Περιφέρεια | Regional Integration: Politics, Economics, Governance

Τόμ. 18 (2024)

Περιφέρεια | Regional Integration: Politics, Economics, Governance: Addressing Climate Change in Turbulent Times


Autumn | Φθινόπωρο 2024 Issue | Τεύχος 18

ΠΕΡΙΦΕΡΕΙΑ
REGIONAL INTEGRATION
politics economics governance

Επιστημονική επιθεώρηση για την περιφερειακή ολοκλήρωση-πολιτική, οικονομία & διακυβέρνηση

Οικονομική του Κλίματος: Κεντρικά θέματα και εξελισσόμενες συζητήσεις

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doi: 10.12681/ri.40697

Regional Integration | Issue 2024 (18), 17-39
Περιφέρεια | Τεύχος 2024 (18), 17-39

Climate economics: central themes and evolving debates

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Abstract

This paper examines central themes in climate economics by addressing three interlinked questions: Why has the economy failed to protect us from climate change? What is the optimal level of climate change mitigation? What are the best means to achieve these goals? The evolving debates and approaches economists have taken to answer these questions have profoundly shaped the broader discussion on the strength and strategies of climate action.

Keywords: Climate economics, climate change mitigation, carbon pricing, climate-economy models, sustainability

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Περίληψη

Αυτό το άρθρο εξετάζει κεντρικά θέματα της οικονομικής του κλίματος, απαντώντας σε τρία αλληλένδετα ερωτήματα: Γιατί η οικονομία απέτυχε να μας προστατεύσει από την κλιματική αλλαγή; Ποιο είναι το βέλτιστο επίπεδο μετριασμού της κλιματικής αλλαγής; Ποια είναι τα καλύτερα μέσα για την επίτευξη αυτών των στόχων; Οι εξελισσόμενες συζητήσεις και οι προσεγγίσεις που έχουν υιοθετήσει οι οικονομολόγοι για να απαντήσουν σε αυτά τα ερωτήματα έχουν διαμορφώσει καθοριστικά τον ευρύτερο διάλογο σχετικά με τη δύναμη και τις στρατηγικές της κλιματικής δράσης.

Λέξεις κλειδιά: οικονομική του κλίματος, μετριασμός της κλιματικής αλλαγής, τιμές άνθρακα, υποδείγματα κλίματος-οικονομίας, βιωσιμότητα

1. Introduction

Three broad and interlinked questions set the scene for economic analysis of climate change or climate economics. Why does the economy fail to protect our climate? What level of climate change should we aim for? What policy tools are needed to achieve our climate goals? How economists have attempted to answer these questions has had a profound impact on the broader debate about such matters as how strong climate action should be, what are the costs of the energy transition, what kinds of climate policies should governments pursue.

A well-functioning economy is expected to manage all resources in a way that advances our welfare. There are many reasons why the market system may fail to do so, mismanaging, wasting or damaging valuable resources. Several market failures have contributed to damaging anthropogenic climate change that far outweighs the benefits of using our atmosphere as a repository for our greenhouse gas emissions. In an ideal market system resources are protected by property rights. Until recently there were no property rights, or other forms of protection, in the use of the atmosphere to deposit greenhouse gas emissions. The atmosphere was treated as an open access resource, as if it had an infinite capacity to absorb our emissions while maintaining critical services like keeping temperatures and weather variability at levels that sustain our wellbeing. The lack of property rights means that no one pays a price for the right to emit greenhouse gases. It is treated as a free resource when in fact it is a critically valuable scarce resource. So, one important reason the economy fails to protect our climate, is that unlike most other resources like oil, natural gas, iron ore and silicon chips, there are no property rights for its use and no price to register its scarcity. This leads to overexploitation of greenhouse gas assimilating services of the atmosphere that directly competes with the vital climate regulating services of the atmosphere.

What further aggravates this problem is that greenhouse gases contribute to climate change from wherever the emissions arise. The climate regulating services of our atmosphere is a global public good and there is no single jurisdiction that can set global regulations or property rights. As each country emits greenhouse gases, they generate damages to all other countries while only incurring a small fraction of these damages. No country, on its own, has an adequate incentive to curb their emissions or to address this market failure by taking action to limit greenhouse gas emissions.

Another market failure is that the private sector has inadequate incentives to invest in research and development of technologies like renewables that do not damage our atmosphere. The initial investment in research and development can be very costly but most of the benefits of new knowledge and learning accrue to other companies that have not put in the effort and expense. The private sector will underinvest in the needed technologies to address climate change.

If there are failures preventing the market system from protecting nature's vital atmospheric climatic services, how can we correct these failures and how do we know what the right uses of the atmosphere are or what level of climate change is acceptable? On the latter question economists try to identify and measure potential benefits and costs of using the atmosphere as a waste depository of greenhouse gases. Burning fossil fuels have been a very cheap and an effective way of heating our homes, providing transportation, generating electricity, and producing many critical materials like cement, steel and fertilizers. It's hard to imagine the great strides in world development that started with the Industrial Revolution without our access and use of coal, oil and gas. These benefits come with increasing costs in terms of climate change and the associated damages like rising sea level, heat waves, floods and extreme weather. Economists build models to measure, project and compare the benefits of our fossil intensive energy system against the costs of using our atmosphere for dumping our greenhouse gases. Besides helping us better understand the potential economic impacts of climate change these have been used to suggest the 'right' level of climate change.

