the points for which the $k_{\varepsilon c} = 0$, that is, it represents all the utility functions for which the lottery that gives (ε_M, c_M) and (ε_m, c_m) with 50% probability is equivalent to the lottery that gives (ε_M, c_m) and (ε_m, c_M) with 50% probability.

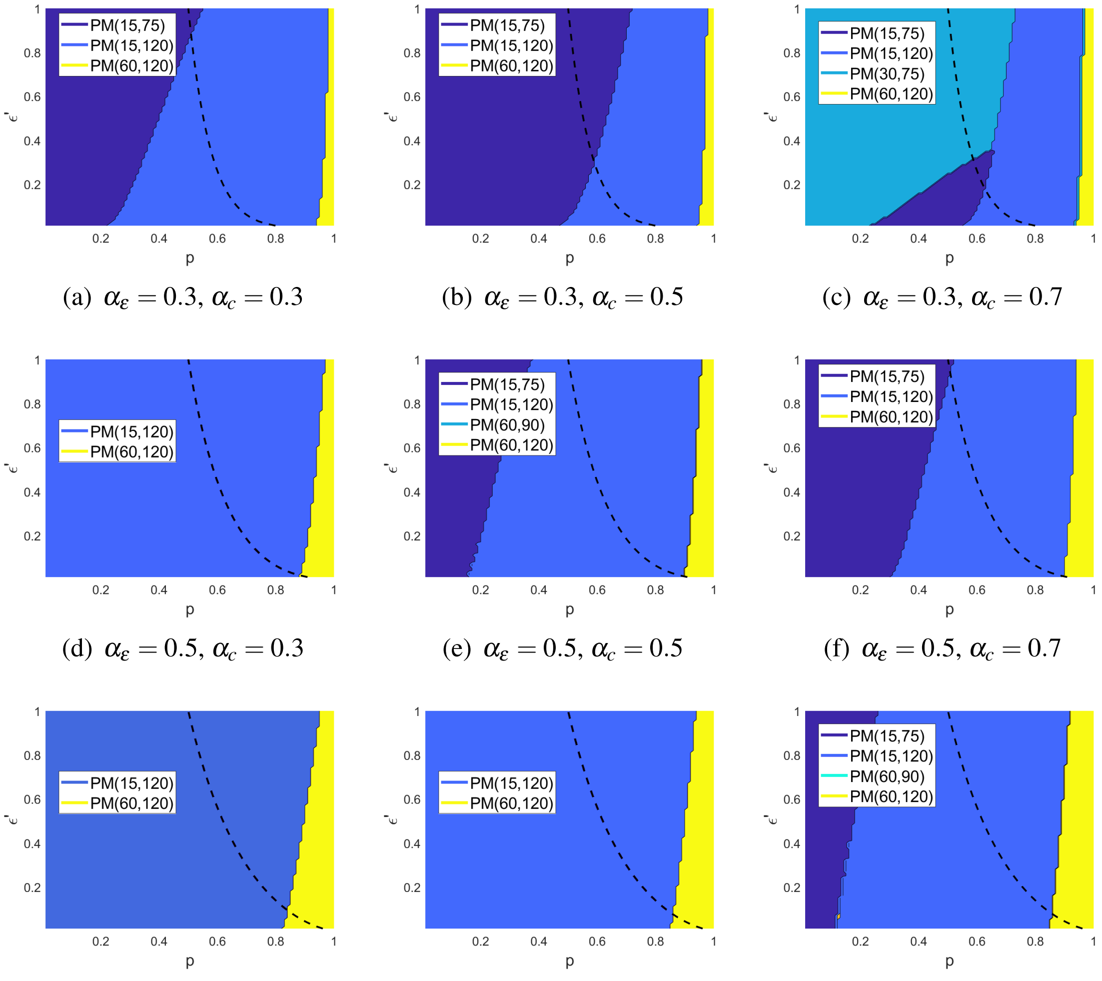
interest, similarly for the FITs, it is found that PM(15, 120) dominance region is greater than that of PM(15,75).

Under climate damages, the results of the analysis are quite different, in particular those concerning the policy mix. As regards the single policy comparison, Fig. 4.17 shows that the FIT is always preferred to the CT, as previously obtained. The dominance region of the FIT 120 has grown at the expense of that of FIT 75 with respect to the no-damage case. This result confirms the hypothesis that stricter policies bring greater benefits because of a higher climate impacts reduction. In the region of interest mentioned above there is no more competition for dominance: FIT 120 is the best single policy.

Fig. 4.18 shows that, in contrast with the no-damage case, there are regions in which a single policy, FIT 120, dominates. Comparing Fig. 4.18 with 4.16 we can see that, while PM(15, 75) and PM(60,120) are still among the non dominated policies, PM(15, 120) has been replaced by FIT 120, meaning that this mix is outperformed by its FIT component. The dominance region of FIT 120 is greater than that of PM(15, 120) in the no-damage case, that of PM(15, 75) is reduced while that of PM(60, 120) is roughly unchanged. In conclusion, FIT 120 is considered the best policy for almost all the values of parameters defining the region of interest mentioned above, PM(60, 120) dominates only in small regions where reducing emissions is far more important than minimizing consumption losses.

4.5 Concluding remarks

Most environmental economics works have focused on the analysis of single policies or on the comparison between two or more instruments (Lehmann (2012)). However, several studies (e.g. Görlach (2014); Jaffe et al. (2004); Lehmann (2012)), showed that a mix of instrument is more appropriate for climate mitigation because of the multiple objectives of climate policies and the multiple market, behavioral and government failures of the real economy. According to Krogstrup and Oman (2019), the literature does not provide the optimal policy mix. Indeed, one of the two main questions (Bouma et al. (2019)) of the policy mix research is the definition of optimal mix. The second question is to understand the role of each instrument in the mix in order to discern the combinations that lead to superior performance from those outclassed by one of the single components. This work contributes to this field of research examining a policy mix (PM) of a carbon tax (CT) and a feed-in tariff (FIT) through the EURACE agent-based model. To disentangle the effects of the policy mix components, we first studied the economic and environmental performances

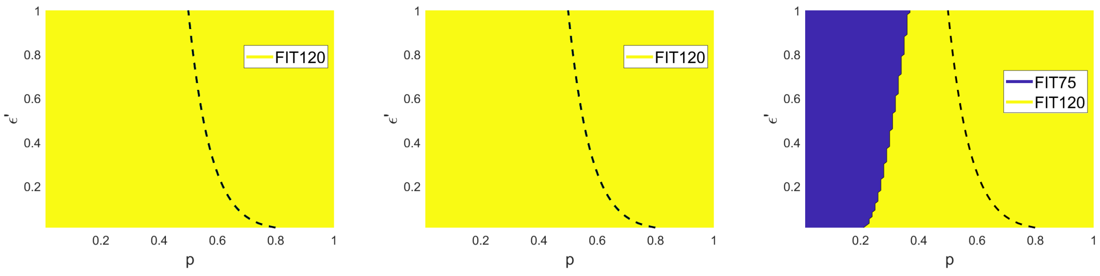


(a) $\alpha_\varepsilon = 0.3$, $\alpha_c = 0.3$
(b) $\alpha_\varepsilon = 0.3$, $\alpha_c = 0.5$
(c) $\alpha_\varepsilon = 0.3$, $\alpha_c = 0.7$

