NBER WORKING PAPER SERIES

THE SOCIAL COST OF CARBON, RISK, DISTRIBUTION, MARKET FAILURES: AN ALTERNATIVE APPROACH

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Working Paper 28472
http://www.nber.org/papers/w28472

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
February 2021

Nicholas Stern acknowledges support from the Grantham Research Institute on Climate Change and the Environment, at the London School of Economics, and the ESRC Centre for Climate Change Economics and Policy (CCCEP) (ref. ES/R009708/1). Joseph Stiglitz acknowledges support from the Institute for New Economic Thinking (INET). The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

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JEL No. H0,Q0

ABSTRACT

Designing policy for climate change requires analyses which integrate the interrelationship between the economy and environment, including: the immense risks and impacts on distribution across and within generations; the many failures, limitations or absences of key markets; and the limitations on government, both in offsetting these failures and distributional impacts. Much of the standard economic modelling, including Integrated Assessment Models, does not embody key aspects of these essentials. We identify fundamental flaws in both the descriptive and normative methodologies commonly used to assess climate policy, showing systematic biases, with costs of climate action overestimated and benefits underestimated. We provide an alternative methodology by which the social cost of carbon may be calculated, one which embraces the essential elements we have identified.

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1. Introduction

In one of his first acts in office, on January 20, President Biden issued an executive order establishing an Interagency Working Group on the Social Cost of Greenhouse Gases (usually referred to as the social cost of carbon, SCC). The idea is simple: if we can identify the SCC[2], then in evaluating public projects or regulations, we incorporate this "price" in assessing actions involving the reduction in carbon emissions. If the price (SCC) is high, there are many things we will want to do to reduce emissions, but far fewer if it is low. The SCC makes sure that we don't do anything foolishly expensive. On the other hand, if the SCC is set too low, there are many regulations and/or projects that won't be undertaken—the value of carbon reduction simply isn't worth the cost; but that means the level of carbon emissions, and climate change, will be greater than it otherwise would have been. In addition to its use as a shadow price in government cost-benefit analysis, SCCs can be used as internal prices by private firms and, where possible, as a carbon tax, acting as a market price. It is accordingly extraordinarily important that the SCC be calculated correctly.

There are broadly two ways to do this. One is to look at the future damage from emitting an extra unit of carbon and the other is to look at the prices that could guide the economy towards trajectories limiting the increase in temperature to 1.5 to 2 degrees C., the accepted target of the international community, including the Paris Agreement which President Biden has led the US to rejoin (Stern and Stiglitz, 2017). If our models modelled everything appropriately—both the behavior of the economy and the social costs associated

[1] London School of Economics and Columbia University. This paper is largely based on a joint paper, "The economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change," Grantham Institute, February, 2021.
With special thanks to Charlotte Taylor for outstanding research support. With thanks to Tim Besley, Amar Bhattacharya, Simon Dietz, Geoff Heal, Cameron Hepburn, Haaris Mateen, Sanjay Reddy, James Rising, James Rydge and Bob Ward for valuable discussion.
Nicholas Stern acknowledges support from the Grantham Research Institute on Climate Change and the Environment, at the London School of Economics, and the ESRC Centre for Climate Change Economics and Policy (CCCEP) (ref. ES/R009708/1). Joseph Stiglitz acknowledges support from the Institute for New Economic Thinking (INET).

[2] The SCC we refer to throughout this paper is the marginal cost.

with climate change, including the enormous risks which it imposes—then, under some conditions, there would be a presumption that the two prices would be the same. But in practice the use of the estimates from standard Integrated Assessment Models (IAMs), focused on marginal damages from climate change, has resulted in estimates of the SCC that are markedly lower than the prices required to guide the economy towards trajectories in which climate change is limited to 1.5 to 2 degrees C.[3] With the Biden Administration moving forward to re-join the Paris Agreement and a commitment to 1.5 degrees Celsius, adopting the Obama era SCC is setting the stage for an intellectual and policy collision: those low carbon prices will not support the required policy measures. The disjunction has been clear for a long time: using standard IAMs, with their choice of calibration, has led some prominent economists to conclude that "societal optimization" entails accepting an increase in temperature of around 4 degrees Celsius (Nordhaus, 2018), an increase seen as catastrophic by many, especially climate scientists. Conceptually, now that a target has been adopted by the Biden administration, the appropriate notion of the carbon price is one that would guide decisions to achieve the target. Nevertheless, an understanding of the estimation of marginal social damages remains of importance and thus methodologies for how it is done are of real significance.

The world has not seen 3 degrees Celsius for around 3 million years, at a time when sea-levels were 10-20 meters higher than now (Dumitru et al., 2019). We are already seeing devastating effects from fires, storms and droughts from the 1 degree we are experiencing now. The IPCC 2018 Special Report showed that risks for 2 degrees were far higher than 1.5 degrees Celsius (IPCC, 2018). The risks of 4 and 5 degrees Celsius, which are possible in 100 years or so if we fail to act, would carry serious risk of far more devastating effects. IPCC reports, starting in 1990, have indicated that the potential risks are ever larger as the evidence builds still more strongly. This is not the place for a detailed study of the risks indicated by the science[4]; but it is clear that climate change involves the management of

[3] For instance, the Interagency Working Group in the Obama Administration, focusing on a 3% discount rate, suggested a SCC for 2030 of around $50 (2007$), while the Stern-Stiglitz Commission (Stern et al., 2017) reached a consensus that a price of around $100 would be required to achieve the Paris goals. The range of prices suggested in that report was, for 2030, $50-100 per ton. But since then ambitions have been strengthened (with targets at 1.5 degrees C rather than "well below 2"), and net-zero emissions by 2050, and emissions have gone on rising. Thus we suggest that the top of that range would be relevant.
[4] For a discussion of these risks see DeFries et al. (2019).

risks of enormous magnitude and multiple dimensions, which could destroy lives and livelihoods across the world, displace billions, and lead to widespread, prolonged, and severe conflict.

In determining the pace and magnitude of climate change, tipping points such as the thawing of the permafrost and the release of methane, the collapse of the Amazon Rainforest, or the melting of the West Antarctica ice sheets, will play a large role. Such phenomena could unleash unstable processes, greatly accelerating the possibility and magnitude of devastation. The fact that we don't fully understand the highly non-linear processes associated with these tipping points—including the extent of climate change which will trigger them—is just one aspect of the uncertainties associated with climate change.

The idea of integrating economics and the environment makes eminent sense, but the devil is in the details. The fact that the overwhelming consensus in the international community, including the scientific community, differs so markedly from the results of the IAMs raises a key question: is it sloppy thinking, perhaps an excess of compassion for the species that may be extinguished as climate change proceeds apace to the 3.5 to 4 degree "recommended" by the IAMs, that has led the international community to irrationally embrace a goal involving excessive costs from the perspective of a hard-headed analysis of society welfare maximization; or is it that the IAMs have left something—or many things—out of their analysis? Or is their whole conceptual apparatus so deeply flawed as to give us little guidance either for the calculation of SCC or the level of climate change that should be acceptable? The objective of this paper is to answer that question, and in doing so, to formulate another approach, which better reflects the risks, the distributive effects, and the market failures that are integral to the analysis of climate change.

1.1 Making policy when key markets are absent or imperfect

Changing the structure of an economy will involve a host of private-sector decisions, including on investment and innovation, in the context of markets. Government policy will shape those decisions. In a world where the emission of GHGs were the only market failure then basic Pigouvian theory would indicate that we could achieve optimality with a tax equal to the marginal damage associated with the externality. [5]

But the world is not like that. There are multiple crucial market failures beyond that of the GHG externality which are highly relevant. That this is so has multiple implications. For instance, optimal interventions will likely involve additional tools to that of a corrective tax; regulations, with quantity constraints, may be superior. [6]

Decisions on investment and innovation look to the future and a full set of future markets for all relevant goods and services in the future does not exist. This is important because then expectations about the future become very important to investment and innovation and these expectations are influenced by many things, including the stability and functioning of institutional structures and the credibility of government commitments. Similar issues of commitments and credibility relate to regulatory and legal structures.

Other failures of fundamental importance are associated with: (i) R&D and innovation; (ii) capital markets; (iii) networks (including grid structures, public transport, broadband, recycling) in which there is extensive need for coordination, in which prices play only a limited role in that coordination, and in which a variety of externalities arise; (iv) information (including around new products, carbon content of products); (v) co-benefits (including air, water and soil pollution).

The standard methodological approaches in the economics of climate change have, in large measure, ignored these further market failures, as they focused on the GHG externality. That is indeed at the heart of the story but a methodology that does not take into account the multiple market failures may give a grossly distorted view of appropriate climate policy, as the theory of the second best has long warned.

[5] The standard form such intervention takes is a "corrective" tax, ensuring that social costs and benefits are aligned with marginal private costs and benefits (e.g. Sandmo, 1975).

[6] A large literature focusing on imperfect information, incomplete markets, and limited redistributive tools has shown that interventions beyond simple corrective taxes are desirable (see, e.g. Atkinson and Stiglitz, 1976; Stiglitz, 2018; Weitzman, 1974). The relevance of these concerns in the context of climate change has been emphasised by Stern (2007, 2015) and Stiglitz (2019).

1.2 Values and distribution

Climate change raises deep issues of values (how we treat future generations relative to the current) and distribution which must be at the center of any discussion of action. Climate change has, of course, profound impacts across generations.

Unfortunately, much of the literature has suppressed these difficult issues as well as those posed by differential effects at a moment of time, including by dealing with models with a single representative agent (or one for a very large region). In other cases, the issue has been "dealt with" by supposing that values can be read off from markets, for example, via interest rates—using these to interpret the value to be placed on future generations; that is simply a methodological mistake. What information is conveyed by interest rates depends on market imperfections; but in any case, capital markets do not represent moral valuations across individuals.

Any realistic assessment of the "social cost of carbon" has to embrace the possibility of an equalitarian risk averse social welfare function, which, even if it is individualistic, recognizes that agents are themselves risk averse. Thus, ineffective action on climate could generate climates so hostile that future generations would be much worse off than that of today; the expected marginal social utility associated with expenditures today which reduce the risks that these future generations face can be very high.

Climate change has very unequal impacts: it is usually the poorest people who are hit earliest and hardest; they live in more vulnerable areas, are less-well insured, and have weaker coping mechanisms. Those least responsible for emissions are among those most adversely affected. Moreover, using any equalitarian social welfare function would put greater weight on the adverse effects that they experience. (There are also large inequalities in climate impacts within a generation, differing for instance across age, gender, and location, as well as income; these can have large economic, social, and political effects, which policy might want to take into account.) Further, it cannot be assumed that governments can carry out perfect redistribution programmes so that "equity issues" can be dealt with "somewhere else" in the system.[7]

Moreover, unmanaged climate change could cause loss of life and biodiversity, possibly on a massive scale, and a worsening of health. That forces us to face difficult problem in evaluation of alternative policies.

1.3 Plan of the paper and main conclusions

The challenges we have described in integrating the science and the economics make it clear that we must have economic analyses whose methodologies:

(i) Take account of extreme risk, including possible large-scale and many unforeseeable consequences, whose nature may be difficult to describe and where it may be difficult or impossible to define, in any meaningful sense, probabilities.

(ii) Recognize that many key markets, in which the decisions of firms and individuals will be vital for implementing any strategy for action, have critically important failures; crucial markets may even be absent. It is a fundamental mistake to begin the analysis of climate change under the premise that, but for the mispricing of emissions, the economy is efficient. And there are limits on the ability of government to "correct" these market failures.

(iii) Can embody rapid technical and systemic change, often exhibiting increasing returns to scale, and corresponding rapid changes in (endogenously determined) beliefs and preferences, placing pace, dislocation, and disequilibrium at center stage.

(iv) Take into account differences: in impacts across individuals, both at a moment of time and over time, and limitations in the instruments to limit those impacts—including offsetting the potentially large distributive effects—both within a country and on a global scale; and in preferences and judgements on climate uncertainties and on economic interactions. Assessment of differential impacts requires value judgements, and these require explicit analysis and discussion.

[7] To put it differently, it cannot be assumed that the second welfare theorem holds.

There are two parts to an analytic framework for assessing alternatives: descriptive and normative. The former analyzes the relationships between *actions* and *consequences.* Any substantive framework has to integrate economics and environmental science. The *descriptive* analysis examines the co-evolution of the economy and the climate in a "business-as-usual" scenario, and the consequences of any change in policy. By contrast, Section 4's normative framework asks: understanding, as best we can, the consequences of alternatives, what is the appropriate way for society to *decide*?

The underlying positive theory is the subject matter of the next two sections. Section 2 outlines the standard model and provides a broad critique, while the implications of the deep uncertainties are explored in section 3. Methods for approaching normative and policy issues which follow from sections 2 and 3 are discussed in section 4.