Having a good understanding of how the economy fails to protect us from climate change and the related question of what level of protection we should aim for is key to designing policies, instruments and institutions to correct or supplant the market system. While it would be nice to imagine an economic system that automatically gauges the health of the environment and appropriately incentivizes us to take the right decisions, or self regulates, the nature of climate change requires a central role for governments. Governments need to set targets for greenhouse gas emission reductions and develop the regulatory framework that will achieve these. Once targets for limiting greenhouse gas emissions have been set (with or without the help of economic analysis) the focus of climate economics turns to the most effective means or instruments to achieve these targets. Besides mitigation of greenhouse gases there are two other main dimensions of economic analysis. Economies need to adapt to the new conditions that result from climate change and here again there is the question of how many resources need to be invested, and by what means, in protecting our wealth and health from potential damages. In addition, as the world transitions to a low or zero carbon economy we need to ensure that our economies are resilient to these new conditions.

This paper will focus on some of the central themes of climate economics by presenting the ways that economists have attempted to answer the three interlinked questions: Why the economy has failed us? What is the right level of climate change and thus climate action? What are the best means of achieving our goals? Section 2 will investigate the special challenges of climate change to economics and how economists have been modeling the interaction between the economy and climate change. Section 3 will present criticisms of the early climate-economy models that have important implications on how economists have evolved their views on the need for strong and early climate action. Section 4 will explain the importance placed by economists on the role of carbon prices, whether in the form of a carbon tax or emissions trading system. Section 5 will present the need for complementary policies to carbon prices and a holistic systems approach to climate change.

2. Challenges of climate change to economics and economic modelling

2.1 What makes climate change a special challenge for economics

There are several features of climate change that together make it unique among environmental challenges to the economy, a specially wicked problem. We have already referred to one which is the global nature of climate change that requires action at a global level. If one country adopts tougher mitigation then carbon leakage can occur where greenhouse gas industries migrate to other less regulated regions, largely voiding the benefits of the initial mitigation. Climate change is also special due to the long-time horizon between the moment of emissions and the physical impacts of accumulated greenhouse gases in the atmosphere. This strong temporal disconnect between those generating the damages and those experiencing the damages severely blunts any incentives to mitigate emissions, especially when action may be costly or perceived as such.

Climate change is characterized by radical uncertainty along so many dimensions including the magnitude of future impacts, the regional variability of impacts, the unpredictable nature of potential tipping points like the ice sheet collapse or permafrost thaw, the long term economic consequences of climate change, the ecological impacts like species responses and ecosystem disruptions as well as the broader human responses to climate change in terms of future mitigation, adaptation actions, geopolitical shifts, migration, etc. As we will see the nature of uncertainty of climate change can strongly influence the way economists model the phenomenon and the usefulness of models in guiding action.

Any effort to effectively mitigate greenhouse gases requires broad based system changes across sectors and across economies, like how we produce and consume energy, how we build are cities, how our transport system works, how we direct technological change, how we produce food, and how our trade and finance systems work. The sheer scale of the needed changes and the way these changes are interdependent and need to take place in tandem add to the uniqueness of the challenge for economics. For instance, to move rapidly to electric vehicles we need technological advancements in batteries, recharging infrastructure, new resource demands, expansion of renewables. The broad expansion in use of electric vehicles with appropriate changes to the grid so that car owners can sell energy from their batteries while they are parked will further reduce the cost of owning an electric vehicle and will help balance the fluctuations of energy related to renewables.

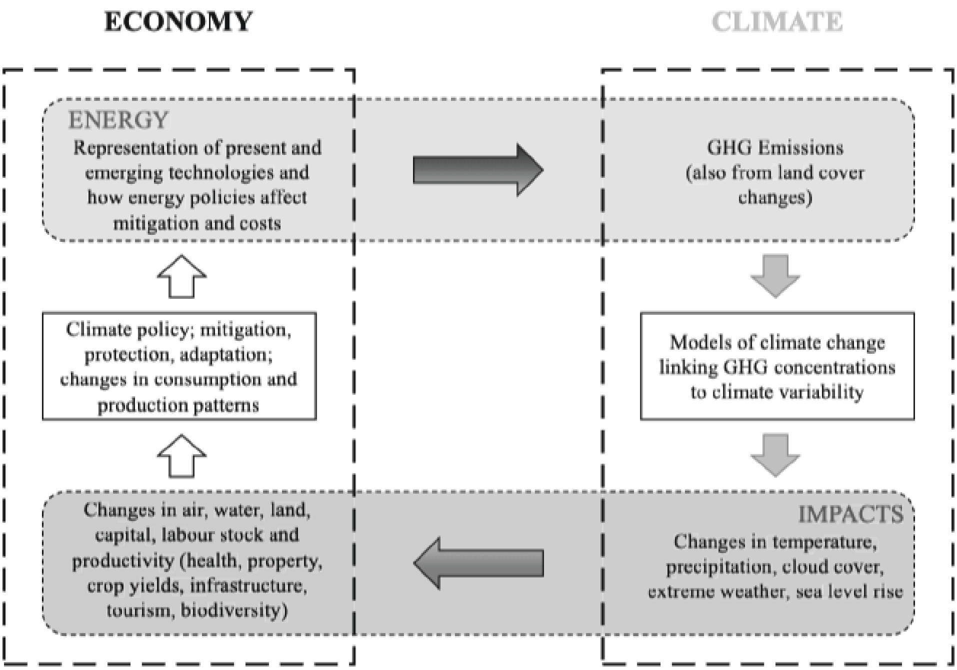
Many of these unique features of climate change pose special challenges to economics that raise fundamental questions, inter alia, of how economists model the climate-economy interaction and their underlying assumptions.