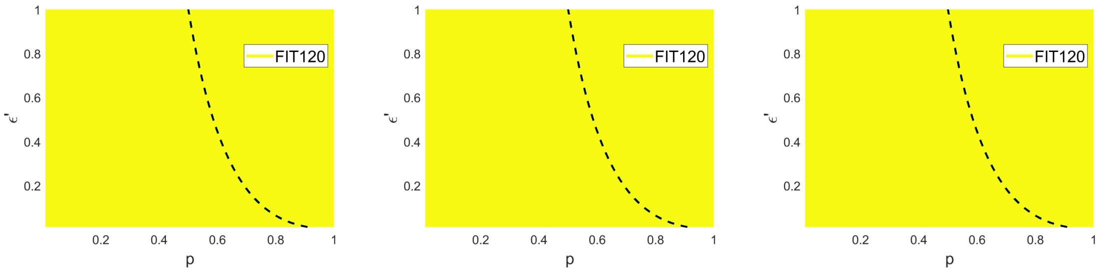
(d) $\alpha_\varepsilon = 0.5$, $\alpha_c = 0.3$
(e) $\alpha_\varepsilon = 0.5$, $\alpha_c = 0.5$
(f) $\alpha_\varepsilon = 0.5$, $\alpha_c = 0.7$

(g) $\alpha_\varepsilon = 0.7$, $\alpha_c = 0.3$
(h) $\alpha_\varepsilon = 0.7$, $\alpha_c = 0.5$
(i) $\alpha_\varepsilon = 0.7$, $\alpha_c = 0.7$

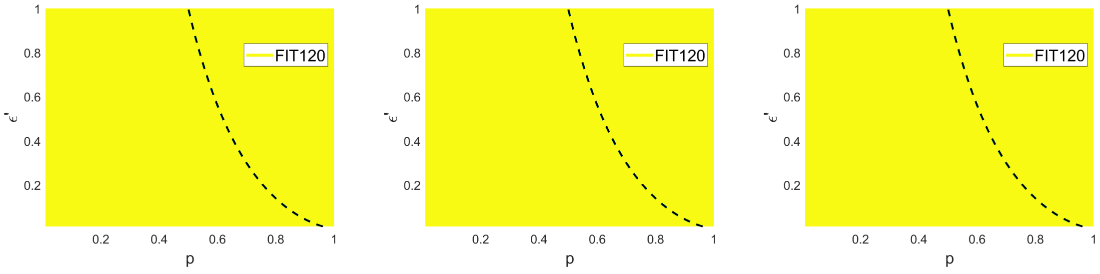
Figure 4.16 The figure shows the results of the extended MCA used to evaluate the performances of the single policies and to of the policy mix, without climate damages. Each panel represents a bidimensional projection of the space of utility functions obtained fixing α_ε and α_c. Each bidimensional projection is partitioned in different regions such that the utility functions belonging to the same region choose the same policy as that with the highest expected utility. The dashed line represents the points for which the $k_{\varepsilon c} = 0$, that is, it represents all the utility functions for which the lottery that gives (ε_M, c_M) and (ε_m, c_m) with 50% probability is equivalent to the lottery that gives (ε_M, c_m) and (ε_m, c_M) with 50% probability.



(a) $\alpha_\varepsilon = 0.3$, $\alpha_c = 0.3$ (b) $\alpha_\varepsilon = 0.3$, $\alpha_c = 0.5$ (c) $\alpha_\varepsilon = 0.3$, $\alpha_c = 0.7$

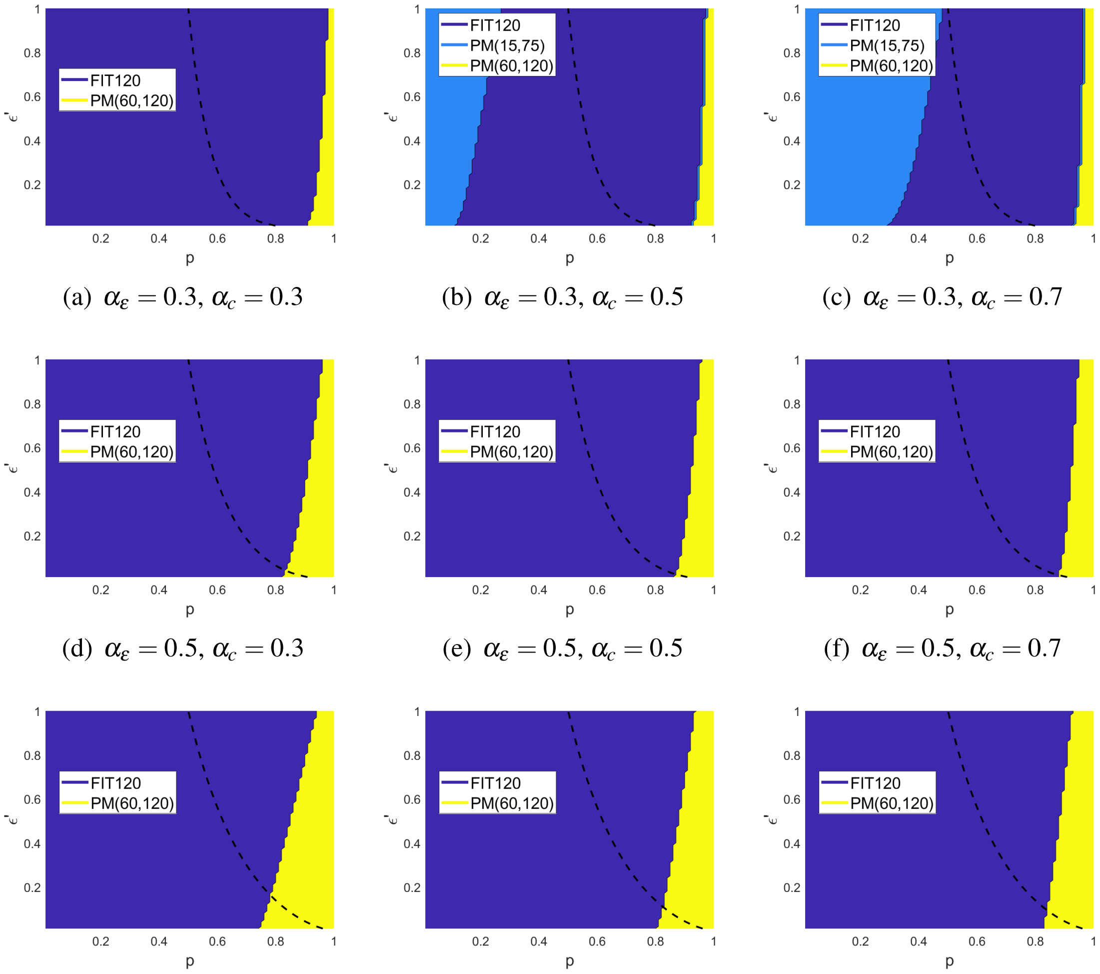


(d) $\alpha_\varepsilon = 0.5$, $\alpha_c = 0.3$ (e) $\alpha_\varepsilon = 0.5$, $\alpha_c = 0.5$ (f) $\alpha_\varepsilon = 0.5$, $\alpha_c = 0.7$



(g) $\alpha_\varepsilon = 0.7$, $\alpha_c = 0.3$ (h) $\alpha_\varepsilon = 0.7$, $\alpha_c = 0.5$ (i) $\alpha_\varepsilon = 0.7$, $\alpha_c = 0.7$

Figure 4.17 The figure shows the results of the extended MCA used to evaluate the performances of only the single policies, with climate damages. Each panel represents a bidimensional projection of the space of utility functions obtained fixing α_ε and α_c. Each bidimensional projection is partitioned in different regions such that the utility functions belonging to the same region choose the same policy as that with the highest expected utility. The dashed line represents the points for which the $k_{\varepsilon c} = 0$, that is, it represents all the utility functions for which the lottery that gives (ε_M, c_M) and (ε_m, c_m) with 50% probability is equivalent to the lottery that gives (ε_M, c_m) and (ε_m, c_M) with 50% probability.