Section 5 argues that much of the standard economic modelling, including IAMs, does not embody these basic methodological essentials described in sections 1 to 4, which are crucial for any economics of climate change. Methods and models failing to do so do not provide a good description of the effects of any policy; and models based on maximizing utility of a representative individual are likely to be less helpful than alternative approaches—including that actually being employed now, entailing setting a consensus target (say 1.5 or 2 degrees Celsius) accompanied by an analysis of the merits of different paths to achieving that target. Our analysis suggests that the IAM methodology and common model choices may result in systematic bias, downplaying the importance of strong action on climate change and underestimating the social cost of carbon. Many of the modelling deficiencies we describe result in underestimation of underestimation of the social cost of carbon. But we also describe modelling deficiencies that result in overestimation of the costs of climate action. While we will emphasize the former throughout this paper, we also highlight examples of the latter. Section 6 outlines an alternative approach.

2. The descriptive and analytical framework for economics

A descriptive analysis of how markets work provides the foundation for assessments of what government intervention is desirable for climate change. And central to that is an understanding of "market" failures—apart from those associated with the environment--and the limits of government policy in correcting them and redistributing income.

In a world where individuals fully understood the consequences of their actions, where they were fully altruistic, took fully into account how their actions might harm others, and had full access to all the relevant information and options, no public intervention would be required. But this is not the world we live in.

Early dynamic economic models did not take into account interactions between the economy and the environment. That deficiency was remedied by a host of scholars, especially in the 1970s. But it was not until twenty years later that IAMs, integrating economic activity and climate change, were developed (Cline, 1992; Nordhaus, 1991a, b).

These early attempts were built upon a class of earlier intertemporal models which, even at that time, had been shown to be flawed in describing economic dynamics and of limited value in providing policy guidance. In these models, the economy was described *as if* there were a representative agent maximizing intertemporal utility (Ramsey, 1928). Of course, all models are a partial representation of reality. But the assumptions underlying the IAMs meant they led to biased judgments: suggesting too little and too circumscribed action and an acceptance of too much climate change, as we shall see. (In section 1, we have already noted one major difference: one does not necessarily want to rely just on a price intervention.)

There are several central analytical failures upon which this paper focuses, including: a host of ***market failures*** (including how risks are handled and large structural changes are managed) which mark the economy; the treatment ***of uncertainty***; and of ***distribution***, of both income and other dimensions. For instance, the absence of a full set of Arrow-Debreu markets, pricing risk and the future, means that there are not prices to guide and coordinate investments. Under highly idealized conditions of a representative agent in the context of stationary probability distributions, with rational agents forming rational expectations so there is common knowledge, it might seem as if the economy could do without a full set of markets. But climate change is an instance where the stochastic processes describing the evolution of the economy are far from stationary, and there is ample evidence of the lack of common knowledge. In that case, the consequences of the absence of these markets can be particularly severe.[8] Moreover, the "rational actor" model underlying standard economic analysis does not provide a good description of human behavior, and especially so when it comes to intertemporal behavior and behavior in the presence of uncertainty—two of the key elements of climate change.

There is a more fundamental problem with the approach taken by IAMs: the market equilibrium is that generated (as in the standard Ramsey-Koopmans analysis) by an intertemporal maximization problem solved by the representative individual, and that is precisely the same maximand confronting society as it calculates the social cost of carbon and delineates the optimal growth/climate change trajectory. We explain why that is not the case, and why assuming that it is also leads to too low a social cost of carbon/too little climate action relative to what would be generated by a more plausible social maximand.

This section is divided into 6 further parts. In 2.1, we set out the "standard model", *assuming no other market failures, no risk, and, with its single representative agent, no concerns about distribution.* 2.2 examines the relation between the climate market failure and other market failures. In 2.3 we turn to innovation, in 2.4 to the broader market failures associated with structural transformation, and in 2.5 to the dislocations and associated distributive effects to which such transformations gives rise. Section 2.6 discusses some of the implications of endogenous preferences.

2.1 The standard model

The standard model describes society *as if* there were an infinitely-lived representative agent maximizing intertemporal utility, subject to resource constraints, with dynamic equations describing the co-evolution of capital accumulation and the economy. Intertemporal welfare is described by a time-separable utility function; here we simplify by assuming a single aggregate consumption variable, C, and an environmental variable E.

[8] Even with rational expectations, the equilibrium will not be Pareto efficient (Newbery and Stiglitz, 1982). In the absence of common knowledge, the market may experience high levels of volatility, as individuals engage in bets with each other based on their different perceptions. For a broader discussion of macroeconomic dysfunctions that arise in the absence of a full set of risk and futures markets, see Guzman and Stiglitz (2020).

(1) $W \equiv \int U(C, E)\, e^{-\delta t} dt$.

where δ is the pure rate of time preference, measuring the extent to which *utility* in future years is weighed less than utility today.

The individual maximizes W subject to resource constraints and taking E(t) as given[9]:

(2) $Q = F(K, E) = C + I + e$

where I is investment and e is expenditure on carbon mitigation. In the most simplified version of the model, E, the environment, is simply the level of atmospheric concentration of greenhouse gases.

The evolution of E and K are described by

(3) $dE/dt = \psi\ (F(K(t), E(t)),e)$,

and

(4) $dK/dt = I - \mu K$

where μ is the rate of depreciation of capital. (3) implies that the increase in greenhouse gas concentrations (measured by E) is a function of output and effort at emissions abatement, e. [10]

Since the environment is a (global) public good, in the absence of carbon pricing or regulations, individual would set e at 0. This, together with the a transversality condition, defines the trajectory "business as usual."

By contrast, the optimal trajectory is that where e(t) is set to maximize social welfare, defined as the same maximand (1) as above. This is a crucial methodological assumption. If it is to be achieved via individual choice then private and social objectives, incentives and

[9] A more general formulation would have C + I = F(K, E, e), and a still more general formulation would be based on different production functions and abatement functions in different sectors. Empirical applications of these models typically embrace such generalisations. The purpose of this paper is to uncover the underlying logic of the models and the limitations in the overall approach.

[10] More generally, the change in concentration could be a function of the composition of output and sectoral efforts at abatement. Long-run and more detailed models would take into account other determinants of atmospheric greenhouse gas concentrations.

understanding of the way the world functions must be aligned. We argue below that it is far more plausible that (a) individuals maximize an objective that is distinctively different from that which society maximizes, or which a policymaker contemplates in considering alternative policies; and (b) the constraints facing an individual may be markedly different from those facing government, so that even if the unconstrained maximands were the same, the constrained maximands differ.

Key for public decisions on activities and for aligning private incentives, is determining the appropriate price of carbon. The marginal social cost of carbon (MSC) describes how much we are willing to pay today to improve the environment. The MSC, measured in today's dollars, is

$$\text{MSC} = \frac{\partial W}{\partial E} \Big/ U'(C_0) \qquad (5)$$

Setting the marginal cost of abatement (the cost of reducing carbon) equal to the marginal social cost of carbon, and making such calculations along the whole optional time trajectory allows us to calculate the "optimal" carbon (and capital accumulation) trajectory.

Infinitely-lived individuals

It is obvious that individuals are not infinitely-lived. Advocates of the model have responded by saying each generation cares about the next, passing on to them inheritances, so that it is *as if* there were a single individual maximizing utility over an infinite lifetime. This, sometimes referred to as the *dynastic model*, has been well-studied, both theoretically[11] and empirically, and been rejected as a satisfactory representation of the

[11] For instance, in the stochastic frameworks with heterogeneous individuals, the dynastic model would imply that some families leave negative bequests. In most societies, negative bequests are not part of the economic and social arrangements. Recent macroeconomic models (the so-called HANK models) have shown quantitatively the importance of constraints in shifting income intertemporally by large fractions of the population.

economy.[12] A majority of individuals leave no (significant) bequests to their children[13], and not surprisingly changes in the economic environment which would, in the standard dynastic utility framework, lead to changes in bequests, do not (Wilhelm, 1996).

Optimal intertemporal redistribution

Alternatively, it is hypothesized that government engages in optimal intertemporal (intergenerational) redistributions, so that again (1) becomes the relevant maximand. But in this interpretation too the model is flawed: changes in the economic environment which would lead to changes in government behavior, do not.

In either case, there is a simple relationship between the marginal utility of consumption (income) at time t and t + 1 given by the Euler equation (in discrete time)

(6) $U'(C_t) = U'(C_{t+1})\,(1 + r)/(1 + \delta)$

where r is the rate of interest. The intertemporal discount rate (the proportional rate of fall of marginal utility) is related to the pure-time preference, but also to the rate of growth of consumption and the elasticity of marginal utility, η; it is δ plus η times the growth rate of consumption[14].

There is a simple empirical test of the relevance of (6): changes in the rate of increase in consumption (per capita) should be associated with a change in the short-term interest rate, r—the intertemporal price. A decrease in the rate of increase in C of Δg_c should lead to an increase in r by an amount $\eta\,\Delta g_c$, implying that as the rate of growth of consumption declined in the decades after the mid 70's, the short-term rate of interest would increase.

[12] There are many "tests" of the model. It provides strong predictions, for instance, about responses to increases in taxes or government debt, in savings and bequests. In each area, those predictions have been rejected. In this model, there is "Ricardian equivalence," i.e. decreases in taxes at date t have no effect, because individuals realize that there must be a corresponding and fully offsetting increase in taxes at a later date in order for the government's long-run budget constraint to be satisfied. There is evidence not only that tax decreases can have effects, but that how the funds are dispersed (either as a lump sum at the end of the tax year or with every pay check) matters. The former reflects the importance of credit constraints (Stiglitz, 1988); the latter insights from behavioural economics (see, e.g. Thaler, 1992).

[13] Hurd and Smith (2002); Wolff and Gittleman (2014).

[14] There have been various attempts to estimate η in the literature, using, e.g. saving behaviour of individuals, expected utility theory in relation to behaviour under uncertainty, and government transfer/ tax policy. The underlying assumptions vary and results are very sensitive to them (see, e.g. Drupp et al., 2018; Evans, 2005; Groom and Maddison, 2019; Lebègue, 2005; Stern, 1977).

In fact, real short-term interest rates have a low and slightly positive correlation with short-term interest rates.

Advocates of the model at this point turn to the multiplicity of interest rates—not just the short-term T-bill rate (the return on safe government bonds). But the model has within it no coherent explanation for the existence of this multiplicity. The multiplicity in fact is largely related to risk. If risk is important, as it obviously is, one needs to bring risk formally into the analysis; one cannot simply attach some ad hoc remarks in interpreting the model for the real world. Other reasons for the multiplicity of interest rates have to do with capital market imperfections, again a phenomenon that has been shown to be of first-order importance in understanding the dynamics of the economy, but left out of the standard model. The basic point here is that this simple model performs badly.

The overlapping generations model: an alternative framework

An alternative is an overlapping generations model, which has each generation maximizing its own well-being. In the absence of government intervention, as before, $e = 0$, and we can solve for the coevolution of the economy, described by a discrete-time version of (3) and (4).[15] [16]

The overlapping generations model has two key implications that differs markedly from the dynastic model*: there is no relationship between what the representative individual maximizes and the social maximand, and accordingly there is no relationship governing the marginal utilities of different generations corresponding to (6).* Only if government optimally redistributes income across generations according to some intertemporal social welfare function, such as

[15] A straightforward generalization allows for some concern for the welfare of one's descendants, reflected in the utility function, with the resulting inheritances and bequests reflected in budget constraints. Our critique of IAM models holds even if some individuals care to some extent about the well-being of their descendants. The maximand of the individual and that of society still differ, and (6) does not necessarily hold.

[16] While in the simplistic dynastic economy, there is a unique rational expectations dynamic path, in the life cycle model there can be an infinite number of paths consistent with rational expectations (Hirano and Stiglitz 2021). This makes both predicting the future ("business as usual") and assessing the effects of alternative policies particularly problematic. The economy can be trapped in a bad equilibrium, with a high level of pollution, from which it cannot easily emerge, without strong government intervention. Such possibilities are not even contemplated in the standard IAM.

$(7)\ W^* = \Sigma\ U_t/(1 + \delta),$

subject to the standard intertemporal societal resource constraints, would an equation analogous to (6) be satisfied.[17]

There is rightly considerable skepticism of this model of the “benevolent government” maximizing an intertemporal social welfare function of the form (7). The evidence presented earlier against the dynastic utility functions and Ricardian equivalence implies that the economy does not behave as described by such a model.

Recent research helps us understand what is going on: in a class of models in political economy, public actions are a result of the interactions of political forces.[18] Public policy analyses then seek to understand how information or changes in the rules of the economic/political game affect the political outcomes. The outcome of a particular proposed intervention, were it to be accepted, may be markedly different in such a political economy model than in one in which there is a benevolent dictator.