2.2 Two main types of economic analysis

An important part of climate economics has been the development and use of models incorporating the interaction of the economy with the climate. Models can be used to illuminate specific elements like understanding the economic impact of climate change to agriculture, how agriculture can adapt to climate change or reduce greenhouse gas emissions, and the best policy instruments to achieve these aims. Two broad types of models are bottom-up models that tend to be detailed and focuses on a specific sector like energy, forestry, tourism or transportation, and top-down models that look at the whole economy or global economy and are more abstract focusing on major trends like population growth, broad technological development, levels of consumption (GDP) and how these interact with climate change. Top-down models are called Integrated Assessment Models or IAMs in that they integrate climate models with models of the economy.

Broadly speaking the following interlinked chain of interactions are modeled in top-down models. Human-induced climate change results from increases in GHG emissions and their levels of concentration in the atmosphere. Levels of emissions resulting from economic activity will depend on population growth, technological advancement, forms of production and patterns of consumption. Climate science tells us how different concentration levels of GHGs may affect the temperature, precipitation, cloud formation, wind and sea level rise. These in turn lead to different physical, environmental and social impacts like change in mortality rates, crop yields, water supply, species loss and migration. Physical impacts can be translated into monetary terms to provide a common metric of damages or benefits to a sector or the entire economy. The figure below depicts the circular nature of interaction as the economy generates emissions changing the climate which leads to physical impacts affecting the economy and its emissions. There is a bewildering array of climate-economy models that vary by the different ways parts of this highly interconnected process are modeled and the differing assumptions made (Nikas et al., 2018).

Figure 1:
Climate-economy dynamics with four modules: Economy, climate, impacts, and energy



Source: Nikas et al. (2018)

2.3 Climate-Economy models or Integrated Assessment Models

Integrated Assessment Models have played an outsized role in framing the economic debate around climate change and in shaping economists' views on the timing and strength of action needed to mitigate climate change. These models were first used in the Intergovernmental Panel on Climate Change (IPCC) reports in the Second Assessment Report in 1995. IAMs became more central in subsequent IPCC reports where they are used extensively to model scenarios and provide economic estimates of potential damages from climate change and the economic implications of different policy choices and mitigation pathways. Though they are not used by the IPCC to recommend a specific target for climate change, this has been a key focus of many such models and has influenced the broader debate on the urgency of climate action.

William D. Nordhaus is the pioneer in building integrated assessment models and received the Nobel Prize in Economics in 2018 for his contribution. He developed the Dynamic Integrated Climate-Economy (DICE) model in the early 1990s. The model combines a simplified representation of the global economy with a model of the Earth's climate system[1]. It models how the global economy grows over time where greenhouse gas emissions increase if there is no abatement policy. Rising CO_2 concentrations lead to climate change which in turn imposes ecological and economic impacts. The impacts can be addressed by policies that mitigate emissions. Such policies mean that societies give up consumption today to reduce damages in the future. All damages and costs are measured in monetary units. Higher growth early on leads to higher consumption and welfare but also higher damages. The main objective of the model is to allow the comparison of outcomes and welfare of different policies. The model "is a highly simplified representation of the complex economic and geophysical realities" (Barrage & Nordhaus, 2024). While such simplicity has many disadvantages it offers transparency and versatility allowing researchers to consider the implications of different assumptions.

The model is also used to determine the optimal policy or levels of mitigating CO_2 emissions that maximizes welfare over time. This entails an optimal trajectory of economic growth, levels of emissions, and increases in global mean temperature. There have been many revisions of the DICE model since its first development. Revisions reflect changing assumptions and refinements with advances in knowledge related to both the economic and climate components of the model. The latest version is DICE-2023 is described in Barrage & Nordhaus (2024). The baseline scenario estimates current policies as of 2023 and extends them indefinitely. The associated temperature change for 2100 is 3.6 °C. The optimal scenario that maximizes welfare leads to 2.6 °C by 2100.

The fact that this and many other IAMs have suggested that policy should aim at higher levels than the Paris target of holding global average temperature at well below 2 °C and pursuing efforts to limit the rise to 1.5 °C relative to pre-industrial levels, has been a source of controversy. Among economists the controversy goes back many years and older variations of DICE models have suggested even higher optimal levels of global average temperatures for 2100. For instance in the previous DICE-2016R3 model the optimal temperature by 2100 rises to over 3 °C (Nordhaus, 2019).[2] From the outset DICE models (and many other IAMs) prescribed moderate climate action as they tended, according to critics, to greatly underestimate the damages associated with climate change in the future and overestimate the costs of transitioning away from fossil fuels.

[1] For an introduction to several of the central themes of climate economics see Nordhaus (2021). Tol (2023) also provides a good textbook account of many of these themes as well as an introduction to integrated assessment models and DICE. Roos & Hoffart (2020) also introduce climate economics while presenting alternative perspectives to mainstream approaches.

[2] Glanemann et al. (2020) use an older DICE model but incorporate other assumptions and show that an optimal policy comes very close to the politically determined Paris Agreement target of below 2 °C.

3. Economic arguments for stronger climate action

From the earliest climate-economy models in the 1990s many economists had raised serious concerns about how they were formed and their underlying assumptions. An important landmark was the Stern Review of the Economics of Climate Change (2006) that had been commissioned by Tony Blair's government in 2005 (Stern, 2007).[3] It had the impact of greatly raising awareness among the public about the economics of climate change and provided a fundamentally different narrative to economists' mainstream view of climate action. In contrast to the dominant climate-economy models of the time that suggested a long-term rise in global average temperature around 3°C would be optimal and that mild and gradual mitigation was warranted, the Stern Review argued that the economics of climate change required far more aggressive and immediate climate action. It did so by providing a far more expansive economic analysis of climate change and by questioning many of the central assumptions of many IAMs. In the following sections I will present some of the key assumptions of many IAMs that have come under attack, starting with the role of discounting.