(a) $\alpha_\varepsilon = 0.3$, $\alpha_c = 0.3$ (b) $\alpha_\varepsilon = 0.3$, $\alpha_c = 0.5$ (c) $\alpha_\varepsilon = 0.3$, $\alpha_c = 0.7$

(d) $\alpha_\varepsilon = 0.5$, $\alpha_c = 0.3$ (e) $\alpha_\varepsilon = 0.5$, $\alpha_c = 0.5$ (f) $\alpha_\varepsilon = 0.5$, $\alpha_c = 0.7$

(g) $\alpha_\varepsilon = 0.7$, $\alpha_c = 0.3$ (h) $\alpha_\varepsilon = 0.7$, $\alpha_c = 0.5$ (i) $\alpha_\varepsilon = 0.7$, $\alpha_c = 0.7$

Figure 4.18 The figure shows the results of the extended MCA used to evaluate the performances of the single policies and to of the policy mix, with climate damages. Each panel represents a bidimensional projection of the space of utility functions obtained fixing α_ε and α_c. Each bidimensional projection is partitioned in different regions such that the utility functions belonging to the same region choose the same policy as that with the highest expected utility. The dashed line represents the points for which the $k_{\varepsilon c} = 0$, that is, it represents all the utility functions for which the lottery that gives (ε_M, c_M) and (ε_m, c_m) with 50% probability is equivalent to the lottery that gives (ε_M, c_m) and (ε_m, c_M) with 50% probability.

of the single instruments with respect to a business as usual (BAU) scenario, then we studied their interactions in the policy mix.

The EURACE model comprises an energy sector constituted by two different power producers (Ponta et al. (2018)), one that uses renewable energy sources while the other uses fossil fuels to produce energy, and it allows energy intensity improvements via exogenous innovation and endogenous diffusion of new less energy intensive capital (Raberto et al. (2019)). We have enriched the EURACE model with a climate module in order to account for the climate-economy feed-back: the climate receives GHG emissions from the economy as an input for the evolution of the atmospheric temperature and in turn damages the economy destroying a fraction of the productive capital dependent on the temperature anomaly.

Computational results allow to identify the multiple channels that lead to the desired emissions reduction and to the costs (consumption loss with respect 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 determines also an increase of the consumption good price that lead to a reduction of real consumption, of the employment rate in the private sector and of the households purchasing power. For the highest values of CT the reduction of consumption affects the government budget since the tax proceedings increase due to CT revenues is more than offset by the reduction of general tax revenues due to lower GDP. Furthermore, to reduce 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, and therefore it increases the share of the renewable energy (Fig. 4.2(b)) reducing the emissions generated by the unit of energy produced by the economy. The economic cost (consumption loss with respect 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. labor and capital.

When both policies are implemented, emissions are reduced both through the renewable share increase, through the reduction of energy demand via energy intensity improvements and through consumption reduction. As for the carbon tax, the energy intensity improvements lead to negligible emission reduction. The renewable energy share increase is determined by the feed-in tariff component because the guaranteed price p_E^r for the 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 energy price increase due to the carbon tax component. The consumption loss arise from the consumption price increase due to both the higher energy price (carbon tax component) and by the higher tax rate due to the feed-in tariff policy cost. However, comparing policy mixes with the same feed-in tariff in Fig. 4.7(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. 4.6(a)).

We chose to compare policies performance looking at the emission reduction and the consumption loss with respect to the BAU scenario implied by each policy. We argued that to determine if the mix is better than its components and to choose the best policy it is necessary to explicit a preference structure. Multi-criteria analysis (Keeney et al. (1993)) recommends to represent the preference structure through an utility function and it provides restrictions on the utility to determine the attitudes of the decision maker. Following Keeney et al. (1993), we imposed a set of constraints (e.g. risk aversion) that led to an utility function dependent only on four parameters: the first two regulate the risk aversion toward emission reduction and consumption loss, the third regulates the utility of achieving only one of the objectives relative to the utility of achieving both, finally the fourth regulates the utility of avoiding consumption loss relative to the utility of achieving higher emission reduction. We proposed an extension aimed at reducing the arbitrariness of the method: instead of choosing a single utility function by setting the parameters, these are varied to find the sets of utility functions that choose the same scenario as the best alternative.

We found that both with and without climate damages, the feed-in tariff is preferred to the carbon tax when policy mix is excluded from the analysis. In this case, two FITs compete for dominance; the FIT with the highest value (FIT 120) and an intermediate FIT (FIT 75) that lead to higher emissions but lower consumption loss. For fixed risk aversion degrees, the latter is preferred when it is more important achieving both the objectives than achieving only one and when the utility of avoiding consumption loss is similar to the utility of reducing emissions. Increasing the risk-aversion of emission reduction, or decreasing the risk aversion of consumption loss expands the dominance region of the intermediate FIT. Under climate damages the dominance region of the highest value FIT expands.

In the absence of climate damages, when the policy mix is included in the analysis, it is found that it dominates its components. Basically, only three PMs compete for dominance: the first (PM(15, 120)) composed by the highest value FIT and by the lowest CT, the second

(PM(60, 120)) by the highest FIT an intermediate CT and the third (PM(15,75)) by an intermediate FIT and by the lowest CT. PM(60, 120) is the policy that achieve the highest emission reduction and the highest consumption loss; PM(15, 120) is very similar but reaches lower emission reduction and lower consumption loss while in the PM(15,75) scenario both the consumption loss and the emission reduction are sensibly lower than those generated in the other two scenarios. PM(60, 120) dominates only when it is important achieving only one objective and when the utility of reducing emissions is higher than that of avoiding consumption loss. PM(15,75) dominates when it is important achieving both the objectives and when the utility of reducing emissions is similar to the utility of avoiding consumption loss. Increasing the risk-aversion of emission reduction, or decreasing the risk aversion of consumption loss expands the dominance region of the PM(15, 75). Under climate damages the PMs performance worsen and it does not outperform its components. In this case the dominance is contended by the highest FIT and by the PM(60, 120), however the latter dominates in a small region of the utility space.

Future research will investigate with the same method the policy mixes composed by fiscal instruments such as those studied in this work and by financial ones, e.g. green Basel-type capital requirements, the green supporting factor or the brown penality.

Conclusions

A synthesis of the research work and main findings

The main purpose of my research is to provide a scientific contribution to the research on the transformation pathways that achieve climate mitigation objectives. My research activity can be ideally divided in three parts: the enrichment of the Eurace model, the development of an extended multi-criteria analysis to evaluate and compare policies consequences and finally experiments with the Eurace model.

I have enriched the agent-based macroeconomic Eurace model with a new agent in order to include the climate-economy nexus: the climate module receives GHGs emissions produced by the energy sector, it updates temperature and carbon stocks accordingly and it responds to the economy causing the destruction of a fraction of the capital stock of firms depending on the atmospheric temperature anomaly. Moreover, I introduced another type of capital good producer, indicated as the green KGP, making the sector heterogeneous. The green KGP can update the energy intensity of the new produced machines, allowing firms that invest in green capital to decrease their energy needs per unit of output. In order to conduct experiments I chose an initialization procedure based on imposing physical constraints on the economy, in this way establishing a relation between model and real world quantities.