The absence of such a dictator in turn has marked implications for the calculation of the social cost of carbon. If one believes that there are optimal intertemporal redistributions, one would (incorrectly) infer that the observed interest rate reflects the (social) marginal rate of substitution over time.[19] But no such presumption exists if the current generation is not making adequate provision for the future. Because the representative agent model discounts impacts on future well-being at a higher rate, the social cost of carbon is lower.[20] Making such presumptions about future environmental benefits and risks (which is the whole objective of the IAM analyses) also entails assumptions about the substitutability of these with those of ordinary consumption goods. Only if there is perfect substitutability can

[17] Even with optimal intertemporal redistribution, if there are constraints on the costless redistribution of income within a generation (which there are) and if the allocation of capital affects the market distribution of income (which it does), then the posited relationship no longer holds (Stiglitz, 2018).

[18] For instance, a model of a “contestable” democracy attempts to analyze a two-party system with different preferences in a stochastic game (Korinek and Stiglitz, 2008; Persson and Svensson, 1989). The provision of information may affect the formation of coalitions, Stiglitz (1998)

[19] Even with optimal intervention, this interpretation is not warranted under the conditions of fn. 17.

[20] This is seen most dramatically in the limiting case with no technological progress. In that case, asymptotically in the overlapping generations model, there is no discounting if $\delta = 0$, but the market interest rate can still be very high. The dynastic model would assume that a high r *implies* that the representative individual does not care much about the future.

one used the goods' discount rate to evaluate future environmental effects. And with a lower social cost of carbon, optimal interventions are smaller, and the "optimal" long-run increase in temperature higher.

2.2 Interactions of the climate market failure with other market failures

The externality posed by climate change is an obvious "market failure". But there are important interactions between the climate market failure and other market failures. They affect how individuals behave, how they respond to government intervention, and the social cost of carbon.

The Hamiltonian reflecting social optimization has to embed the societal constraints implied by the inability to attain the first-best optimum. Thus, for the moment ignoring risk, and in the absence of constraints on government behavior, the Hamiltonian can be written

$$(8)\ H \equiv U(C) + p_E\, \psi + p_K\, \Omega\ .$$

where p_K is the shadow price on capital and p_E is the shadow price on carbon, $\psi = dE/dt$ and $\Omega = dK/dt$. The previous analysis assumed that there were no constraints on government policies to mitigate emissions, no market failures and/or no costs to implementing policies that undo market failures, so that the time path of {e(t)} was the unconstrained trajectory that maximized W. But there are constraints on and costs to government actions, which we simplify by assuming that the set of controls $\{C(t),\ e(t)\} \equiv \mathbf{a}$ are constrained to a set which for simplicity we express through $\Gamma(\mathbf{a}) = 0$.[21] We rewrite our Hamiltonian as[22]

$$(9)\ H \equiv U(C) + p_E\, \psi + p_K\, \Omega + \gamma\, \Gamma.$$

[21] Given {K,E}, specifying {C, e} implies a particular level of investment.

[22] A more general model might stipulate that the constraint itself is affected by some other state variable z, whose evolution is a function of the actions taken today, so that actions today affect the set of future feasible actions. For instance, one could (at a cost) invest more today to make high-emission capital goods more convertible into low-emission capital goods, lowering consumption today, but increasing flexibility and expected consumption in the future.

where now output achievable given K and E may be impaired by a set of market failures, **Θ**, themselves affected by government actions.[23] If the constrain binds (γ > 0), $\mathbf{p_i}$ (E,K) and **a**(E,K) will be different from what they would have been in the absence of the constraint. Thus, IAMs that ignore market failures and the ability of government to correct them (which is typically the case) misestimate the social cost of carbon, potentially by a significant amount.

The intuition behind this general result is simple and illustrated by the following example. Assume that it is not very costly to remove carbon from the atmosphere. Then the social cost of carbon—the extent to which more carbon in the atmosphere would lower social welfare—is low, bounded by the cost of removal. Were it ever to exceed that level, we would spend that amount of resources to bring the (marginal) social cost of carbon down. But now, assume that there is a constraint in implementing this technology; then the social cost of carbon may be much higher. *Restrictions on what we cannot do make it all the more desirable to do what we can.*

Costs of adjustment, for instance, provide an important set of constraints (which might more appropriately be modelled as part of the underlying economic system). It is expensive and politically difficult to shift workers from coal mining to producing and installing solar panels. Formally, one could reflect these adjustments costs in specifying, say, two kinds of capital goods, each associated with different emission levels, and with the constraint that one kind of capital good cannot be converted into the other. The decision of what kind of capital good to make depends on beliefs about the social cost of carbon in the future, over the asset life of the capital good. Thus, one shifts into the production of the low-emission capital good well before it would pay to do so if capital were fully malleable and one could convert a high emission capital good into a low emission capital good. If there is a rising

[23] i.e. F(K, E, **Θ(a)**). We noted that market failures may also affect the environmental generating processes: ψ (F(K(t), E(t)),e; Θ), and that some government actions entail expenditures, so (2) is replaced with Q = C + I + e + G(**a**). The set of relevant government actions is now broader than just the choice of {e,C}.

social cost of carbon, one acts *today* as if the social cost of carbon is far higher than it is today.[24]

More generally, the social cost of carbon $\{p_E(t)\}$ depends on the actions the government takes to correct other market failures. In particular, the social cost of carbon today, where there is no or little government intervention to tackle climate change, may be markedly different from that along the optimal trajectory, where $a = a^*(\Gamma)$, where the optimal trajectory itself is affected by the set of constraints imposed on the government, Γ; and it will be markedly different from that along a trajectory in which there are no constraints on government and/or no market failures. For the purposes at hand—such as the decision to allow another coal-fired plant today-- the social cost of carbon along a hypothetical path in which the government had the ability to correct all market failures and had actually done so is irrelevant.

Because any analysis that calculates the social cost of carbon assuming optimal unconstrained intervention at every date in the future, implies that the benefit of reducing carbon today may be lower and the cost higher than under more realistic scenarios with non-optimal and constrained government actions, the "optimal" level of global warming in such models may be higher, and the social cost of carbon is likely to be higher.

These observations are strikingly illustrated by situations in which there are multiple market equilibria, one of which is superior to the other (either in social welfare, or possibly even Pareto superior). Such multiplicities can easily arise, especially in the presence of externalities and non-convexities, such as those associated with technological change. If government intervention is limited, it may be insufficient to move the economy out of the "bad" equilibrium. The social cost of carbon may be markedly different (and larger) in say the bad equilibrium than in the good equilibrium. It is of little relevance to assert that if only the government could take actions to ensure that we would be in the good equilibrium then the social cost of carbon would be very low.

[24] These are standard and long-established results in the theory of growth with "putty clay" models, the insights of which have typically been ignored in more recent work in economic dynamics which assume full malleability (see, e.g. Cass and Stiglitz, 1967).

2.2.1 Market failures and the financial sector

One of the most important sets of market failures—particularly relevant for understanding the inadequacies of the standard model—are associated with the financial sector. In the following paragraphs, we describe a few facets of those.

Capital markets

Capital market imperfections are pervasive. Perfect capital markets entail no restrictions on the ability to borrow. But credit rationing is pervasive.[25] This leads to underinvestment in certain key areas, and such underinvestment is likely to be especially important in investments in areas where price signals are not working, and where uncertainty is large, as is the case with climate change. Investments in, say, solar panels or better insulation might easily pay off in a world where capital is accessible at the T-bill rate or even twice or thrice that, but not at the high "shadow" cost associated with credit constraints.

Capital markets and firms are also short sighted, acting as if future benefits and costs are less important than they should be. That this is so is widely recognized, and reflected, for instance, in the behavior of financial markets in the run-up to the Great Recession. Short-sightedness is partly a result of deficiencies in corporate governance, where organizational objectives may not coincide with those either of society or of decision-making managers.

Socializing losses

One of the reasons that organizational goals do not coincide with those of society is that when there are large and correlated societal losses, there is a high probability that such losses will be socialized, even as the profits associated with actions giving rise to those losses are privatized. The knowledge that there will be such bailouts leads to "collective moral hazard" (Farhi and Tirole, 2012), with excessive risk taking. For instance, oil companies and coal-fired electricity generators may make investments that they would not otherwise have made, knowing that government will take actions to at least partially "protect" their investments when these assets become stranded assets, whose value

[25] Advances in the theory of information explained the reasons. There is an extensive subsequent empirical literature documenting its importance.

markedly diminishes with a stronger public response to climate change. That, in turn, means that there would be more fossil-fuel investment and carbon emissions than there would be in a trajectory in which the government could bind itself not to bail-out such investments.

The commitment problem

However, society (the government) cannot commit itself not to bail-out those who do the wrong thing when the "disaster" occurs, if enough of them engage in such behavior. The societal consequences of not engaging in a bail-out are greater than those associated with a bail-out. And firms (individuals) know this. This induces excessively correlated behavior, and excessive investments in fossil fuels. Only through regulation forbidding the firms from making these socially unprofitable investments can the risk of future socialization of losses be mitigated.

Systematic flaws in managerial incentives

At the same time, managerial incentives are not aligned with organizational incentives, again inherently so, for reasons associated with imperfections and asymmetries of information. Managers often engage in investments that increase short-run profits at the expense of future losses or risks[26] Again, the implication in this context is that managers may undertake actions entailing excessive climate risk—with possibly adverse effects even on the firm in the long term—because of short-term benefits accruing especially to managers.

2.3 Innovation

One way to imagine making the green transition is that magically, technology for renewable energy, including storage, suddenly advances to the point where the cost is a fraction of that of energy from fossil fuel.[27] The fossil-fuel economy was borne of innovation, and it could as well die as a result of innovation.

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[26]Evident in the run up to the 2008 crisis-- commented upon by chairman of the Federal Reserve, Alan Greenspan, in his Congressional testimony on October 23, 2008 on the financial crisis. For a broader discussion, see Stiglitz (2010).

[27] As the cost of renewal energy comes down, so too will the price of fossil fuels. One is essentially comparing the cost of renewables with that of fossil fuels in a world with zero rents associated with fossil fuels.

Implicit in the “perfect market but for climate” analysis is the presumption that the pace and direction of innovation is optimal, or would be optimal if we just got the right price of carbon. Such a conclusion, based neither on theory nor evidence, has an important implication: greater expenditures on climate R & D are likely to be wasteful. To the contrary, if there has been underinvestment in R & D, government efforts to promote climate research could have, at low cost, large societal benefits. That is, in the presence of this additional market failure, government interventions to reduce carbon emissions are less costly, i.e. the marginal abatement cost is lower. A consequence of failing to discover or ignoring cheaper ways of doing things is that the cost functions fed into IAMs might be based on exaggerated cost estimates. Overestimating costs in this way acts as a bias against action.

The fact that as attention has shifted to climate, innovation has soared suggests a wealth of possibilities. A whole range of low emission technologies which are already competitive with fossil-fuel based technologies without subsidy or a carbon price has emerged. This is true of renewable electricity across much of the world. Many electric vehicle technologies are now close to competitive in this sense. Most of these dramatic changes were not predicted by and not embodied in standard models. Systemiq (2020) shows that around a quarter of emissions are in sectors for which zero-carbon technologies are already lower cost than fossil-fuel counterparts and that could rise to around three-quarters, with good policies, in a decade.

These remarkable changes have been on the back of fairly modest policy. Entrepreneurs, researchers and innovators have developed ideas and technology as they have recognized increasing pressures and need for emissions reductions. But it is at least conceivable that far more could have been accomplished with stronger direct incentives and a stronger sense of direction to guide future commitments in circumstances where detailed futures markets are not available.[28]

[28] There can be multiple expectational equilibria: if no one undertakes emission reductions, the political economy is such that there will not be support for emissions curbs; if they do undertake emission reductions, the political economy will support emission curbs. The Paris climate negotiations were in part predicated on shifting the expectation/political economy equilibrium to the low-carbon trajectory. Systemiq (2020) shows how five years of these expectational effects have generated rapid technological progress.

Recent years have seen significant advances in understandings of the economics of innovation and help us understand market distortions in this area. For our purposes, three insights are central:

(a) **Innovation is at least in part endogenous, affected by incentives, the explicit and implicit returns to innovation**.[29] This is, of course, as true for innovation directed at reducing the carbon footprint as it is for innovation directed at saving labor. Prices and regulations both affect those incentives. If there is no price of carbon, enterprises have no incentive to economize on the use of carbon, and no incentive to develop innovations that would do so. Regulations also affect incentives: if a car is required to meet certain energy standards, and there is a high penalty for failing to do so, then that provides strong incentives. We should not have been surprised then at a lack of innovation reducing the carbon footprint of the economy in an era in which there were neither explicit nor implicit prices for carbon.