3.1 Discounting matters: weighing benefits and costs across time

Because money and resources today are worth more today than in the future, economists use a discount rate when comparing values across time. Most people prefer to receive €100 today than €100 in the future and may even prefer €100 today to €105 in a year's time. We thus need to account for the different value of a benefit or money at different times when comparing values across time. Another reason future values are discounted is that money today can be invested and grows over time. With a 5% interest rate investing €100 today would give you €105 in a year or €13150 in 100 years. So, with a 5% discount rate we would put a weight (or discount) on any value in 100 years of less than 1% (0.76% to be precise) when comparing it to present day amounts. A damage of €10.000 in 100 years would be treated as equivalent to a damage of €76 today. This illustrates the profound impact of discounting future values.

Since the costs of mitigation are mostly in the near future while the greatest damages of climate change appear in the more distant future, the rate at which these future damages are discounted strongly influences the 'optimal' emissions path. High discount rates mean that we place less value on future damages, so climate change appears less of a threat. The selection of discount rates in climate-economic models is a subject of intense debate involving both empirical and ethical considerations about the valuation of future wellbeing.

Strong arguments have been put forward to support the use of a very low discount rate. There are many factors that influence the choice of discount rate. One factor relates to differentiating how a single person compares values over time to how society should make comparisons of values across generations. Most indi-

[3] See also Stern (2008) that provides a great overview of the Stern Review.

viduals tend to value immediate consumption more highly over future consumption. While this may be a reason to put a higher value on benefits or costs in the present within a person's lifetime it does not warrant putting lower values on benefits and costs on people that haven't yet been born. We should not put a lower weight on future lives just because they are born later.

Another important factor influencing the choice of discount rates is the expected growth of the world economy in the future. If modelers assume a high growth rate this will mean that future generations will be much better off so any damages to them should be weighed less when compared to damages or sacrifices in the present from shouldering costly mitigation. If on the other hand, climate change is likely to lower growth rates and leave future generations worse off than the present, we have a greater responsibility in undertaking mitigation.

There is already a vast literature on the issue of how to select the appropriate discount rate for climate-economy model, but the growing consensus is towards the use of a low discount rate.

3.2 Most likely or worse outcomes

Another critical issue in climate-economy models has to do with how they understand and model uncertainty. Uncertainty pervades all aspects of climate change whether considering the potential physical impacts resulting from climate change or how the economy will contribute to climate change, the pace of technological advancement, the form of policy interventions, or the changing winds of politics. Unavoidably we must make decisions in the presence of these many and often deep uncertainties. One critical uncertainty is the extent of future damages we can expect from climate change. Some climate-economy models incorporate varying risks about future damages by associating probabilities to different levels of damages and then estimating a weighted average of the damage to our welfare. Very high damages may be less likely so they will be given a lower probability with more likely mid-levels of damages getting a higher probability. By adding the weighted average of these damages to our welfare we get something like the central value or most likely damages. This is then used in determining an optimal climate policy.

A problem with this approach is that we don't really have any good estimates of the probabilities associated with future damages from climate change and climate action. As we delay climate action the needed energy transition may become highly disruptive and costly, or as we broach tipping points that are hard to predict we may have cascading extreme climate events like the complete melting of the Greenland ice sheet. In addition, as climate change at the present pace has no precedent in human history highly catastrophic damages cannot be ruled out and may have non-negligible probabilities. Weitzman (2009) sets out what he called the "Dismal Theory" in that if a future catastrophe had a non-negligible probability, then these damages would overwhelm any costs of climate action and the IAMs would recommend that present generations pay an infinite amount to avoid these. Whether we focus on what is a highly contentious 'most likely' scenario or frame our decision problem on the possibility of some catastrophic worse outcomes substantially affects our approach to climate action.

In many areas of our daily life, we focus on improbable bad outcomes and accordingly take a precautionary approach. Our house catching on fire is an unlikely outcome, but we take out insurance to protect ourselves from such severe outcomes. Airport security is not based on the most likely outcome but on preventing a worse scenario. The Atlantic Meridional Overturning Circulation (AMOC) is a crucial component of Earth's climate system, redistributing heat and influencing weather patterns, particularly in the North Atlantic region. While there are divergent views on the likelihood and timing of the collapse of the AMOC with profound global consequences, one recent study contends it is likely to occur within the century given present trends in global temperature (Ditlevsen & Ditlevsen, 2023).

Many prominent economists have suggested a precautionary or guardrail approach that views climate action as an insurance policy against potentially catastrophic damages and questions the value of optimizing approaches of climate-economy modeling (Stern & Stiglitz, 2021; Stern et al., 2022).

3.3 Other issues with modeling damages from climate change

There are many other aspects of climate-economy models that have been criticized by economists. For purposes of illustration, I mention just two more. Most IAMs reflect damages from a global temperature increase by a proportionate reduction in overall output of the economy when there is good reason to believe that damages will increase in a non-linear fashion with many tipping points. The possibility that there may be accelerating damages or dramatic worsening of climate damages after certain thresholds are passed alters the calculus of benefits and damages. Climate-economy models often do not consider how damages to vulnerable populations of the world that are least able to protect themselves should be weighed more heavily than damages to more affluent regions. Modified IAMs that incorporate equity weighting can lead to significantly higher damages from climate change (Schumacher, 2018).

3.4 The cost of decarbonization

Much of the debate on the limitations of climate-economy models has focused on the problems in modeling damages resulting from climate change. Much less attention has been given to how costs of mitigating greenhouse gases have been modeled.