In order to evaluate policies consequences and to compare different policies within my experiments, I used multi-criteria analysis (MCA), that allows to deal with multiple objectives and with uncertainty of the policies consequences. I developed an extended MCA that overcomes the arbitrariness of choosing a single utility function: instead of determining a single utility function to select the best performing policy, the methods finds all the utility functions that choose the same policy as the best one.

I have performed different experiments with the Eurace model through which I studied three different climate policies, namely a carbon tax (CT), a feed-in tariff (FIT) policy, and the mix of the two policies (PM). The use of the Eurace model as a laboratory to test policies allows to understand and observe for each policy the channel through which emission reductions and consumption loss with respect to the business as usual scenario emerge. The first main result of the experiments is that there are values of the emission price (that determine the CT) and of the renewable energy guaranteed price (determining the FIT) above which all the three policies are effective in decreasing GHGs emissions and avoiding the remaining carbon budget complete depletion. However, the higher the emission reduction the higher the consumption loss with respect to the BAU scenario.

Experiments have shown that the carbon tax is not the best performing single policy. For similar average emission reduction level, the carbon tax leads to higher consumption loss than those caused by the FIT. Moreover, the extended MCA showed that, independently from the preference structure (utility function), the best performing policy is one of the FITs when the policy mix is excluded from the analysis.

Finally, in absence of climate damages the PM performs better than its components: a policy mix leads to an average emission reduction higher than or equal to the highest emission reduction achieved by its components and it leads to lower consumption loss than that associated to the component reaching the highest emission reduction. The extended MCA confirmed the superiority of the policy mix showing that it is preferred independently from the preference structure. However, the interaction between the two single policies is no longer beneficial under climate damages: the PM leads to an average consumption loss equal or greater than that associated to the component reaching the highest emission reduction. According to the extended MCA, the FIT leading to the highest emission reduction is considered the best performing policy except where avoiding consumption losses is as important as reducing emissions.

Limitations

It is worth mentioning some enrichment of the framework developed that can improve the analysis presented above. First, including fossil fuels reserves and modelling the processes that lead to their evolution is key to improve the Eurace model capability in dealing with transition risks deriving from the revaluation of carbon-intensive assets.

Given the uncertainty about the impacts of climate change, the research work can be enriched considering alternative damage functions of the climate module, for example damage functions that cause more severe damages for each value of the temperature anomaly, or functions with higher sensitivity to temperature increase.

Future research

There are theoretical arguments for preferring policy mixes to single instruments, and climate mitigation policies adopted world wide are de facto policy mixes. Therefore, I will focus my future research on investigating policy mixes of fiscal and financial mitigation policies, for example a mix of a carbon tax and a green supporting factor policy, with the aim of understanding the interactions between the two types of policy and to give insights on the best performing options.

References

Albert, R., Jeong, H., and Barabási, A.-L. (1999). Diameter of the world-wide web. *nature*, 401(6749):130–131.

Albert, R., Jeong, H., and Barabási, A.-L. (2000). Error and attack tolerance of complex networks. *nature*, 406(6794):378–382.

Allen, T., Dees, S., Caicedo Graciano, C. M., Chouard, V., Clerc, L., de Gaye, A., Devulder, A., Diot, S., Lisack, N., Pegoraro, F., et al. (2020). Climate-related scenarios for financial stability assessment: An application to france.

Arrow, K. J. and Debreu, G. (1954). Existence of an equilibrium for a competitive economy. *Econometrica: Journal of the Econometric Society*, pages 265–290.

Arthur, W. B. (2021). Foundations of complexity economics. *Nature Reviews Physics*, 3(2):136–145.

Arthur, W. B., Holland, J. H., LeBaron, B., Palmer, R., and Tayler, P. (2018). Asset pricing under endogenous expectations in an artificial stock market. In *The economy as an evolving complex system II*, pages 15–44. CRC Press.

Balint, T., Lamperti, F., Mandel, A., Napoletano, M., Roventini, A., and Sapio, A. (2017). Complexity and the economics of climate change: a survey and a look forward. *Ecological Economics*, 138:252–265.

Barrat, A., Barthelemy, M., and Vespignani, A. (2008). *Dynamical processes on complex networks*. Cambridge university press.

Bator, F. M. (1958). The anatomy of market failure. *The quarterly journal of economics*, 72(3):351–379.

Battiston, S., Dafermos, Y., and Monasterolo, I. (2021). Climate risks and financial stability. *Journal of Financial Stability*, 54 (in press).

Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., and Visentin, G. (2017). A climate stress-test of the financial system. *Nature Climate Change*, 7:283–288.

Bennear, L. S. and Stavins, R. N. (2007). Second-best theory and the use of multiple policy instruments. *Environmental and Resource Economics*, 37(1):111–129.

Boardman, A. E., Greenberg, D. H., Vining, A. R., and Weimer, D. L. (2017). *Cost-benefit analysis: concepts and practice*. Cambridge University Press.

Boss, M., Elsinger, H., Summer, M., and Thurner 4, S. (2004). Network topology of the interbank market. *Quantitative finance*, 4(6):677–684.

Bouma, J., Verbraak, M., Dietz, F., and Brouwer, R. (2019). Policy mix: mess or merit? *Journal of Environmental Economics and Policy*, 8(1):32–47.

Bretschger, L. and Pattakou, A. (2019). As bad as it gets: how climate damage functions affect growth and the social cost of carbon. *Environmental and resource economics*, 72(1):5–26.

Caiani, A., Catullo, E., and Gallegati, M. (2018). The effects of fiscal targets in a monetary union: a multi-country agent-based stock flow consistent model. *Industrial and Corporate Change*, 27(6):1123–1154.

Caiani, A., Godin, A., Caverzasi, E., Gallegati, M., Kinsella, S., and Stiglitz, J. E. (2016). Agent based-stock flow consistent macroeconomics: Towards a benchmark model. *Journal of Economic Dynamics and Control*, 69:375–408.

Carbon Tracker Initiative (2011). Unburnable carbon: Are the world's financial markets carrying a carbon bubble. Technical report, Carbon Tracker Initiative.

Carney, M. (2015). Breaking the tragedy of the horizon–climate change and financial stability. *Speech given at Lloyd's of London*, 29:220–230.

Castro, J., Drews, S., Exadaktylos, F., Foramitti, J., Klein, F., Konc, T., Savin, I., and van den Bergh, J. (2020). A review of agent-based modeling of climate-energy policy. *Wiley Interdisciplinary Reviews: Climate Change*, 11(4):e647.

Cincotti, S., Raberto, M., and Teglio, A. (2010). Credit money and macroeconomic instability in the agent-based model and simulator eurace. *Economics: The Open-Access, Open-Assessment E-Journal*, 4(2010-26):1–32.

Cincotti, S., Raberto, M., and Teglio, A. (2022). Why do we need agent-based macroeconomics? *Review of Evolutionary Political Economy*, 3(1):5–29.

Crawford, P., Young, T., et al. (2009). The credit crunch: The roller coaster ride continues. *Journal of Business & Economics Research (JBER)*, 7(1).

Crotty, J. (2009). Structural causes of the global financial crisis: a critical assessment of the 'new financial architecture'. *Cambridge journal of economics*, 33(4):563–580.

Debreu, G. (1974). Excess demand functions. *Computational Economics*, 1(1):3–34.

Dosi, G., Fagiolo, G., and Roventini, A. (2010). Schumpeter meeting keynes: A policy-friendly model of endogenous growth and business cycles. *Journal of Economic Dynamics and Control*, 34(9):1748–1767.