(b) **The incentives that matter for long-term investments relate to the implicit or explicit price of carbon over the life of the asset. Firms are risk averse,[30] and the greater the uncertainty about say future carbon prices, the greater the uncertainty about the returns to green investments (including the development of new technology) and accordingly the lower the level of investment.**

This means that what is important is not just the price signal today but expectations concerning those signals in the future, including government's commitment, and this is especially so given the importance of increasing returns to scale in discovery and production.

Pricing and regulatory policies have to take into account their dynamic impacts on private investments in R & D. Regulations can increase the shadow price of carbon, and can do so in ways that may help focus attention in the innovation process.[31] Earlier, we discussed the

[29] The theory of induced or directed innovation dates back to the 1960s, with contributions by theorists like Samuelson (1965) and economic historians, like Salter (1960). (For further discussion of induced innovation, see Stiglitz and Greenwald, 2014). The theory was revived some decades later, especially in a series of papers by Acemoglou (2002), and Stiglitz (2006, 2014) establishing the lack of efficiency and the possible dynamic instability.

[30] This is a consequence of the absence of adequate insurance markets and the presence of equity rationing, both in turn a consequence of pervasive asymmetries of information.

[31] There is a large literature on the importance of focusing managerial attention. One of the main criticisms of regulatory regimes is that they divert managerial attention away from increasing productivity to satisfying

advantages of specifying quantities versus prices in a world in which there is an incomplete set of markets/incomplete contracts/incomplete regulatory specification (as a function of the state of nature). In the context of innovation, the advantages of quantity regulation may be even greater: researchers' attention is focused on meeting a particular goal, rather than exploring a wider variety of ways by which costs of production might be reduced. When the costs of failing to meet that particular goal are very high (a very non-linear damage function), it makes sense to have researchers focus their attention on achieving that goal.[32]

The time profile of carbon prices (or regulations) matters, with high early prices having the benefit of incentivizing early innovations, the benefits of which are therefore enjoyed for a longer time, especially relevant in the period before the world moves away from fossil fuels. Innovation is path dependent, as Atkinson and Stiglitz (1969) and the economic historian Paul David (2001) have emphasized. This means that by setting the economy along a "green discovery path," one innovation follows another—and one can obtain reductions in the carbon footprint that were unimaginable at the onset.[33]

(c) **Even when there are appropriate prices for carbon, there is a presumption that private sector allocations affecting the level and *direction* of innovation (e.g. whether scarce research resources are directed at saving or replacing labor or protecting the environment) will not be socially desirable**.[34] Natural market processes lead to "biased" innovation (relative to a Pareto efficient allocation), with too much emphasis on innovation

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regulatory constraints. But when the objective of policy is to enhance productivity in the particular sense of reducing the carbon footprint, enhancing appropriately directed innovation and satisfying regulatory constraints are aligned.

[32] There is an isomorphism: the specification of a non-linear price (penalty) function is equivalent to the specification of a regulation, with a schedule of penalties for not meeting the regulation which increases with the extent to which the regulation has failed to be met. A fixed penalty is similar to a linear price system, except there is no reward in the regulatory system for doing better than the regulatory threshold.

[33] Because so much of the benefits of setting out on a different trajectory might be captured by others, any single private firm has little incentive to begin to explore these alternative trajectories. There needs to be a push from the government. The benefits of setting out on an alternative exploration path (renewable energy) may be particularly large when diminishing returns has set in in the "old" (fossil fuel) path.
For discussions of path dependency in this arena, see, e.g. Acemoglu et al., 2019; Aghion et al., 2016.

[34] The lack of efficiency is obvious, once one takes into account that research can be viewed as the production of information, and markets in which information is imperfect are generically inefficient (Geanakoplos and Polemarchakis, 1986; Greenwald and Stiglitz, 1986; Stiglitz, 2002).

which “saves” labor, and too little emphasis on innovation which saves the planet—that is, addresses climate change, and this may be so even with carbon appropriately priced. These natural biases can be aggravated by distortions induced by public policy, e.g. tax policies which disproportionately tax labor, encouraging labor-saving innovation.

The innovation process itself is marked by large and inherent spill overs and externalities. Because knowledge is a public good, for it to be produced in the optimal amount it must be publicly funded, but that requires taxation, which is inevitably distortionary. Because the most important input in any research process is prior knowledge, if there are restrictions on the use of prior knowledge—an inevitable consequence of strong intellectual property regimes—then knowledge will not be used efficiently, and innovation will be hampered. But if there is no restriction on the use of prior knowledge, private producers of knowledge cannot appropriate the full social value of the knowledge they produce. Thus, the key questions concern the costs of different kinds of distortions and the comparative advantages of different institutional arrangements, in the context of a world with diffuse knowledge, including knowledge about the returns to different research strategies.

An immediate corollary of the above proposition is that there is scope for government intervention, and not only in writing the rules of the game (e.g. specifying the intellectual property framework, which has to be very carefully designed, lest it stifle innovation rather than encourage it). There are an array of instruments to be employed, from intellectual property to research subsidies to publicly-funded research and in some cases publicly-produced research (which often triggers private research) (Eurostat, 2020).

2.4 Structural transformation and changing systems

Climate change involves radical change in all of the core systems of the economy (e.g. energy, land, cities, transportation). Such change requires complex coordination of a kind that goes beyond standard pricing, especially in the presence of multiple market failures. And typically markets on their own don’t manage these changes well, partly because those who are on the losing side don’t have the resources to make the productive investments to enable a more productive reallocation, and imperfections in capital markets mean that they won't provide the necessary finance.[35] Private capital markets are not sensitive to the macroeconomic externalities arising from sectoral reallocations.[36]

Just as with innovation, we cannot expect a one-policy solution, such as a carbon price, to address the challenge of major changes in systems, including cities, land, power and transport. In cities, transport, residences, and workplaces interact very powerfully and thus interventions must be managed through design, zoning, regulation policy and so on (Coalition for Urban Transitions, 2019).

Market failures are pervasive, and governments have corrected these only partially (and in some cases may have exacerbated them.)[37]

2.5 Climate change, structural change, dislocation, and distribution

Radical change inevitably involves dislocation, with the disappearance of some activities and jobs and the emergence of others. Some relative prices will change dramatically, with large consequences for households and firms.

If there were perfect insurance markets, individuals would be able to purchase insurance against the adverse effects both of climate change and the policies designed to mitigate it. But there are not. So too, if the government could provide perfect "social" insurance against these risks, analyses of climate change would only have to pay attention to the direct costs of reallocating resources, not the distributive impacts. If markets worked perfectly, and individuals could costlessly move from old jobs to new jobs, the distributive impacts would be limited. The consequences of these market and government failures for equity and unemployment can be large. Policies that can help manage this change entail

[35] See, e.g. Delli Gatti *et al (*2012).
[36] Because of the pervasive market failures, including the macroeconomic externalities noted earlier, decisions by market participants on the pace of transformation are not in general (constrained) Pareto efficient. There is a need for government intervention. In most countries, the extent of government intervention is limited. Like other market failures, this has implications for the social cost of carbon.
[37] Private incentives in agriculture are distorted, with little attention paid either to carbon emissions or water pollution. But the $600 bn a year worldwide agricultural subsidies may make matters worse. In many cases the result is degraded soil, water and air pollution, and deforestation. All of these are closely related to emissions.

investing in people and their skills, to facilitate the transition from old activities to new, with sensitivity to locations, “investing in places”, and ensuring adequate social safety nets.

Although climate change itself will have vast distributive impacts--from a global perspective, almost overwhelmingly adverse, with the most negative effects borne by those who are less well off-- the adverse distributional effects of climate mitigation policies *today* may be politically more salient. Further, there will be important fossil-fuel and other vested interests that will try to block change.[38] Thus, there is no presumption that governments will have adequately dealt with the within or across generational distribution impacts. (We will discuss further the implications of these distributional impacts for the calculations of the SCC in section 4.)

2.6 Endogenous preferences

There is one other key determinant of the evolution of the economy: the evolution of preferences. Standard economic analyses begin with the *assumption* that preferences are fixed and given. But they are neither. They have been changing and, there is at least a degree of endogeneity in all the key parameters of the economy—demographics, technology, market structure, even preferences are affected by policy, and policy itself is affected by the economic circumstances confronting a polity.

The endogeneity of preferences has important implications for the normative analysis, but it is also clearly relevant for understanding the evolution of the economy and the costs associated with climate mitigation. Many in the younger generation are increasingly moving to a more vegetarian/vegan diet, associated with less emissions, and partly because they care about their environment. Dietary change could have a major effect on emissions. (Food and Land Use Coalition, 2019). With an estimated 30 to 40% of food being wasted, a greater sensitivity to the environmental impacts of waste may induce a reduction in this waste, and again a reduction in emissions.

[38] See e.g. Oreskes and Conway (2010a).

Just as the standard model simply *assumes* that individuals care about the descendants as much as they care about themselves (contrary to any evidence) it simply *assumes* that they do not care at all about the consequences of their actions on their environment. This has important implications. For instance, policies which increase awareness of individuals' adverse effects on the environment may, by itself, curtail emissions. In section 4 we discuss the implications of endogenous preferences for the social cost of carbon.

So too, firms do not have preferences as such but they can respond to pressures from stakeholders and government and the managers can and do reformulate objectives in response. There appears to be the beginnings of change in the corporate world towards new views of the purpose of the firm[39]. If so, that will affect the incentives required to change behavior.

3. Uncertainty

Every aspect of climate change—the drivers, the pace, the economic impacts, the response to interventions—is marked by considerable uncertainty. What we do know is that: with very high probability, the world is warming, there will be large economic impacts, and our actions can affect the pace of climate change and its effects.

Changes in demographics, preferences, and technology—the underlying drivers of the economy-- are hard to predict; and even more difficult are changes in politics, which can have first-order effects on all the relevant variables.

When we combine the uncertainties—about climate science, about the "right" economic model, about the parameters of the models, about the changes in those parameters over time, about the political processes which affect both the environment and economy—climate policymaking is a quintessential example of decision making under uncertainty, where the decisions themselves affect the magnitude of the uncertainties. The uncertainties affect individual and firm behavior, economic trajectories, and the impact of market failures; they have an even bigger impact on the normative analysis, to be discussed

[39] (McKinsey, 2020; World Economic Forum, 2020)

in the next section. Some of the key concerns, such as those posed by non-stationarity, affect both the descriptive and normative analysis.

3.1 Non-stationary analyses

There has been considerable research ascertaining the sensitivity of the results of IAM models to parameters (Gillingham et al., 2018; Neelin et al., 2010). A central problem is that we are moving into unchartered territory: we do not know how an increase in greenhouse concentrations will affect weather and how changes in climate will affect the economy, simply because our economy has never experienced anything like what we are likely to be experiencing. We can extrapolate the future based on the past, but whether in these circumstances that makes sense is highly problematic. The underlying dynamics are not well-described by stationary processes (Milly et al., 2008). It is analogous to the problems of prediction in the years preceding the global financial crisis, when financial markets created new products which they claimed fundamentally changed the way the economy behaved; but the only data to forecast how the economy would behave was from an economy without these financial products. As it turned out, the extrapolations (forecasts) based on that data were wildly off the mark.

Thus, extreme caution is needed in the use of simple extrapolations. Market participants' behavior has not always reflected such caution—there are systematic deviations from rational behavior based on say Bayesian inferences. For instance, while more sophisticated and complex analyses forewarned of the consequences of the new financial products--these analyses took into account systemic risks, complex interactions, feedback mechanisms, non-linearities--few market participants took these complexities into account.[40]   These concerns are equally relevant in the analysis of climate change, with the potential scale of the implications being much bigger.

[40] See, for instance, Battiston *et al. (*2016).

3.2 Imperfect risk markets

A key market failure (not incorporated in the standard models) is that risk markets are very imperfect[41]. Whenever risk markets are imperfect, markets are not constrained Pareto efficient (Geanakoplos and Polemarchakis, 1986; Greenwald and Stiglitz, 1986), thus undermining a central pillar of IAM analyses, which is the efficiency of markets *but for the environmental externality*. Because there is a highly imperfect market for climate risk, there is a presumption that markets on their own will not lead to (constrained) Pareto efficient outcomes. Earlier, we explained why imperfections in capital markets implied that the social cost of carbon was likely to be higher when those imperfections were taken into account than would appear to be the case in models which ignored those imperfections. Here, we explore in more detail some of the reasons that this is especially so, taking into account the absence and imperfections of risk markets.