IPCC (2022) find that mitigation pathways to reach 1.5°C that doesn't include the benefits of avoided climate change impacts nor co-benefits or co-harms of mitigation actions to involve an annualized reduction in consumption growth of 0.04 (median value) over the century. Despite these 'costs' of mitigation the economy achieves higher growth rates when compared to pathways without mitigation where climate damages are included in the scenarios. This does not clarify, however, how costs and benefits are distributed through time leaving open the question of how much needs to be sacrificed now to achieve better outcomes in the future.

The International Energy Agency (2021) estimates that the transition to a net-zero energy system requires a surge in clean energy investment of $4.5 trillion or three times 2021 levels. This investment could drive an average annual increase in global GDP growth by approximately 0.4% through 2030, through the creation of new industries and job opportunities in the clean energy sector.

Until recently most IAMs modeled technological change as exogenous so that advancements were predetermined over time and not influenced by policies or economic activities within the model. Improvements in energy efficiency, reductions in carbon intensity or cost declines for technologies were often derived from historical trends or expert judgments. No allowances were made for policy feedback where investment in research and development or the stringency of climate policies could accelerate technological advancement and cost reductions arising from learning by doing. Evidence from photovoltaics and wind energy have shown how policy support can lead to dramatic reductions in the costs of these technologies brought about through learning as the scale of production increased Organizations like the International Energy Agency consistently underestimated the cost reductions in renewables. [4]

Even though there is strong evidence that policy can have a substantial impact on the direction and pace of technological advancement the difficulty in mathematically incorporating such dynamics in climate-economy models has hampered an appraisal of their impact. More recent IAMs have started to incorporate such policy feedback and show that much higher and earlier investments in clean technologies are warranted than those suggested by earlier climate economy models (Grubb et al., 2024).

Criticisms of the form and assumptions underlying early climate-economy model have had a strong influence on the economics of climate change. Many climate-economy models have been reformulated to address these criticisms and to incorporate advances in our knowledge of how changes in average global temperature cause physical damages, how best to value and weigh benefits from reducing climate damages over time and how to project costs of mitigation and technological advances. What has become clear is that the model results are highly sensitive to the form of the model and its assumptions. Newer climate-economy models, like the DICE2023, have come much closer to aligning with the broader scientific community's and those making the case that climate economics, done properly, endorses strong and upfront climate action to ensure the welfare of this and future generations. We turn now to the issue of how climate economics has shaped our understanding about the right instruments or policy tools to mitigate greenhouse gases.

[4] See Grubb et al. (2021) how the omission of important elements of dynamic realism like inertia, induced innovation and path dependence has meant that IAMs have misspecified abatement costs and their dynamics. See Grubb et al. (2024) for an alternative climate economy model that incorporates dynamic technological change.

4. Putting a price on carbon

4.1 A carbon price

One area where there has generally been broad agreement among economists is the need for there to be a price that greenhouse gas emitters pay. This typically takes the form of a tax on carbon, or the price associated with a tradable emissions permit. A carbon tax is usually levied on carbon-based fossil fuels proportionally, in relation to the estimated amount of carbon in their production and use. It incentivizes consumers to save energy overall but also to direct their demand to alternative energy sources that generate less carbon emissions. This is its main purpose, but such carbon taxes have an additional benefit in that the revenues can be used to reduce other distortionary taxes like payroll taxes that increase the cost of hiring workers. They can also be used to reduce any regressive impacts of carbon prices on low-income households.

Economists argue that a carbon price is the most effective and least costly way of protecting us from climate change or decarbonizing the economy. Prices are the most flexible decentralized way that markets determine the right use of our resources. A carbon price is seen as correcting the key market failure associated with climate change in that the atmosphere is treated as a free open access resource when in fact it is highly valuable and scarce.

4.2 Tim Harford on the beauty of carbon tax

In an FT article Tim Hartford nicely captured the beauty of a carbon tax. He begins by pointing out how difficult it would be for consumers to voluntarily reduce emission.

"How bad is red wine? How bad is an iPhone? Collectively we make many billions of decisions every day about what to buy, how to travel and where to set the thermostat". We can't be expected to calculate the carbon footprint associated with everything we do. "The brilliance of a carbon tax is that we would not have to. The price of everything we buy is tied to the cost of resources required to make and deliver it. If something requires acres of land, tonnes of raw materials, megawatt-hours of energy and days of skilled labour, you can bet that it won't come cheap. The link between price and cost is fuzzy but real. Yet carbon emissions have not been reflected in that cost. A carbon tax changes that by making the climate impact as real a cost as any other. It sends a signal along all those supply chains, nudging every decision towards the lower-carbon alternative. A shopper may decide that a carbon-taxed T-shirt is too costly, but meanwhile the textile factory is looking to save on electricity, while the electricity supplier is switching to solar. Every part of the value chain becomes greener…From frugal shopping to efficient logistics to renewable sources of electricity, carbon taxes gently steer us towards the greener solution every time, whether we are racked with guilt or blithely unconcerned. They should be at the centre of our fight against climate change" (Harford, 2021).

4.3 Carbon markets

Emissions trading has evolved from a textbook idea Dales (1968) to a major instrument in pollution control. Economists view emissions trading systems and carbon taxes as essentially equally effective ways of mitigating emissions. While carbon taxes explicitly set a price or tax on emissions, emissions trading systems issue permits that allow the holder of the permit to emit a specified amount, e.g., in the EU ETS one emission allowance (permit) corresponds to one ton of carbon dioxide or an equivalent amount of another greenhouse gas covered by the system. These emissions allowances can be traded among entities. The total number of allowances available (the cap) is set by the authorities and these can be purchased at auctions or in a secondary market. The price of permits is determined by supply and demand.