Drews, S., Exadaktylos, F., and van den Bergh, J. C. (2020). Assessing synergy of incentives and nudges in the energy policy mix. *Energy Policy*, 144:111605.

Dunz, N., Essenfelder, A. H., Mazzocchetti, A., Monasterolo, I., and Raberto, M. (2021a). Compounding covid-19 and climate risks: the interplay of banks' lending and government's policy in the shock recovery. *Journal of Banking & Finance*, page 106306.

Dunz, N., Naqvi, A., and Monasterolo, I. (2021b). Climate sentiments, transition risk, and financial stability in a stock-flow consistent model. *Journal of Financial Stability*, 54:100872.

Ekholm, T. (2014). Hedging the climate sensitivity risks of a temperature target. *Climatic change*, 127(2):153–167.

Faloutsos, M., Faloutsos, P., and Faloutsos, C. (1999). On power-law relationships of the internet topology. *ACM SIGCOMM computer communication review*, 29(4):251–262.

Farmer, J. D., Hepburn, C., Mealy, P., and Teytelboym, A. (2015). A third wave in the economics of climate change. *Environmental and Resource Economics*, 62(2):329–357.

Ferraro, P. J. and Miranda, J. J. (2013). Heterogeneous treatment effects and mechanisms in information-based environmental policies: Evidence from a large-scale field experiment. *Resource and Energy Economics*, 35(3):356–379.

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., et al. (2017). The marker quantification of the shared socioeconomic pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, 42:251–267.

Gerst, M. D., Wang, P., Roventini, A., Fagiolo, G., Dosi, G., Howarth, R. B., and Borsuk, M. E. (2013). Agent-based modeling of climate policy: An introduction to the engage multi-level model framework. *Environmental modelling & software*, 44:62–75.

Görlach, B. (2014). Emissions trading in the climate policy mix—understanding and managing interactions with other policy instruments. *Energy & Environment*, 25(3-4):733–749.

Goulder, L. H. and Schneider, S. H. (1999). Induced technological change and the attractiveness of co2 abatement policies. *Resource and Energy Economics*, 21(3-4):211–253.

Gourdel, R., Monasterolo, I., Dunz, N., Mazzocchetti, A., and Parisi, L. (2022). The double materiality of climate physical and transition risks in the euro area.

Greening, L. A. and Bernow, S. (2004). Design of coordinated energy and environmental policies: use of multi-criteria decision-making. *Energy policy*, 32(6):721–735.

Gunningham, N. and Sinclair, D. (1999). Regulatory pluralism: Designing policy mixes for environmental protection. *Law & Policy*, 21:49–76.

Haas, A. and Jaeger, C. (2005). Agents, bayes, and climatic risks-a modular modelling approach. *Advances in Geosciences*, 4:3–7.

Hellwig, M. F. (2009). Systemic risk in the financial sector: An analysis of the subprime-mortgage financial crisis. *De economist*, 157:129–207.

High-Level Commission on Carbon Prices (2017). Report of the high-level commission on carbon prices. Technical report, World Bank.

Hope, C. (2006). The marginal impact of co2 from page2002: an integrated assessment model incorporating the ipcc's five reasons for concern. *Integrated assessment*, 6(1).

Huberman, B. A. and Adamic, L. A. (1999). Growth dynamics of the world-wide web. *Nature*, 401(6749):131–131.

IEA (2020a). Key world energy statistics. *IEA Statistics reports*.

IEA (2020b). The oil and gas industry in energy transitions. *International Energy Agency*.

IEA (2021). Net zero by 2050: A roadmap for the global energy sector.

Interagency Working Group on Social Cost of Greenhouse Gases (2016). Technical support document: Social cost of carbon, methane, and nitrous oxide interim estimates under executive order 13990. Technical report, United States Government.

IPCC (2014). *Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the IPCC Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

IPCC (2018). Global warming of 1.5°c. an ipcc special report on the impacts of global warming of 1.5°c above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

IPCC (2021). *Climate Change 2021: The Physical Science Base, Contribution of Working Group I to the IPCC Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Jaffe, A. B., Newell, R. G., and Stavins, R. N. (2004). A tale of two market failures. *Ecological Economics*, 54:164–174.

Kahneman, D. and Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica*, 47(2):263–291.

Keeney, R. L., Raiffa, H., and Meyer, R. F. (1993). *Decisions with multiple objectives: preferences and value trade-offs*. Cambridge university press.

Kirman, A. (2016). Complexity and economic policy: A paradigm shift or a change in perspective? a review essay on david colander and roland kupers's complexity and the art of public policy. *Journal of Economic Literature*, 54(2):534–72.

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., Hilaire, J., Klein, D., et al. (2017). Fossil-fueled development (ssp5): an energy and resource intensive scenario for the 21st century. *Global environmental change*, 42:297–315.

Krogstrup, S. and Oman, W. (2019). Macroeconomic and financial policies for climate change mitigation: a review of the literature. *IMF Working Paper no 19/185*.

Lamperti, F., Bosetti, V., Roventini, A., Tavoni, M., and Treibich, T. (2021). Three green financial policies to address climate risks. *Journal of Financial Stability*, 54:100875.

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., and Sapio, A. (2018). Faraway, so close: Coupled climate and economic dynamics in an agent-based integrated assessment model. *Ecological Economics*, 150:315–339.

Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., and Sapio, A. (2020). Climate change and green transitions in an agent-based integrated assessment model. *Technological Forecasting and Social Change*, 153:119806.

Lamperti, F. and Roventini, A. (2022). Beyond climate economics orthodoxy: impacts and policies in the agent-based integrated-assessment dsk model. *European Journal of Economics and Economic Policies: Intervention*, 19(3):357–380.

Lecuyer, O. and Quirion, P. (2013). Can uncertainty justify overlapping policy instruments to mitigate emissions? *Ecological Economics*, 93:177–191.

Lehmann, P. (2012). Justifying a policy mix for pollution control: a review of economic literature. *Journal of Economic Surveys*, 26(1):71–97.

Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., and Schellnhuber, H. J. (2019). Climate tipping points—too risky to bet against. *Nature*, 575(7784):592–595.

Lipsey, R. G. and Lancaster, K. (1956). The general theory of second best. *The review of economic studies*, 24(1):11–32.

Mantel, R. (1974). On the characterization of aggregate excess demand. *Journal of Economic Theory*, 7(3):348–353.

Marcott, S. A., Bauska, T. K., Buizert, C., Steig, E. J., Rosen, J. L., Cuffey, K. M., Fudge, T., Severinghaus, J. P., Ahn, J., Kalk, M. L., et al. (2014). Centennial-scale changes in the global carbon cycle during the last deglaciation. *Nature*, 514(7524):616–619.

Mazzocchetti, A., Raberto, M., Teglio, A., and Cincotti, S. (2018). Securitization and business cycle: an agent-based perspective. *Industrial and Corporate Change*, 27(6):1091–1121.

Monasterolo, I. (2020). Climate change and the financial system. *Annual Review of Resource Economics*, 12:299–320.

Monasterolo, I., Dunz, N., Mazzocchetti, A., and Gourdel, R. (2022a). Derisking the low-carbon transition: investors' reaction to climate policies, decarbonization and distributive effects. *Review of Evolutionary Political Economy*, 3(1):31–71.

Monasterolo, I., Mandel, A., Battiston, S., Mazzocchetti, A., Oppermann, K., Coony, J., Stretton, S., Stewart, F., and Dunz, N. (2022b). The role of green financial sector initiatives in the low-carbon transition.