If, for instance, climate variability increases with temperature, and temperature increases with greenhouse concentrations, individuals will not take into account the increased costs they impose on others through the increase in risk which others face. This is an additional social cost of climate change *which is not included in any model that ignores risk,* and one which is potentially very significant. Individuals are willing to pay large amounts to divest themselves of risk, especially when it is, as here, large.[42] Thus, IAMs that ignore the increased risk associated with increased climate change may be significantly biasing the results toward inaction.[43]

3.3 Transition risk and (in)efficient markets

Much of standard finance literature assumes that markets are forward-looking, and behave as if all had fully rational expectations. But the hypothesis of fully informationally efficient

[41] Advances in economics understanding the consequences of imperfect information have explained why this is inherent (Stiglitz, 2002).

[42] Many individuals may not be fully apprised of the risks associated with climate change—another market failure, discussed further below.

[43] There is a large literature ascertaining how much individuals are willing to pay to divest themselves of risk. The certainty equivalent of a risky consumption stream can be markedly lower than the mean value.

markets has been subjected to extensive theoretical scrutiny and empirical testing, and widely rejected. [44]

Given that that is the case, the possibility, if action is delayed, of a disorderly financial transition, as the risk of climate change finally becomes generally recognized, cannot be ignored. A "disorderly" transition to a green economy would entail sudden changes in the price of carbon, resulting in sudden changes in asset values. Such changes can trigger a systemic crisis, with macroeconomic consequences that amplify the initial disturbance, as a result of macroeconomic externalities.

The cost of such a disorderly transition would be potentially enormous, and the increase of those costs as the magnitude of the transition increases, as a result of not controlling carbon emissions, are currently missing from the social cost of carbon. The consequences could be greatly mitigated if financial institutions and corporations had more limited exposures to carbon risk.

Unfortunately, without appropriate government regulation there will not be adequate disclosure of risks (Grossman, 1981; Stiglitz, 1975). Without such disclosure, it is impossible to take appropriate actions to limit and mitigate climate risk, enhancing the likelihood that markets engage in excessive climate risk and of a disorderly transition. The externality of climate risk is not fully addressed by having a (single) carbon price, and obviously is not addressed at all by climate models that do not adequately incorporate climate risk in all of its dimensions, including transition risk.

While regulators in a several countries have already begun to recognize the need for disclosure rules concerning climate risk (one example of why *rules matter*), for many countries such rules may be a long time coming, and that would imply the likelihood of

[44] Grossman and Stiglitz (1980), established that if it were true, the only information that would be efficiently reflected in market prices would be costless information. Shiller (1981) subsequently provided a wealth of empirical information documenting the informational inefficiency of markets.

inadequate climate action for an extended period of time, even when there is a price of carbon.[45]

The rules of the economic game matter[46]

Markets do not exist in a vacuum. The rules affect how markets function, both distribution and efficiency, with first-order effects on the nature and extent of market failures. The rules affecting climate change include: corporate governance, disclosure rules, bankruptcy rules, and rules governing fiduciaries.

Many of the rules were designed to address market failures, such as those associated with conflicts of interest in the presence of imperfect information—but some were imperfectly designed, with the result that some of these rules create a bias *against* doing anything about climate change, for instance the rule in some jurisdictions that requires fiduciaries to focus on (short-term) value maximization of their portfolios, ignoring environmental or other social consequences.

Networks and network externalities

Moreover, even if future events were reasonably well reflected in today's prices, there are still pervasive network, macroeconomic and financial externalities; market participants do not fully take into account how their behavior affects the overall economic and financial system and others with whom they are linked.[47] Networks matter, and markets pay too little attention to systemic risk to which networks can give rise (Catanzaro and Buchanan, 2013; Hendricks et al., 2006; Schweitzer et al., 2009).

[45] Even if current governments adopted good climate disclosure rules, there can be significant transition risk. Climate action depends significantly on public action, and that in turn depends on the not-fully-predictable outcome of elections. An election of a "green government" would thus give rise to a "jump" in future expected carbon prices, with all the systemic effects of a disorderly transition described above. The consequences could be greatly mitigated if financial institutions and corporations had more limited exposures to carbon risk.

[46] See Stiglitz and FEPS (2020), Stiglitz et al. (2015).

[47] These are the macroeconomic manifestations of the pecuniary externalities that are ever-present in economies with imperfect information and incomplete risk markets (see Greenwald and Stiglitz, 1986). Macroeconomic externalities have been studied by Davila and Korinek (2018), and Fahri and Werning (2016) among others.

Of particular concern is that these network externalities become severe in the presence of large risks, such as those associated with climate change—severe enough that they give rise to systemic failure, with the failure of one enterprise contributing to that of others, engendering the possibility of bankruptcy cascades with large societal costs, especially if there are (real) bankruptcy costs.[48]

Multiple risks

Battiston *et al.* (2017) have integrated several of these effects. They have explained why and how bringing in finance changes the analysis—and the social cost of carbon and the appropriate responses to climate change.

Rules are necessary to both mandate the disclosure of climate risk and ensure that the disclosure reflects systemic and transitional risk. It is evident that we do not now have such rules. In the absence of such rules, again, there will be underinvestment by the private sector in climate mitigation, increasing the social cost of carbon from what it would be along an "optimal" trajectory.

The consequences of misperceptions of risk

Earlier in our discussion of non-stationarity, we noted that observed behavior sometimes seems at odds with rationality as normally defined. There can be large misperceptions of risk. Assume, for the moment, that somehow one could get individuals to internalize the risk-externality, but that they underestimate the magnitude of the risk. Then again, the carbon price that would be required to induce individuals to act in a way which would maximize their ("true") expected utility (taking into account the correct estimates of the risks) could be much larger than that associated with an accurate estimate of risk.[49] Behavioral economics has explained that there are in fact systematic misperceptions of risk,

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[48] There is now a large literature on these network externalities, bankruptcy cascades, and how individuals in networks do not adequately take into account the effects of their actions on others (Allen and Gale, 2001; Battiston *et al.,* 2012; Stiglitz and Greenwald, 2003). Network externalities also arise in key systems of the economy, such as transport, electricity, cities, discussed in section 3.

[49] The normative question of the appropriate welfare criterion when individuals' perceived probability distributions (beliefs) do not correspond to "reality" is unsettled. All that matters in standard formulations is ex ante expected utility. From an ethical point of view, when we are evaluating the wellbeing of future generations, this perspective is inappropriate.

with the potential underweighting of events like climate change, the main effects of which will be in the distant future.[50] As a result, unless governments employ instruments that countervail these behavioral biases, e.g. through strong regulatory measures, there will be underinvestment in mitigating climate change, and again the social cost of carbon will accordingly be higher than it otherwise would have been.

The consequences of flawed methodologies in risk discounting

Even were market participants to accurately assess risk, there are systematic problems in the heuristics used in response. The standard approach discounts future streams of revenues and expenditures (net profits) at a higher rate reflecting risk. Such an approach confuses time discounting with risk discounting, and does not result in the maximization of intertemporal expected social welfare (the natural extension of maximand (1) to the case of uncertainty[51]). The failing of such an approach is reflected in what it implies about responding to an increase in the uncertainty associated with a future liability (cost), such as the clean-up costs of a nuclear power plant. Greater uncertainty implies (in the standard methodology) a greater discount rate, so that we should pay *less* attention to such costs, the greater the risk. A better approach, in the presence of time separability of utility[52] is to calculate the certainty equivalent of expected utility at each date[53], and then discount those at the rate of pure-time preference.

But because this flawed methodology is widely engaged in within the business community[54], there will be underinvestment in risky climate mitigation—especially perhaps in the case of risk associated with future public actions say concerning climate pricing.

[50] The biases are associated both with misperceptions of risk and time discounting, reflected in hyperbolic discounting (Karp, 2005; Sterman, 2011).
[51] In section 4, we will discuss the limitations in such an approach.
[52] A standard, but highly questionable, assumption in all the IAM optimization models. See the discussion in section 4.
[53] The certainty equivalent is that certain level of consumption that gives the same level of utility as the expected utility of the random level of consumption (Arrow, 1965; Pratt, 1964). Matters are somewhat more complicated, because the expected marginal utility of consumption is greater than the marginal utility at the certainty level of consumption so long as there is diminishing absolute risk aversion, as is conventionally assumed. Thus, there is a presumption that with risk, one should undertake more climate mitigation than one would at the certainty equivalent value of consumption. At the certainty equivalent level of consumption one would undertake more climate mitigation than one would at the mean value of consumption.
[54] The reason for the confusion is perhaps understandable: the required rates of return on riskier projects are higher than on safe projects.

3.4 Climate change viewed as a stochastic process

Here, we extend our formal model of the co-evolution of the economy and the environment (3) to incorporate risk, recognizing the multiple dimensions of the environment:

(10) $d\mathbf{E} = \psi\ (K(t), \mathbf{E(t),e})\ dt + z(\mathbf{E, e})\ dt$

where z is a stochastic variable and **E** and **e** are vectors. Unlike many of the stochastic processes studied in economics, this is non-stationary, non-mean reverting. Human activity affects the rate of climate change and the magnitude of the risk: as the level of greenhouse gases increases, we increasingly move into unchartered territory.

As viewed today, no matter what the policy regime adopted, there will be increasing uncertainty over time—we know where we are today, but we are uncertain where (10) will lead us. Concentrations of greenhouse gases are already higher than the planet has seen for millions of years and rising strongly. Heuristically, if there is increasing uncertainty about the consequences of climate change going out in time, then the certainty equivalent of future generations' income (as viewed today) is lower; the expected value of marginal utility of income is accordingly plausibly higher;[55] and we would want to take stronger precautionary actions today. Markets would, of course, with an infinitely-lived representative agent, do the same, with the "right" price of carbon, but not to the same extent if there are market failures. But precisely because the expected value of the marginal utility of income is higher, the right price of carbon today will be higher than it would have been in the absence of this risk, and even more so in the presence of one or more of the market failures we have described. In an overlapping generations model, where early generations do not compensate later generations for their loss of welfare as a result of climate risk, if the government cannot offset these deficiencies in intergenerational transfers, the social cost of carbon will be still higher.

3.4.1. Threshold effects

[55] See the discussion in fn 53 above.

The full consequences of viewing climate change as a stochastic process are seen most clearly if we assume a high level of non-linearity in the damage function, so that if certain elements of the vector **E** exceed some threshold, there are intolerable consequences, e.g. large losses of biodiversity and human lives and very high levels of physical damage.[56] Assume a single environmental variable E (carbon concentration), with all the symptomatic variables (temperature, weather variability, incidence of extreme events, etc.) being simple functions of E, and assume that below $\hat{E}$, losses are limited, but above $\hat{E}$, losses are effectively infinite. Think of how a rational representative agent with a government representing his/ her welfare making the relevant environmental decisions might plausibly make choices in this situation. Once $\hat{E}$ is reached, expected utility is minus infinity—the disastrous outcomes outweighing everything else. If there is a trajectory which at finite costs avoids $\hat{E}$, such a trajectory should be chosen. Among such trajectories, the trajectory maximizing welfare (using the standard criterion) is chosen. Policy should be directed at keeping the economy well below $\hat{E}$, sufficiently below $\hat{E}$ that it is feasible to take actions that, given the dispersion of z, will ensure a zero probability of crossing $\hat{E}$. The closer the economy approaches $\hat{E}$, the stronger (and costlier) the measures that will need to be taken. Thus, what matters is not the average value of E in the future, but the risk that E approaches $\hat{E}$, and we should be willing to take costly actions today to reduce that probability.[57]

In neither the normative nor the descriptive framework can we blithely replace (10) with (3), even if the expected value of z were zero: the evolution of the average value of various variables will depart markedly from the values that would be obtained by looking at the evolution of those variables ignoring risk. For instance, an increase in risk as reflected in the variance of z should lead to the taking of more pre-emptory actions, to keep E further below the threshold.[58]

[56] The best scientific estimates suggest a threat (risk) of large losses in biodiversity and lives (see e.g. Trisos et al., 2020; Vicedo-Cabrera et al., 2018), let alone physical damage, as temperature rises above say 3 degrees Celsius, implying that the social cost of carbon must be such as to steer the economy to staying below that threshold.
[57] This approach can be extended to decision-making when there is some chance that one crosses threshold.
[58] This is the opposite of the predicted behaviour of real investment in the presence of an increase in uncertainty, where there is typically a delay in investment (Dixit and Pindyck, 1994). It is also the opposite of what one would expect of market participants who confused risk discounting with time discounting.

This is especially so if the distribution of some of the relevant variables is fat-tailed (with significant probabilities of E, for instance, exceeding $\hat{E}$), as Weitzman (2009) has argued is the case. With fat-tailed distributions, for wide classes of utility functions (including those with the most empirical support), expected utility is not defined (formally, it equals minus infinity). Then, the standard descriptive model introduced in section 2.1. breaks down: it provides no guidance about individual behavior. That the standard IAMs ignore this is another example of the deficiencies in the models and the way in which their analysis biases the results. Even short of the extreme case where the model breaks down, if an increase in E is associated with a large increase in risk, it would imply a higher social cost of carbon than would be the case if there were no risk effect, with stronger climate action.