Since greenhouse gas emissions have the same impact irrespective of the location or nature of the activity, the ideal would be to have a single global carbon price. This could either be a carbon tax that would rise through time until we reach zero emissions, as the cost of use fossil fuels becomes prohibitive, or it could be global carbon allowances with a cap that would fall over time until no more emissions are made available. A global carbon price would ensure that no country or economic activity is put at a disadvantage relative to others and would avoid carbon leakage, where entities emitting greenhouse gases shift their activities and emissions to jurisdictions with weaker regulations.

There have been lengthy debates about the relative merits of carbon taxes versus emissions trading systems. These debates have often been portrayed as one between supporters of government intervention demanding taxes versus supporters of the market that believe that an extension of markets (through allowances) to the polluting activities will solve the problem without government intervention. This debate draws on Coase's (1960) famous critique of Pigou (1920) who first recommended the use of taxes to correct market failures in the presence of negative externalities. Though there are differences between the two instruments it doesn't have to do with the extent of government intervention. Both a carbon tax and an emissions trading system require critical government design and oversight, and depending on the design of carbon taxes or emissions trading systems they can amount to the same thing (Stavins, 2022).

Most economists believe that some form of carbon price should be a central plank of mitigation policy (FT editorial board, 2024). Despite this broad and long-standing consensus carbon prices are underused and when they are implemented the carbon price or tax is generally too low to have the needed mitigation impact. According to the World Bank (2024) annual report on carbon prices, there are 75 carbon taxes and emissions trading schemes in operation worldwide. Carbon pricing instruments cover around 24% of global emissions and price levels are lower than that needed to achieve the Paris agreement goals. In 2023, carbon pricing revenues exceeded 100 billion for the first time and come mostly from ETSs. Still the contributions of these revenues to national budgets remains low.

To be on track to limit temperature below 2°C, the High-Level Commission on Carbon Prices concluded that carbon prices needed to be USD 40-80/ton of carbon dioxide equivalent (tCO_2e) in 2020 and rise to USD 50-100/tCO_2e in 2030 (Stiglitz et al., 2017).

4.4 Social Cost of Carbon and the right level of carbon prices

Despite the strong consensus among economists for the need of a carbon price there has been some disagreement about the right level of such a price. This difference is directly related to the issue of how aggressive climate action should be. A key feature of the DICE model (and other IAMs) is something called the "social cost of carbon" or SCC. This is a monetary measure of the cost of an additional ton of CO_2 calculated by summing up all the future damages it causes (and discounting these to their present value). This is like saying, if I were to emit one ton of CO_2 today how much money would I need to set aside to pay for cumulative global damages I cause.[5] The social cost of carbon rises over time reflecting several reasons. For instance, additional emissions exacerbate cumulative concentrations which lead to greater damages. As economies and populations grow more damage can be done by physical climate impacts, damage will also be greater over time as ecosystems that currently act as carbon sinks are expected to become less effective. When the DICE model calculates the optimal emission path it also finds the optimal social cost of carbon. Along an optimal path for the economy the marginal damage caused by one ton of CO_2 will be equal to the marginal benefit of being able to emit an additional ton. This optimal social cost of carbon would also be the appropriate carbon price that emitters would need to pay to ensure that only optimal emissions take place at any given moment.

By setting a carbon price equal to this optimal marginal damage the regulators ensure that only optimal emissions will take place. In this respect many IAMs are used to help policy makers determine the right level of mitigation. If mitigation involves the imposition of a carbon tax, then the SCC might be recommended as the right level of such a tax. Alternatively, an emissions trading system would be seen as effective if the price of allowances aligns with the social cost of carbon.

In DICE2023 the optimal social cost of carbon in 2020 is \$50/tCO_2 and rises to \$125/tCO_2 in 2050. Barrage & Nordhaus (2024) also show that the price would have to be much higher to achieve a global average temperature below 2 °C. In 2020 the social cost of carbon would be \$75/tCO_2 and rises to \$213/tCO_2 in 2050. To give some perspective a \$75/tCO_2 would amount to roughly €0.16 per liter of petrol. The price of gasoline in Germany is about €1.74. This gives a sense of the impact such a carbon price would have on drivers. It would amount to about a 10% rise. Finally, they also state that global carbon price that reflects current policies in the world are \$6/tCO_2.

[5] See Carleton & Greenstone (2022) for a nice presentation of the role of the social cost of carbon and it's use in the United States. Stern & Stiglitz (2021) challenge the standard approach to assessing the social cost of carbon and suggest an alternative.

The point here is to observe that while economists influenced by some climate-economy models have generally recommended less aggressive climate action than would be needed to achieve the Paris Agreement goals, they have long espoused the use of a carbon price or tax that is far greater than most carbon taxes implemented to date. There is broad consensus among economists that the world should be implementing a much higher carbon price or tax than we find in most jurisdictions. The European Union has implemented one of the most comprehensive carbon pricing mechanisms globally, covering a wide array of sectors, and is therefore close to the ideal supported by economists.

4.5 The European Union Emissions Trading System

The European Union Emissions Trading System is the oldest and largest of all the emissions trading systems in operation around the world. Under the system a cap is set on the total greenhouse gases that can be emitted in each time period. This cap is reduced annually to align with the EU climate target. The EU ETS was launched in 2005 and operates in phases. Phase 1 (2005-2007) was the pilot phase that covered only carbon dioxide emissions and focused on large emitters from energy-intensive industries including power plants, oil refineries and cement factories. A cap was set on emissions, and the initial allowances were mostly allocated for free based on historical emissions. Over-allocation of allowances along with lack of robust monitoring and verification mechanisms led to a collapse of carbon prices by the end of the phase. While subsequent phases of the EU ETS addressed some of the issues new challenges appeared. The financial crisis of 2008 reduced industrial activity and emissions and thus the demand for allowances. Other policies that also led to reduced emissions, like renewable energy and energy efficiency policies further reduced the demand for allowances. In addition, surpluses of allowances from earlier phases continued to suppress carbon prices.