Monasterolo, I. and Raberto, M. (2018). The eirin flow-of-funds behavioural model of green fiscal policies and green sovereign bonds. *Ecological Economics*, 144:228–243.

Monasterolo, I. and Raberto, M. (2019). The impact of phasing out fossil fuel subsidies on the low-carbon transition. *Energy Policy*, 124:355–370.

Mullainathan, S. and Thaler, R. H. (2000). Behavioral economics. *NBER working paper series*.

Napoletano, M., Roventini, A., and Sapio, S. (2006). Are business cycles all alike? a bandpass filter analysis of the italian and us cycles. *Rivista italiana degli economisti*, 11(1):87–118.

NGFS (2020). Ngfs - network for greening the financial system - guide to climate scenario analysis for central banks and supervisors 2020.

Nieddu, M., Bertani, F., and Ponta, L. (2022). The sustainability transition and the digital transformation: two challenges for agent-based macroeconomic models. *Review of Evolutionary Political Economy*, pages 1–34.

Nieddu, M., Raberto, M., Teglio, A., Ponta, L., and Cincotti, S. (2023a). Extended multicriteria analysis for policy evaluation. *Working paper.*

Nieddu, M., Raberto, M., Teglio, A., Ponta, L., and Cincotti, S. (2023b). Policy mix in an agent-based model. *Working paper.*

Nordhaus, W. and Sztorc, P. (2013). *DICE 2013R: Introduction and user's manual.*

Nordhaus, W. D. (1993). Optimal greenhouse-gas reductions and tax policy in the" dice" model. *The American Economic Review*, 83(2):313–317.

Nordhaus, W. D. (2007). To tax or not to tax: alternative approaches to slowing global warming. *Review of Environmental Economics and Policy*, 1(1):26–44.

Nordhaus, W. D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, 114(7):1518–1523.

Ozel, B., Nathanael, R. C., Raberto, M., Teglio, A., and Cincotti, S. (2019). Macroeconomic implications of mortgage loan requirements: an agent-based approach. *Journal of Economic Interaction and Coordination*, 14(1):7–46.

Pages 2k Consortium (2019). Consistent multidecadal variability in global temperature reconstructions and simulations over the common era. *Nature geoscience*, 12(8):643–649.

Palmer, R., Brian Arthur, W., Holland, J. H., LeBaron, B., and Tayler, P. (1994). Artificial economic life: a simple model of a stockmarket. *Physica D: Nonlinear Phenomena*, 75(1):264–274.

Ponta, L., Raberto, M., Teglio, A., and Cincotti, S. (2018). An agent-based stock-flow consistent model of the sustainable transition in the energy sector. *Ecological Economics*, 145:274–300.

Provenzale, A. (2014). Climate models. *Rendiconti Lincei*, 25:49–58.

Raberto, M., Ozel, B., Ponta, L., Teglio, A., and Cincotti, S. (2019). From financial instability to green finance: the role of banking and credit market regulation in the eurace model. *Journal of Evolutionary Economics*, 29(1):429–465.

Raberto, M., Teglio, A., and Cincotti, S. (2011). Debt deleveraging and business cycles: An agent-based perspective. *Economics Discussion Paper*, (2011-31).

Randall, A. (1983). The problem of market failure. *Natural Resources Journal*, 23(1):131–148.

Riccetti, L., Russo, A., and Gallegati, M. (2015). An agent based decentralized matching macroeconomic model. *Journal of Economic Interaction and Coordination*, 10:305–332.

Riccetti, L., Russo, A., and Gallegati, M. (2016). Financialisation and crisis in an agent based macroeconomic model. *Economic Modelling*, 52:162–172.

Riccetti, L., Russo, A., and Gallegati, M. (2018). Financial regulation and endogenous macroeconomic crises. *Macroeconomic Dynamics*, 22(4):896–930.

Robalino, D. A. and Lempert, R. J. (2000). Carrots and sticks for new technology: Abating greenhouse gas emissions in a heterogeneous and uncertain world. *Integrated Assessment*, 1(1):1–19.

Roos, M. W. (2023). Climate change from the perspective of complexity economics. In Ping Chen, Wolfram Elsner, A. P., editor, *Handbook of Complexity Economics*. Routledge. in press.

Shogren, J. F. and Taylor, L. O. (2020). On behavioral-environmental economics. *Review of Environmental Economics and Policy*.

Simon, H. A. (1987). Behavioral economics. *The New Palgrave: A dictionary of economics*, 1:221–24.

Sonnenschein, H. (1972). Market excess demand functions. *Econometrica*, 40(3):549–563.

Sorrell, S. and Sijm, J. (2003). Carbon trading in the policy mix. *Oxford review of economic policy*, 19(3):420–437.

Sterman, J., Fiddaman, T., Franck, T. R., Jones, A., McCauley, S., Rice, P., Sawin, E., and Siegel, L. (2012). Climate interactive: the c-roads climate policy model.

Stern, N. (2008). The economics of climate change. *American Economic Review*, 98(2):1–37.

Stern, N. (2013). The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models. *Journal of Economic Literature*, 51(3):838–59.

Stiglitz, J. E. and Weiss, A. (1981). Credit rationing in markets with imperfect information. *The American economic review*, 71(3):393–410.

Teglio, A., Mazzocchetti, A., Ponta, L., Raberto, M., and Cincotti, S. (2019). Budgetary rigour with stimulus in lean times: Policy advices from an agent-based model. *Journal of Economic Behavior and Organization*, 157:59–83.

Teglio, A., Raberto, M., and Cincotti, S. (2012). The impact of banks' capital adequacy regulation on the economic system: an agent-based approach. *Advances in Complex Systems*, 15(supp02):1250040.

Thaler, R. H. (2016). Behavioral economics: Past, present, and future. *American economic review*, 106(7):1577–1600.

Thaler, R. H. (2018). From cashews to nudges: The evolution of behavioral economics. *American Economic Review*, 108(6):1265–87.

Tinbergen, J. (1952). *On the theory of economic policy*. North-Holland Publishing Company, Amsterdam.

Tol, R. (2017). The structure of the climate debt. *Energy Policy*, pages 431–438.

Tol, R. S. (1997). On the optimal control of carbon dioxide emissions: an application of fund. *Environmental Modeling & Assessment*, 2(3):151–163.

Tonelli, F., Fadiran, G., Raberto, M., and Cincotti, S. (2016). Approaching industrial sustainability investments in resource efficiency through agent-based simulation. In *Service Orientation in Holonic and Multi-Agent Manufacturing*, pages 145–155. Springer.

Tversky, A. and Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases: Biases in judgments reveal some heuristics of thinking under uncertainty. *science*, 185(4157):1124–1131.

Twomey, P. et al. (2012). Rationales for additional climate policy instruments under a carbon price. *The Economic and Labour Relations Review*, 23(1):7–31.

UNEP (2021). Emissions gap report 2021.

UNEPFI (2020). Annual overview 07/2019–12/2020.

Uribe, M. and Schmitt-Grohé, S. (2017). *Open economy macroeconomics*. Princeton University Press.

Van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., et al. (2014). A new scenario framework for climate change research: scenario matrix architecture. *Climatic Change*, 122(3):373–386.

Vermeulen, R., Schets, E., Lohuis, M., Kölbl, B., Jansen, D.-J., and Heeringa, W. (2019). The heat is on: A framework for measuring financial stress under disruptive energy transition scenarios.

Weaver, R. K. (2014). Compliance regimes and barriers to behavioral change. *Governance*, 2(27):243–265.

Weitzman, M. (2014). Can negotiating a uniform carbon price help to internalize the global warming externality. *Journal of the Association of Environmental and Resource Economists*, pages 29–49.