These conclusions are reinforced in the context of the overlapping generations model: viewed from today, the expected marginal utility of future generations is likely to be increased as a result of climate risk, and the associated market failures, further strengthening the argument for stronger climate action now.

3.5 The multiple dimensions of uncertainties in climate

The simplistic models described above summarize the impact of the environment on production and individual wellbeing, as if the environment has a single dimensional impact, say temperature, and can be described by a single state variable, E_t. Neither assumption is in general true. Variability over time and across space on key dimensions including temperature, rainfall, humidity, wind speed and so on is immensely important. People can adjust their living standards to small differences in temperatures, but the costs of adapting to large temperature variations can be very large: building a house suitable for both – 20°C and + 30°C can be very expensive. A few days of frost, or of temperatures above 40 degrees Celsius can have devastating effects—on agriculture and human life[59] and productivity. This is especially so if high temperatures are accompanied by high humidity. Extended periods of drought, combined with high temperature, can give rise to fires. Much of the property damage experienced by climate related events arise from extreme events

[59] Every 1°C fall in daily mean temperature within the top 5% of the coldest days, results in a 6% increase in all-cause deaths in England and Wales (Hajat, 2017). For each 1°C beyond 41°C, average all-cause mortality among over 75 year olds increases by 51%, in Seville, Spain (Diaz et al., 2002).

like floods and hurricanes. So too, the damage from rising sea level is not simply related to changes in the average global temperature.

Moreover, the relationship between average temperature change and these extreme events is highly non-linear. A slight shift in the probability distribution of temperatures can increase the incidence of extreme events significantly—and thus the economic costs.[60]

Much of the losses experienced by climate change are associated with these extreme events—such as the 2% of GDP loss by the US in 2017 (NOAA, 2020); yet some of the IAMs rely on studies of the consequences only of one or a few elements of **E** (Diaz and Moore, 2017). Thus, the damage associated with climate change may be greater and the damage function more non-linear than typically assumed.

We can generalize our analysis still further. There is not a single state variable: climate is affected by the atmospheric concentration of greenhouse gases, the quality and scale of land and forests, and the state of the oceans, etc. In some cases there are important interactions, giving rise to complex dynamics marked by non-linear feedbacks, e.g. an increase in temperature can lead to the release of carbon from the permafrost, or a melting of the ice cap, increasing the rate of increase in carbon emissions into the atmosphere and the absorption of energy by the ocean. Such a dynamic system is more consistent with the complex weather systems we actually observe.

Especially when random forcing functions (such as energy received at various places from the sun) are attached to these dynamic equations, the system can lead to high levels of unpredictability of key elements of **E,** and this unpredictability itself is one of the sources of damage: one is unable to take inadequate preventive measures in a timely way to respond

[60] While this paper focuses on analytic issues, it is worth observing that data relating GDP to temperature either over time or space are likely to significantly underestimate the social cost of increased greenhouse gases. The devastation associated with these greenhouse gases often leads to an increase in GDP with the rebuilding efforts that are induced; but such calculations ignore the societal cost of the devastation—the increased GDP only serves to bring the economy back to where it was before the event. Thus, using GDP data, one might even think that global warming is *good* for the economy. At the very least, standard data vastly underestimates the social cost of climate change, a point which we expand upon in section 4.4 below.

to climate variability, or one is forced to take very expensive measures that are effective against the worst contingencies.

3.5.1. The centrality of controllability

A further consequence of this complex system is weakening controllability. In the original model formulated, it is typically assumed that the government could control the evolution of the system, i.e. by setting emissions controls correctly, it can generate the desired level of greenhouse concentrations.

Now the system may be so complex—especially when there are random forcing functions—that government(s) cannot fully control it. The ability to reverse an unanticipated change, at least at reasonable cost in a reasonable space of time, becomes limited. As the world goes into levels of the climate state variables not previously observed, the reliability of the parameters describing the evolution of the system decreases. This increased uncertainty and unpredictability will, of course, be reflected in the stochastic equations describing the evolution of the system and in the losses society will experience, compared to what they would be with full controllability. Models which assume away uncertainty and assume full controllability by definition assume away this important source of losses from climate change. And such models accordingly underestimate the consequences of climate change.

The bottom-line

The implication of this sub-section is clear: any model ignoring or underestimating risk and its complexities cannot provide a reliable basis for analyzing either the "business as usual world" or how that world would be affected by certain policies, and so cannot provide a reliable basis for guiding policy. Section 4 will reinforce this conclusion.

4. The normative framework for economic policy

4.1 Normative frameworks for individual decision-making under extreme uncertainty

A century ago, Knight made a distinction between risk, where there are well-defined probabilities, and uncertainty, where we know that we do not know. Since then, both among economists and decision theorists there has been much controversy, both about how individuals actually behave and what are reasonable frameworks for individual and societal decision-making. While Savage subjective expected utility is used in many subfields in economics, especially where there are repeated events in which there can be some congruence between subjective probabilities and objectively observed frequencies, in a world that is ever-changing, in a world of "unchartered territory," such as climate change, that framework and the axioms underlying it are not fully convincing.[61] Savage himself suggested his framework was more appropriate for "small world" decisions—and if there were ever a set of problems that were *not* small world, those surrounding climate change would be among them. There is far from consensus on the axioms underlying expected-utility, with some arguing for "max-min" solutions, entailing more risk averse behavior, especially over domains where individuals have little basis for forming probability judgments (Gilboa and Schmeidler, 1989).[62]

Focusing for a moment on individual decision-making, one critique emphasizes that individuals at any moment do not have a complete ordering. Life is too complex, especially as we realize that there may be states of nature that we have never experienced or find hard to imagine or describe; many unknown unknowns.

Kreps (1979) has argued that in the presence of extreme uncertainties, individuals do not act as if they maximize expected utility but show a preference for flexibility. This approach is consistent with more precautionary behavior, i.e. taking stronger actions to avert climate change than one would expect to see were individuals maximizing their expected utility with levels of risk aversion normally observed.

4.2 Societal consensus

Here, however, we are concerned about societal decision-making, not individual decision-making. Once we move into a world marked by extreme uncertainty, where there is neither consensus about utility functions (the welfare maximand) or probabilities or damage

[61] We have already noted that expected utility may not be well-defined, especially with fat-tailed distributions.
[62] See Maskin (1979) for a discussion of individual and societal decision making in the presence of extreme ignorance. Maskin (personal conversation) suggests that climate change is an arena where, while there is a high level of uncertainty, we still know somethings with relative confidence, and that the Gilboa-Schmeidler framework may thus be more appropriate than that provided by Maskin's 1979 paper.

functions, the question arises: how can we reach societal agreement about what to do? How we aggregate disparate preferences and beliefs has been a longstanding question in economics and political science (see Arrow, 1951).[63]

In the case of climate change, we can observe how the global consensus was reached: it became clear, and broadly accepted, that with temperature increases over 2 degrees Celsius there was a significant probability of extremely bad outcomes, potentially so bad that there was a consensus that we should act strongly to try to avoid them. One did not have to have full agreement on the utility function, the damage function, discounting, or the probabilities. One did not have to have complete preference rankings. All one needed was convincing evidence of sufficiently high probability of very adverse outcomes that could be avoided at moderate costs. This is consistent with the normative approach more fully described in section 6.[64]

Having agreed on a reasonable, consensus goal, the task then is to find the best way of achieving that goal. The difference is analogous to that between cost-benefit and cost-effectiveness analysis. In many arenas of policy where the benefits are hard to evaluate—wars, regulations which affect health and life itself or biodiversity—there is often resort to cost-effectiveness analysis. An agreement is first reached on goals and constraints, and economic analysis centers on the best way to achieve the given goals within the constraints.

4.3 Intergenerational values

Climate change represents a special set of social decisions: the current generation is making decisions which affect future generations. Since those generations are not here to express their voice, the issue of societal decision-making is moral/ethical. Section 4.5 will discuss one way of doing so within the standard utilitarian framework.

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[63] There is also no consensus among economists about how to make welfare judgments in a world where ex ante some individuals' probability judgments are clearly off the mark, e.g. where beliefs about climate change or future interest rates are untethered to reality; or in a world where those beliefs are changing and/or endogenous.

[64] Sen (2009) refers to this as a realization-focused comparative approach.

But at least from the Justinian code on, the public interest doctrine has held that the sovereign (the state) holds natural resources (here the environment) as a fiduciary, in trusteeship for future generations. Even if *on average* future generations are assumed to be much better off than the present, a course of action which would entail some chance of extreme adverse climate impacts on future generations, if those impacts could have been avoided by a modest expenditure of resources today, would be a violation of that principle.[65]

In economics, standard approaches to ethical questions have embraced consequentialism and the use of explicit utility functions. In Stern (2015, chapter 6 and 2014a, b), approaches from other perspectives on moral philosophy to the economics of climate change are examined, including Aristotelian (or virtue ethics), Kantian (categorical imperatives) social contractarian, and liberty, justice and rights in the tradition of Isaiah Berlin and Amartya Sen. From these perspectives there is a profound injustice from unmanaged climate change in denying or limiting the right to development of future generations. These moral perspectives point to strong action on climate.

4.4 What is to be maximized

The normative approaches just described stand in marked contrast to the standard IAM, where society is modeled as seeking to maximize social welfare, expressed as the sum of the (discounted) utility of aggregate consumption at each date, as in equation (1). A wealth of literature in recent years has emphasized the many dimensions in the assessment of economic performance and social progress.[66] Most important here are the value of life itself, health, and biodiversity.

In principal, broadening the objective function could easily be accommodated within the IAM framework, though one would have to introduce equations analyzing the risks to lives, health, biodiversity and other key aspects of the environment. Including these would

[65] Rawls (1971) can be read as supporting this perspective. It is especially consistent with utility functions in which the environment explicitly enters into utility functions and is imperfectly substitutable with conventional consumption goods. (See fn. 92).
[66] Costanza et al., 2014b; Stiglitz et al., 2010, 2018; Wealth Economy, 2019

substantially increase the damages associated with climate change. A small increase in death rates times the value of a life, typically estimated at 100 to 200 times GDP per capita[67], can generate a cost of climate change, that is commensurate with the property damage. An incremental death rate of one in a thousand would "cost" 10 to 20% of GDP so the fraction of GDP "lost" would be km, where k is the increase in fraction of the population dying and m is the multiple of GDP per capita generating the cost of a life. Similarly, some, understandably, place a very high cost on the loss of biodiversity (Costanza et al., 2014a). Whilst many, including ourselves, would have reservations about this methodology towards valuing life, the issues involved are of immense importance in the case of climate change. Omission induces large biases.

4.5 Intergenerational welfare

Ramsey (1928) argued that future generations should be weighed equally with the current generation. The argument has received close attention[68] and substantial support. Chichilnisky et al. (2020) have shown that under the standard assumption of symmetry of social preferences across individuals, and with bounded expected population, and bounded utility, the only valid reason for pure-time discounting is probability of extinction. They provide extensive references to a long literature. Essentially, the Ramsey argument is that pure-time discounting is discrimination by date of birth- it attaches lower weight to a life that is otherwise identical, simply because a person is born later. That discrimination is without foundation in most moral frameworks. That argument suggests that society should maximize not (1) but

(11) $W = \Sigma U_t$,

putting aside the problem that (11) may not be defined.[69] The sum of utilities could be undefined, or "go to infinity" either with unbounded expected population or unbounded

[67] Such estimates of the value of life have their problems but most would surely accept that life has a high value whatever concepts are used to "measure" it.
[68] See Stern (2015) chapters 5 and 6 and Stern (2014a, b) for references.
[69] There are approaches in the literature to dealing with this issue, such as assuming a very low discount rate or using an "overtaking" criterion, but the basic questions concern boundedness of expected population and of utility.

utility associated with zero consumption levels or consumption levels tending to infinity. The "zero-consumption" case is of real relevance here as climate change can destroy lives and livelihoods on great scale. The real possibility of these catastrophic outcomes, as we have discussed, supports the case for the move to a methodological framework which puts particular emphasis on the management of such outcomes.

The one modification of this is to take into account the possibility of extinction, discounting future utility at the rate δ_s, so that instead of (11) one maximizes

(12) $W = \Sigma\, U_t/(1 + \delta_s)$

While (12) looks superficially similar to (1), there is a marked difference: there is no reason that individuals' pure rate of time preference δ should be equal to δ_s. Thus, even in the absence of climate change, there is no presumption that the intergenerational market equilibrium will be social welfare maximizing. Moreover, even if there is discounting, based only on the risk of survival, δ_s itself is an endogenous variable—one which the representative individual takes as given, but which is affected by public policy, e.g. towards climate change.[70]

There is accordingly no reason to believe that, even if we use a utility-based framework, the relative *social* marginal utility of consumption of different generations bears any neat relationship to the (safe) interest rate: the former takes into account impacts on extinction probabilities, the latter does not. A corollary is that, even with a dynastic model, the market rate of interest does not provide the discount rate appropriate for valuing future costs and benefits.