In the present Phase 4 of the EU ETS (2021-2030) several innovations have strengthened the system. A larger proportion of allowances are auctioned than distributed for free. The overall emissions cap is reduced annually by 2.2%, up from 1.7% in Phase 3. The Market Stability Reserve (MSR) introduced in Phase 3 to prevent the collapse of carbon prices (and offer greater stability) by withdrawing allowances when there is an oversupply has been made more effective. These and other reforms have led to a significant increase in the carbon price which had been lower than €20 euros per metric ton of carbon dioxide equivalent (CO_2e) between 2007 and 2020 and since 2022 has mostly fluctuated between €60 and €100 euros. Besides a strengthening of of the system, the Fit for 55 package of reforms and new legislation has extended the ETS to cover maritime transport and a new, separate ETS 2 has been introduced for buildings and road transport emissions, and waste incineration is likely to be added in the near future. In this sense, the EU comes closest to following the prescription of economists on the use of a broad-based carbon price and in terms of the stringency or level of carbon price.

5. Beyond carbon pricing

Despite the merits of carbon pricing, it has been more the exception than the rule when it comes to implementation of climate policies. For several reasons, carbon taxes and emissions trading have been resisted strenuously by industry relative to other regulatory measures, particularly when compared to measures like direct subsidies for clean technologies or voluntary standards. One strength of carbon prices is that they are very transparent and thus not prone to capture from influence groups relative to detailed and opaque regulations (Helm, 2010; Sunstein, 2005). However, this strength is also a weakness when it comes to public perception. The very visibility of carbon prices makes an easy target. The use of carbon prices is also unpopular to the broader public as illustrated by the gilets jaunts (yellow vests) in France when Macron attempted to impose a carbon tax. They are perceived as regressive though appropriately designed they are not. Instead, people seem to prefer non price policies like green infrastructure programs, bans on polluting cars in city centers, subsidies for green technologies, etc. (Dechezlepretre et al. 2022; Ewald et al. 2022), even though these are likely to impose substantially greater costs.

Traditionally, regulatory approaches in the form of command-and-control climate policies have been the norm. These include such measures as emission limits for specific industries or facilities, mandates for technology standards, fuel economy standards, renewable energy mandates, building codes and outright bans on coal or internal combustion vehicles by a certain date. Economists have usually favored the broad use of a single carbon price to a possible patchwork of different non flexible standards across regions and sectors. The primary reason being the cost effectiveness of a carbon price, i.e., that it will achieve the greatest reduction in emissions at the least cost to society. Subsidies for insulation or boilers may be popular measures since their cost is not seen by those receiving the support though they may be a far more expensive way of reducing emissions. Early support for renewables reached a cost of over €1000 per ton of CO_2 emissions saved but this cost is not apparent to the voter who ends up paying it through other taxes (Blanchard et al., 2023).[6]

For all the elegance and advantages of carbon pricing it is very hard to envisage a global carbon mechanism or market, though efforts at harmonizing carbon prices among countries and regions are likely to increase. In some sectors like shipping and aviation with separate global governance institutions we are more likely to see the implementation of global carbon prices. But even if carbon prices could be implemented as envisaged by economists, and though they still should be the main

[6] It should be noted however, that such support while expensive at the time helped the development of a new renewables industry that eventually through learning by doing and scale brought about dramatic reductions in costs of clean technologies. The failure of the market to account for the positive externalities of research and development and the impact of the scale of activity on costs is different from the negative externality related directly to greenhouse gas emissions.

mitigation policy, there remain important reasons for pursuing additional complementary climate policies including such command-and-control instruments like industry standards, bans on internal combustion cars after a certain date, and targeted adoption incentives for clean energy and energy efficient products.

Both markets and governments are a far cry from the ideal systems envisage in most economic models. Indeed, this has been another reason why many climate-economy models have been criticized as they tended to treat the economy like an ideal market. There are many market and government failures that are highly relevant to climate change beyond the greenhouse externality (or the fact that the atmosphere has been an open resource for our emissions) that is seen as the primary cause of market failure. Putting a price on carbon addresses this key market failure but does not address other failures of the market that can strongly impact the transition to a low carbon economy.

Firms are unable to fully appropriate gains from their research and development in clean energy or other mitigation technologies. On their own they will lack the required incentives to advance our knowledge in this area. Even with a carbon price the market system will fall short of inducing the kind of technological change needed. Governments need to step in and support such research and development through tax incentives, direct funding of demonstration and deployment and publicly funded research. Capital markets are also imperfect making it difficult for firms and individuals to access capital even for privately profitable climate mitigation investments. For instance, a startup develops a new mitigation technology, but potential investors lack the knowledge to assess its profitability and demand higher returns to offset perceived risks. Institutional investors prioritize projects with quick paybacks over energy efficient infrastructure which may involve a longer payback period. A landlord is reluctant to invest in energy-efficient appliances for a rental property because tenants pay the utility bills. These market imperfections highlight the need for targeted policies and interventions such as green bonds, risk-sharing mechanisms, public subsidies, and regulatory reforms to address capital market failures and unlock profitable climate mitigation investments.

When it comes to addressing failures in the market system economic analysis of potential corrective measures typically assume that most of the market system is functioning well and piecemeal interventions in specific markets can provide the remedy, like imposing stricter regulations on a monopoly or limiting the amount of fishing that can take place to prevent overfishing. Any effort to effectively mitigate greenhouse gases requires broad based system changes across sectors and across economies, like how we produce and consume energy, how we build are cities, how our transport system works, how we direct technological change, how we produce food, and how our trade and finance systems work. An important aspect of the energy transition is the broad-based network and system changes needed that cannot be achieved by a single carbon price (Stern et al., 2022).