Weyant, J. (2017). Some contributions of integrated assessment models of global climate change. *Review of Environmental Economics and Policy*, 11(1):115–137.

World Bank (2022). State and trends of carbon pricing 2022. Technical report, World Bank.

Appendix A

Temporal evolution of the Eurace model

This appendix shows the dynamics that the model generates under seven selected scenarios, namely the BAU scenario, two policy mix scenarios and the corresponding two carbon tax and two feed-in tariff scenarios. Since the analysis presented in the main text involves only quantities referred to the entire time span of simulations, the scope of the appendix is to give the reader an insight on the dynamic behavior of the economy described by the model, and on how climate policies impact the economy evolution. Figures from A.1 to A.4 shows the temporal evolution of the main climate and economic variables relative to montecarlo simulations of the above cited scenarios, all performed with the same seed of the random generator.

Fig.A.1 shows that the PMs environmental performance are similar and better than those of the corresponding FITs, and better than those of the carbon tax policies. The same can be deduced also looking at Fig.A.1(a), that shows the evolution of the share of renewable energy.

Fig.A.3 reports the prices and sold quantities of the consumption and investment goods. The figure shows the effects of climate policies on the consumption goods market described in the main text: the introduction of the policies is associated with an increase in the prices of consumer goods and a decrease in real consumption compared to the BAU scenario. Fig.A.3(b) shows further that consumption loss under the policy mix scenarios is lower than that under the corresponding FITs scenarios.

Finally, Fig.A.4 shows the policies impact on the labor market. In particular, panel (c) of the figure shows that climate policies lead to an increase of unemployment volatility with respect to the BAU; this effect is more evident in the feed-in tariff scenarios than in the policy mix.

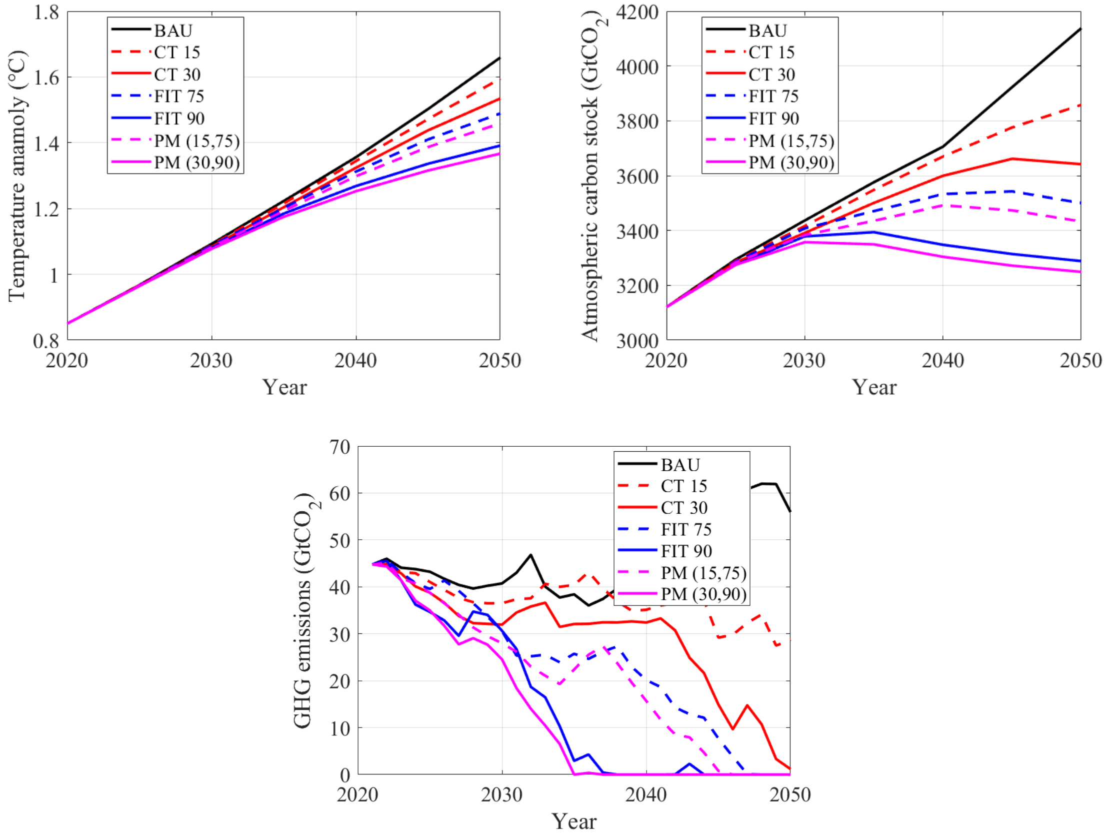


Figure A.1 The figure shows the temporal evolution of the variables of interest for a selected set of scenarios without climate damages among those considered. In particular it shows: (a) the temperature anomaly, (b) the atmospheric carbon stock and (c) the yearly GHGs emissions.

Although the figures shown here confirm the conclusions set out in the main text, it should be noted that they refer to a single montecarlo experiment for each scenario and cannot be used by themselves to compare the different scenarios analysed.

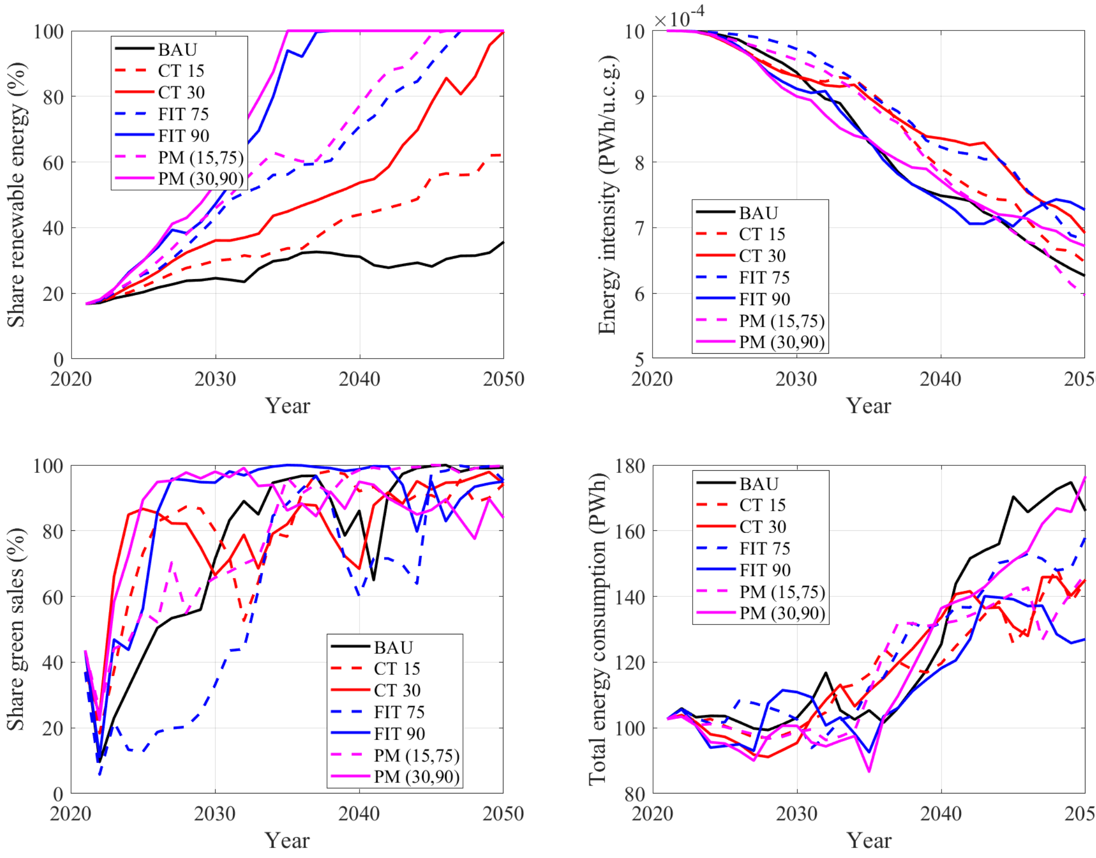


Figure A.2 The figure shows the boxplots of the temporal mean of the variables of interest for all the scenarios without climate damages considered. In particular it shows: (a) the energy price, (b) the share of renewable energy, (c) the energy intensity, (d) the share of green investments and (e) the total final consumption of energy.