[70] A more general welfare function, embracing an explicit concern about survival, is: $W = W(\mathbf{C_t, x_t})$ where x_t is the probability of extinction at date t.

4.6 Intragenerational welfare

Climate change also has large intragenerational distributive effects, which are not typically undone by redistributive policies.[71] A normative approach can take these into account by replacing (12) with

$$(13)\ W = \sum_i \sum_t U_{it}/(1 + \delta_s)$$

where we now sum both over time t and individuals, i. *If climate change adversely affects poor individuals disproportionately* (either because they experience more of its effects or have a lower capacity to cope), and there is no offsetting redistribution, *then average future social marginal utility of income (consumption) will be higher* (than it would be in the representative agent model, relative to current marginal social utility, along any given environmental trajectory)—*implying the desirability of stronger climate change policies and a higher social cost of carbon*.

There is another important source of differentiation: that of individuals by place. There will be high variability in impacts of weather, not perfectly offset by compensatory payments from those areas that are less affected to those that are more affected. This implies (with any inequality averse social welfare function) that social welfare will be lower, and more affected by, climate change. Again, ignoring these spatial disparities results in a marked bias towards inaction.[72]

There is a third basis of differentiation: among individuals similar in circumstances within any location (at any income level), there are horizontal differences that can sometimes play an important role in political economy, e.g. among those differing in sensitivity to climate

[71] The assumption of optimal redistribution is clearly wrong: with a utilitarian equalitarian social welfare function, incomes would be redistributed so all individuals had the same income. That the government undoes any distributive effects arising from climate change is also clearly wrong and to base normative conclusions about appropriate climate policy on that predicate is methodologically wrong. We know that the second theorem of welfare economics, relating Pareto efficiency to a competitive equilibrium, requires the right lump sum transfers. Almost surely, the polar assumption that government will do nothing is nearer the truth. A good normative approach would prescribe the action to be taken *as a function* of the redistributive actions undertaken by the government.

[72] Some IAMs do have differentiation across regions but this is usually at a very aggregated level.

change because of health conditions.[73] Again, the social consequences of climate change, with reasonable social welfare functions, may be markedly greater than they would be if one ignored these horizontal differences.[74]

4.7 Risk

Within the utilitarian framework, in the simplest representation, in the presence of risk, in each of the maximands described so far, we replace U with its expected value. (In 4.1 to 4.3, we have explained why that is almost surely an inadequate approach; but it is the simplest, and most in line with conventional economics.) Because of concavity, EU(C) < U(E ($\bar{C}$)), where $\bar{C}$ is the expectation of C, and given the level of uncertainties and reasonable estimates of the degree of risk aversion, the disparity is large. Thus, as climate change proceeds, risk increases the gap between the putative welfare of the "central or average case" analyzed in any model that does not fully embrace uncertainty and risk, and the expected utility of future generations along actual trajectories becomes increasingly large, and *biased:* the difference between expected utility on paths in which climate action has been curbed to say 1.5 degrees Celsius and 3 degrees Celsius are far larger than in a model ignoring risk. That implies, of course, a greater willingness to pay to reduce the (likely) magnitude of climate change.[75]

4.7.1 Extreme risks and stochastic processes

This is especially so once we take into account some of the compounding economic risks associated with a non-orderly transition, as described earlier (e.g. the costs associated with

[73] Stiglitz (2019) explains why it may be impossible for public intervention to fully undo these climate effects and the policies adopted to mitigate them.
[74] As we introduce each complexity, we note the impact on the costs of climate change (the impact of that particular complexity on the change in social welfare resulting climate change. Denoting by ΔW_c the change in social welfare as a result of climate change, we have argued, for instance that considering inequalities among individuals leads to a larger value of ΔW_c. We would pay more to stop climate change. But much economic policy is made at the margin, and at the margin, we focus on the MSC. That, in turn is related to impacts on the average values of marginal utilities. While it is not inevitable that a larger value of ΔW_c is associated with a larger value of expected or average marginal utilities, in each of the major cases examined, we have shown that to be the case.
[75] Effects on the social cost of carbon are sensitive to the particular parameterisation of the utility function, suggesting another reason why a framework for policy analysis centred around the social cost of carbon may be of limited usefulness.

systemic fragility), and incorporate damage functions reflecting risks to life, health and biodiversity, and the consequences of extreme events, leading to the risks of extreme losses. Then, for t sufficiently far into the future EU(C) may not be well defined. The standard criteria of choosing policies to maximize expected intertemporal utility may fail, because with some widely used utility functions, all trajectories within a wide class[76] may yield seemingly the same outcome, minus infinity.[77]

There may still be some trajectories whose outcomes are bounded, and these may be achievable at moderate costs. Societal welfare is best enhanced by taking actions which avoid the extreme outcomes occurring (with a significant probability) just as we argued earlier was the case for individuals.[78] This is the course taken for the UN Paris climate agreement of 2015. The world's leaders may have had a better sense of the correct societal decision problem than did the IAM modelers. If there are actions that strongly limit the probability that disastrous outcomes occur, and these entail modest costs, then it can be argued that these actions should be undertaken. The relevant choice is only among those trajectories that avoid, or radically reduce the probability of, the disastrous outcomes, i.e. do we take preventive action today by not allowing carbon emissions to enter the atmosphere, or do we take action later, removing the carbon that has already entered the atmosphere [79].

4.7.2 Correlation of risk with marginal utility

The cost of variability (e.g. as measured by the percentage of mean income that one would be willing to give up to eliminate risk or to reduce it at the margin) depends critically on the correlation of risk with the marginal utility of income—that is, if losses occur in states of nature where the value of income is particularly high, then the cost of risk will be

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[76] Including possibly the central trajectory labeled as "optimal" by the IAMs.
[77] Our late friend Marty Weitzman was concerned with these issues and discussed them with us over the years.
[78] This is the approach also advocated by Kaufman *et al (*2020).
[79] If there is going to be a significant probability of a disastrous outcome no matter what we do, so on all trajectories beginning today, using some standard utility functions, expected intertemporal utility is minus infinity (unbounded), we still be may able to rank alternative trajectories, much as economists studying growth paths attempted to rank trajectories when the intertemporal utilities that they were seeking to maximize were unbounded. The welfare notion is intuitive and straightforward: we want to maximize the time before the "cataclysm," i.e. delay, as far as possible, the likelihood of the extreme event; and among trajectories with the same expected date of death, maximize expected intertemporal utility in the period before death.

particularly high. But this is the case for climate risk, because in those states of nature where the consequences are severe, incomes will be low, and so will the capacity to respond. The value of the (marginal) dollar will accordingly be high. The implication is that the cost of inaction is even greater than would be the case in a standard risk model, and that investments in climate mitigation are like insurance— there is good reason for undertaking them even if the expected return is negative; or equivalently, the “risk discount factor” is negative.

There is another intuition that reinforces this conclusion: discounting links the relative standard of living now and in the future. Earlier we noted that if consumption is growing, the discount rate is increased to reflect that growth, by an amount which is proportional to the elasticity of marginal utility. By the same token, if climate change leads to a decline in standards of living, broadly defined, with a high enough probability, the discount rate is lower than δ—and if the decline is large enough, the discount rate is negativ.

Thus, models incorporating risk and time discounting support the use of an effective discount rate for evaluating climate projects that is small—smaller than the normal social rate of discounting. If there are important possibilities of catastrophic climate change in the future and very low living standards for those who survive, social rates of discount could be negative (Arrow, *et al.* 1996).[80]

4.8 Discounting intergenerational welfare and markets

In evaluating any action directed at reducing the emissions of CO_2 and other greenhouse gases, we compare the social cost of carbon with the cost of the action. Since the costs of climate change will be greatest years into the future, the question is, how do we value *today* these distant effects, i.e. how do we “discount” the future. In simple form; we would link discounting to the relative standard of living now and in the future with λ, the social discount factor, defined as the relative social value of an increment in consumption in the

[80] This analysis assumes, in effect, that individuals care only about goods, and climate change affects production possibilities. In (1), we considered the possibility that individuals directly value E. If $U_{12} > 0$, the effect we just described would be strengthened.

future relative to now. The social discount rate is defined as the proportional rate of fall of λ. Following a treatment similar to expression (6) above we can see that then

(14) $-\dot{\lambda} / \lambda = \eta g + \delta$

in a simple aggregate model, where η is the elasticity of social marginal utility of consumption, g is the growth rate and δ is the pure-time discount rate ((14) is often described as the Ramsey equation). If climate change causes negative growth, this discount rate could be negative. In any case, we would emphasize that it is the discount factor that is the logically prior concept and that is dependent on relative living standards.

There is a large and conceptually flawed literature that suggests that the market rate of interest is an appropriate discount rate for evaluating the costs and benefits of climate mitigation actions. Markets are not about social values and most capital markets have serious imperfections

The consequences of using a high interest rate, even 7%, are obvious: a dollar in 50 years is worth 3 cents, a dollar in a hundred years is worth 0.1 cent: implying we should essentially do nothing to avoid large calamities a hundred years from now.

In the standard models with no risk, no taxes, and no other distortions, of course, the only interest rate is the safe rate of interest. The safe rate of interest reflects the (representative) individual's marginal rate of substitution between today and tomorrow. The safe (real) interest rate is very low—in recent years negative, over the long run, around 1 to 1 ½ percent. In the standard model, the return on investment would be correspondingly low.

But, as we have emphasized, even that rate of interest is *not* the appropriate interest rate from a normative point of view: for we care about the marginal rate of substitution across generations. To say that if we really cared more about future generations we would have redistributed more—so that what we observe is the "revealed" social welfare preference—does not provide a convincing response. When we consider climate policy, we are addressing a difficult intergenerational ethical issue, of the sort that we normally, as a society, do not address.

As we think about social security, public investments in infrastructure, or a host of other issues which affect the intergeneration distribution of income, while we may be cognizant of the longer-term effects, it is the current generation whose voice is heard most clearly. The fact that we do not adequately address these issues in other contexts does not mean that we ignore them in the context of climate policy. Policy analyses are designed to provide guidance on how to think about alternative policies from a long-term ethical point of view, i.e. using an ethically justifiable intergenerational social welfare function.[81] With no pure-time discounting (i.e. discounting of future life or utility), in the absence of risk, the only discounting of future consumption or incomes reflects the increase in incomes as a result of advances in technology. Median per capita real income in the US has been increasing far less than 1% per year. Assuming a logarithmic utility function would imply (again ignoring risk) a discount rate of far less than 1%. And, to emphasize again, this leaves out the possibility of very low future income, indeed future loss of lives on a major scale, as a result of badly managed climate change.

Risk and Time Discounting

Risk complicates matters. As we have emphasized, risk discounting and time discounting are distinct concepts. The fact that corporations often confuse the two is not justification for doing so in public policy analysis. Indeed, it reinforces the need for stronger government action.

Heuristically, as we noted in section 2, one way to approach risk analysis is to calculate the certainty-equivalent utility level at each date (in each generation). If there is increasing uncertainty about the consequences of climate change going out in time, then the certainty-equivalent of future generations' income (as viewed today) is lower, and the expected

[81] Even without risk, but taking into account the intragenerational distributional impacts, the effective discount rate that one should employ may differ markedly from the pure rate of time discount, adjusted for changes in consumption over time (see Fleurbaey and Zuber, 2015; Stiglitz, 2018). The degree of inequality may be changing over time and investments may affect the degree of inequality.

marginal utility of income is accordingly higher.[82] With increasing uncertainty, the certainty-equivalent consumption level is increasing more slowly than the average (or expected) consumption level—indeed, if risk is increasing enough, it may be decreasing. Given the increasing uncertainty, under plausible conditions, the expected value of marginal utility is increasing. This means that we would want to take stronger precautionary actions today—the discount rate is lower, possibly far lower, possibly negative. With fat-tailed stochastic processes, these effects will be particularly large.

In short, the fact that the average return to capital is, say, 7 per cent is not an argument for using a 7 per cent discount rate in climate change.[83] Risk induces firms to demand a higher expected return to justify any investment. With climate change, it is exactly the opposite: increasing risk over time justifies using an interest rate that is lower than the safe interest rate.[84]

Once we take into account the correlation between marginal utility of income and the benefits of climate mitigation, it means that the appropriate discount rate may be even *lower* than that which would prevail in the absence of risk. It is rational to engage in investments which hedge risk, even when such investments yield a negative expected return. [85]

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[82] For a fuller analysis and references, see fn. 53.

[83] Some have argued for using the 7% discount rate because it represents the *opportunity costs.* But the opportunity cost for a save investment is the safe rate of interest, say 1%. The difference between that and 7% is the compensation for risk (or monopoly returns.)