However high a carbon tax on fuel consumers will continue to purchase internal combustion cars if electric vehicles remain expensive, if there are not enough stations for recharging, or there isn't infrastructure for charging where people park their cars, or they can't service their cars or find parts easily. However cheap solar energy has become, and however their adoption is further incentivized by a carbon tax, without expansion in electricity distribution networks, their adoption is constrained. Support for renewables must go hand in hand with appropriate infrastructure development, like improved and extended distribution networks that go beyond borders. A carbon price may induce shipping companies to invest in energy efficiency measures, but without support for research in new zero carbon fuels like ammonia, hydrogen or carbon capture technologies, the available zero emissions technologies will simply not exist. Coordinated efforts will also be required throughout the shipping industry to ensure that ports have the facilities to support new energy forms, companies producing new clean fuels will need to reach a scale to provide for the industry, insurance companies will cover new safety issues associated with new fuels, ultimately the design of new ships will depend on the low carbon fuel that is best suited for the energy transition. For these complex networks of stakeholders to move at the pace required and in coordination so that infrastructure development is aligned with the market, new forms of regulation and governance are required.

Other policies are needed also to ensure appropriate compensation of those that bare the greatest brunt of the energy transition both for reasons of equality and justice but also for legitimizing climate action. In the case of a carbon tax or emission trading this must ensure that the most vulnerable receive a check from the revenues that will protect them from the higher costs but incentivize them to switch to cleaner energy options. In addition, there are important policies to ensure that a country that takes climate action protects its industry from potential loss in competition as well as avoiding carbon leakage. The EU's Carbon Border Adjustment Mechanism (CABM) is such a measure. It requires importers in the EU to purchase carbon certificates equivalent to the carbon price that would have been paid if the goods had been produced under the EU's Emissions Trading System (ETS). This applies to goods from countries that do not have comparable carbon pricing mechanisms or regulations in place. The cost is calculated based on the carbon footprint of the imported product. This not only protects EU industry form competition and carbon leakage it also incentivizes trading partners to take more action in reducing their emissions.

While economists have generally preferred flexible instruments like carbon pricing they increasingly recognize the need for many more complementary policies for effective climate action. This more holistic approach is needed given the special challenges associated with climate change in terms of the unprecedented breadth and pace of the system transition needed. The economics of climate change has been evolving from a focus on a single instrument like carbon prices to considering how a broader set of policies need to be implemented in a coordinated fashion. In addition, new roles are being envisaged for key economic actors. Governments have been considering new forms of green fiscal policy to help economies out of recession while boosting clean energy infrastructure. Policies are being advanced to make economies more circular so that waste products of one firm are used as inputs by another ensuring lower extraction and use of raw materials, energy saving and lower emissions. Central banks and the finance sector are developing new tools to strengthen financial flows toward the green transition while avoiding risks to the financial system from stranded assets in companies that are over invested in fossil fuels and their products. The very nature of the firm as seeking profits with disregard to broader stakeholder interests is put into question. New accounting and due diligence rules, like the EU Corporate Sustainable Reporting Directive and the Corporate Due Diligence Directive, are being implemented to ensure that companies are disclosing their climate impact and are bound to achieve reductions in greenhouse gases in line with the Paris Agreement. These developments are both the outcome of climate economics and are reshaping the way economists are thinking about the climate-economy nexus. The EU Green Deal, the Climate Law and Fit for 55 are both a product of this more holistic approach and a challenge to climate economics to strengthen its theory of broad-based systems transformations.

6. Conclusion

Economists are increasingly recognizing this broad new governance mandate. Their analytical tools have been shaped under the premise that the system generally works well and small-scale failures can be brought in line with highly targeted measures. They have not been trained to think in terms of whole systems change. This is a challenge that they are increasingly coming to grips with and are thinking about how a whole suite of measures that can work effectively together or avoid working at cross purposes (Meckling & Allan, 2020; Blanchard et al., 2023).

The fundamental questions that have defined climate economics remain pertinent here. Why do market systems fail to protect us from climate change? As we deepen our understanding of the many failures of markets, governments and institutions, we are in a better position to determine the best path to net zero as well as the forms and combinations of policies required to achieve this goal. The economics of climate change have been evolving. The first climate-economy models have come a long way in incorporating new research and taking on board criticisms of their underlying assumptions. As such their results come much closer to the broader scientific consensus on the need to meet the Paris Agreement goals. This is important because of the influence of the economic profession in policy circles and the broader public. There remain important reservations on the usefulness of these models in addressing certain issues, like the optimal path of decarbonization. An alternative approach given the deep uncertainty is to take a precautionary or guardrail approach that suggests we do all we can to avoid playing dice with our future. Climate policy is not about acting optimally in the face of the most likely physical impacts, it is insurance against potentially catastrophic impacts that remain a real possibility.

Carbon pricing remains the first tool of choice for most economists and broad agreement exists about the need for much more stringent carbon pricing. Had politicians taken the advice of most economists that were calling for the implementation of carbon prices from the 1980s we would be at a much better place now. Why such instruments have proven so hard to implement is an important political economy question (Papandreou, 2016a; Papandreou, 2016b). Carbon prices today are not enough to bring about the necessary energy transition. Increasingly, climate economics is addressing the challenge of a whole system approach envisaging the use of multiple instruments and reappraising the roles of government, the private sector, civil society and individual behavior. This paper has focused on just a few of the central themes of climate economics and how these have evolved.

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