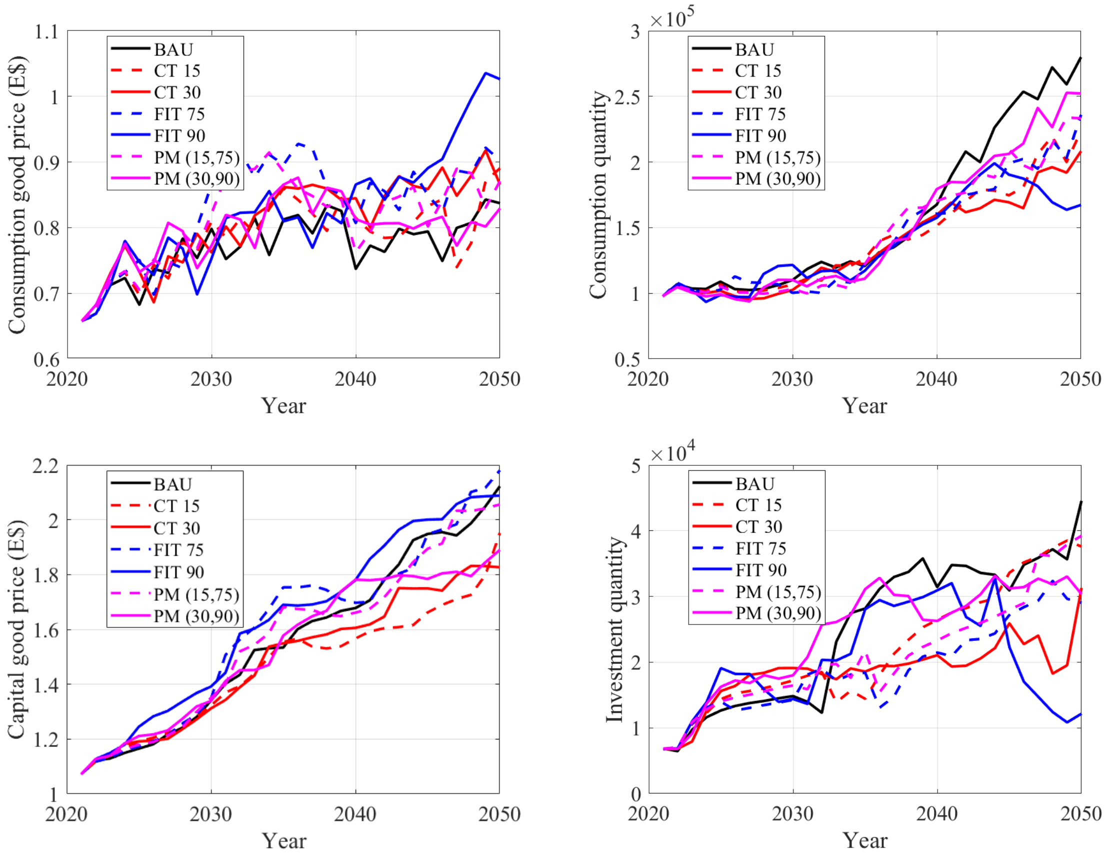


Figure A.3 The figure shows the temporal evolution of the variables of interest for a selected set of scenarios without climate damages among those considered. In particular it shows: (a) the temperature anomaly, (b) the atmospheric carbon stock and (c) the yearly GHGs emissions.

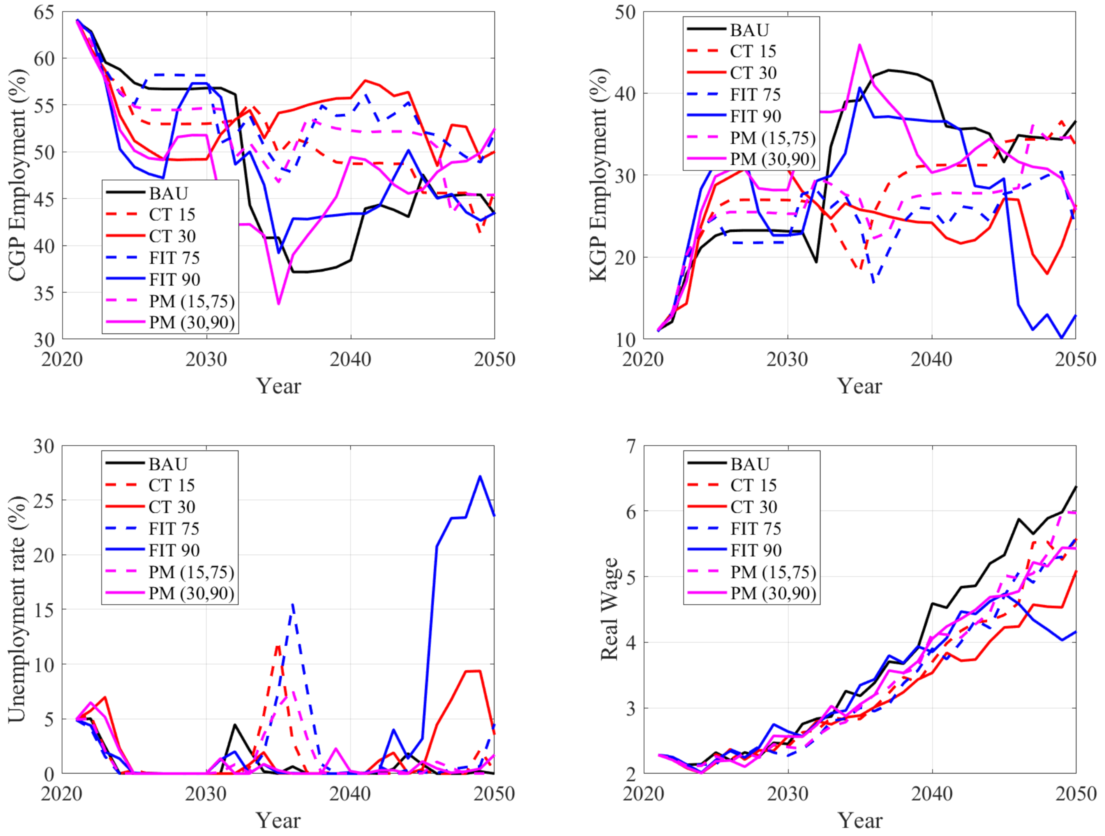


Figure A.4 The figure shows the temporal evolution of the variables of interest for a selected set of scenarios without climate damages among those considered. In particular it shows: (a) the employment rate of the consumption goods sector, (b) the employment rate of the capital goods sector, (c) the unemployment rate and (d) the mean real wage.