[84] Moreover, the risks that the firm looks at are its *private* risks, which are distinctly different from those of society as a whole. More broadly, there is no reason that the appropriate compensation for risk for a typical private investment has anything to do with that for a climate investment.

[85] There are further complexities in discounting associated with taxation, and which provide further reasons that the observed average returns on capital do not provide an appropriate basis for time discounting, especially in the context of climate change (see Gollier and Hammitt, 2014; Stiglitz, 1982).

One reason for the multiplicity of interest rates is the prevalence of capital market imperfections, associated with market segmentation, market power, and imperfect information. These imperfections provide another rationale for not using average returns to private capital as the basis for discounting for social investments, including climate change.

4.9 Endogenous preferences

We commented earlier (section 2.7) that preferences are endogenous, changing, and diverse. While this has implications for the coevolution of the economy and the environment, the more profound implications relate to the normative analysis. Standard welfare economics (and IAMs) is based on the presumption that preferences are fixed and unalterable, but they are not.

There are two reasons to believe that changing and endogenous preferences might lead to stronger climate policy being desirable than suggested by the IAMs. First, at least some weight needs to be given to those who care intrinsically about the environment and its preservation, and the evidence is that it is an increasing fraction of the population. Forecasting these trends and reflecting Ramsey's dictum of no discrimination against future generations supports the case for placing heavy weight on the environment. Moreover, as we note further below, the costs of mitigation by behavioral adaptation may be low: is there any loss in well-being, properly calculated, if individuals adapt their diet, coming actually to prefer diets with less or zero meat? If not, it implies that one can achieve substantial reductions in carbon emissions with essentially no loss in "well-being."

5. How most of the existing IAM literature follows misguided methodology and misleads policy

Previous sections have analyzed the importance of risk, market failures, distribution (both within and between generations), and the limitations in government correcting market failures, undertaking redistribution, and in particular undoing the adverse distributional effects of climate change. These are central to understanding the nature of economic and climate trajectories in the business-as-usual scenario and with various forms of intervention, in evaluating alternative policies, and in calculating the social cost of carbon.

Unfortunately, a key analytical work horse at the heart of much of the existing literature, Integrated Assessment Models (IAMs), fails badly in reflecting these elements which are essential for any adequate analysis. While there is a recognition that there is considerable uncertainty about key parameters, the response has been to conduct simulation exercises with different parameters, *assuming that all market participants know these parameters* *and believe that they describe the economy accurately.* That is, they ignore the deep uncertainty which pervades all economic agents' behavior and well-being, and the effect of climate change on this uncertainty and insecurity. This is but one example where the "damage" associated with climate change has typically been underestimated in these models.

Still another fundamental flaw with these models is that they assume that the maximand of the (representative) individual corresponds to that of society. As we emphasized in sections 1 and 4, there is a compelling case that that is not so.

These methodological and modelling faults, as embodied in most of the IAMs, make these models an inappropriate basis for *assessing* the desirability of alternative policies. They result in "optimal" stabilized temperatures which are very high, much higher than the vast majority of the scientific community believe should be acceptable. In particular, William Nordhaus (Nordhaus, 2018 and 2019) points to a long-run "optimum" temperature trajectory of around 4 degrees Celsius (reaching 3.5 degrees Celsius by around 2100). The scientific evidence we have described indicates that this would carry immense risks of devastation to lives and livelihoods that would be regarded by most climate scientists as absurdly risky and fundamentally unacceptable.

Some of the failings of the standard IAMs can be addressed, and in the robust literature, many have been [86]. One can, for instance, incorporate into the damage function some

[86] Hänsel et al. (2020) show that adjusting the parameters of DICE, to reflect the latest findings on economic damage functions, some of the latest climate science and a broad range of expert recommendations on the pure rate of time preference and the elasticity of marginal utility, as elicited by Drupp et al. (2018), brings the economically 'optimal' climate policy path in line with UN climate goals. Schumacher (2018) has demonstrated how equity weighting can lead to significantly higher global damages from climate change than those reported by unmodified IAMs. Moore and Diaz (2015) show that implementing temperature effects on GDP growth rates in DICE results in optimal climate policy that stabilizes global temperature change below 2 °C. Explicit modelling of adaptation in IAMs shows that joint implementation of mitigation and adaptation is welfare improving (de Bruin et al. 2009; Bosello et al. 2010). Work by Carleton and Hsiang (2016), Ciscar et al. (2019) and others feed into better calibration of damage functions. Climate and social tipping points have been incorporated into IAMs (see e.g. Cai et al 2016; Grubler et al. 2018; Yumashev et al. 2019). Completely different approaches to IAMs are under development, e.g. analytical IAMs (Gerlagh and Liski, 2018a; Gerlagh and Liski, 2018b; Golosov et al., 2014; Hassler and Krusell, 2012; Hassler et al., 2018; Iverson and Karp, 2017; Karp, 2017; Rezai and van der Ploeg, 2016; Traeger, 2018) and agent-based IAMs (Czupryna et al., 2020; Lamperti et al., 2018).

account of the loss of lives and destruction of biodiversity. When that is done, the IAMs turn out not to be robust: one obtains a wide range of estimates of the social cost of carbon and of the optimal maximal acceptable temperature change. (Sometimes policymakers are tempted just to look at the range of estimates say of the social cost of carbon, and pick one in the middle. That methodology is flawed. The low estimates might be from models that assumed risk were zero; higher estimates might include reasonable ranges of uncertainty. If that were the case, clearly the latter estimates are to be preferred to the former.)

One of the objectives of this paper is to provide a framework for assessing, who is right? Is it that most scientists are thinking sloppily, with a soft heart clouding cold reason? Or is it that those building IAMs made use of readily available tools within the economists' standard toolkit, notwithstanding that those models are methodologically, and in other ways, inappropriate for the analysis of the problem at hand, and further that most of them have, so far, failed to adapt the models in ways which make them relevant?

The early attempts (e.g. Nordhaus, 1991a, b; Cline, 1992) were worthy attempts to analyze a phenomenon fairly new to economic attention, using standard tools of exogenous growth theory and marginal perturbations. It is interesting to note that at that point of time there was a concern that over-reaction should be avoided—avoiding over-reaction was even called a "precautionary principle". But over the next two decades, as the science advanced, evidence was building that the risks from climate change were so large that the methods inherent in such models were an inadequate basis for capturing the key issues and for making policy.

5.1 Damage functions

The damages from a global temperature increase are reflected, in most of these models, by a proportionate reduction in overall *output*. Thus, for example, in Nordhaus' DICE models, losses from a 3 degree Celsius temperature increase are around 2% of GDP and for a 6 degree Celsius temperature increase around 10-12% of GDP. There is no damage to capital stocks in these models, nor any reduction in the underlying growth rate, which is assumed to be exogenously determined. A 6 degree Celsius increase in temperature would likely involve a massive disruption in livelihoods and severe loss of life across the world. It would involve sea-level increases of scores of meters and lead to temperatures last seen on the planet tens of millions of years ago. Multiple tipping elements in the climate system could have passed critical thresholds[87] (Lenton et al., 2008), risking a global cascade of tipping points which would be an existential threat to civilization (Lenton et al., 2019).

Given that many parts of the world would have to be abandoned as submerged, or vulnerable to severe weather events, including outdoor temperatures intolerable to human beings, for extended periods (wet-bulb temperatures above 35 degree Celsius) (Xu et al., 2020), the assumption of no reduction in, or damage to, capital stocks is clearly untenable. So too the idea that there could be an unchanged underlying growth process. These assumptions imply that the estimates of damages from climate change in these IAMs is much smaller than is likely to occur. Not surprisingly, results on optimal policy change dramatically if the assumed damages from climate change are much larger. Dietz and Stern (2015) show how stronger damage functions transform the results.

5.2 Broader societal losses

Losses from climate change include impacts on lives, health, and biodiversity. Each of these involves difficult valuation issues (see the discussion in section 4). The magnitude of these impacts is currently, poorly incorporated into IAM damage functions (Diaz and Moore, 2017; Howard, 2014). Incorporating better estimates of these losses increases the magnitude of damages associated with high increases in global temperatures by a significant amount (DeFries et al., 2019; Weitzman, 2009).[88]

[87] Boreal forest dieback; Amazon rainforest dieback; Sahara/Sahel greening and West African monsoon (WAM) shift; change in El Niño–Southern Oscillation (ENSO) amplitude or frequency; Atlantic thermohaline circulation (THC) shutoff; West Antarctic ice sheet (WAIS) collapse, Greenland ice sheet (GIS) collapse; Arctic summer sea-ice loss.

[88] See also the rough calculations included in section 4.

5.3 Exogenous growth

The models have underlying growth processes which essentially embody standard growth models with exogenous growth of 1-2% p.a. over the indefinite future. Given the extraordinary disruption likely at 3-6 degrees Celsius, this assumption would seem to be absurd given the deterioration of productive opportunities likely to arise with a transformation of the environment which likely results in immense loss of life, destruction of capital, collapses in biodiversity, and a recasting of where was habitable. Moreover, the high levels of expenditure necessary to adapt to climate change, especially in the more adverse scenarios, implies that resources will be diverted away from innovation and investment and the social cost of carbon in those states of nature will be high.[89]

The assumption of exogenous growth has a powerful effect on results. A 1.5% growth rate would roughly quadruple output in a century. A 10% loss of output at 6 degrees Celsius 100 years from now, if that occurred, would seem very little in the context of a quadrupling of output. If that were what climate change and growth looked like, why would one bother with trying very hard to limit climate change? By contrast, because of compounding, even a small impact on growth rates over an extended period has enormous impact.[90] It is surely clear that the assumptions on damages and growth are unpersuasive in the context of the likely destructive effects of climate change.

5.4 Distribution of risk

The above discussion works largely in terms of damages associated with particular temperatures. Of course, there are real uncertainties about both the consequences of different temperature increases, and what temperature increases might occur from different paths of emissions. Even if the mean expected temperature were limited to 3 degrees Celsius (itself very dangerous), there would be risks of much higher temperatures, the costs of which could be disproportionately higher. With damages that are likely to be

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[89] The global financial crisis, a much smaller perturbation than the climate crisis, has had a markedly adverse effect on growth rates in US and Europe. Part of the reason may be the diversion of energy (talent) to deal with the crisis.

[90] Especially so because of evidence of near-unit roots in the stochastic processes describing GDP.

strongly convex functions of temperature, those risks of high temperatures would weigh heavily in the assessment of possible damages from climate change. Thus, the certainty equivalent level of consumption along paths entailing larger climate change is likely to be markedly lower than in the IAMs, and by an increasing amount over time, because of the higher level of risks associated with such trajectories. Models ignoring risk lead to insufficient action even more so because the marginal utility of consumption will be high and growth rates low in precisely those states of nature where the damage resulting from climate change is high.

To put it another way, when damage functions are adjusted to reflect risk, both the level and the slope of the damage function shift up, and possibly markedly so. This is especially true if the probability distribution of losses is fat-tailed as Weitzman (2009) and others (Ackerman et al., 2010; Dietz, 2011; Pycroft et al., 2011) have argued.

5.5 Distributional issues

Intragenerational

Most IAMs deal with aggregate consumption as the argument of a social utility function, sometimes using broad regional sub-aggregates. This approach misses crucial distributional issues as it is the poorest who are hit hardest by the effects of climate change; see, for example, the cyclone in Mumbai and Hurricane Katrina in New Orleans both in 2005. And it is the poorest people who are least insured, who have the least resources to adapt and usually live in areas that are least protected. The hardship that they bear, would, for the value judgements of many, require strong weighting in valuations of damage and this is largely missed by the aggregate approach in IAMs. Nor, as we have emphasized, can it be assumed that government will simply undo these distributional effects[91].

Intergenerational

In the literature pure-time discount rates of 1-2% are common (e.g. Anthoff and Tol, 2014; Nordhaus, 2017). A pure-time discount rate of 2% would count a life which began 35 years

[91] Implicit in IAM analyses which ignore distributive costs is some version of the second welfare theorem (see fn. 71). The conditions under which that theorem holds are sufficiently restrictive as to make it irrelevant for policy (Stiglitz, 1994).

from now at one-half an otherwise identical life starting now. There is no plausible articulation of such an assumption and sometimes is justified by vague appeal to markets. As we saw in sections 4.3 and 4.8, such arguments are unsound relative to most moral foundations and the basic economics of capital markets.

5.6 Absence of market failures

A central point raised in section 2 was that the presence of market imperfections (market failures) likely raises the level of emissions compared to what they would be in a world without such failures, and raises the social cost of carbon while reducing the marginal cost of abatement.

One of the most important insights in economics in the middle of the last century was the theory of the second best. It observed that the consequences of removing a market failure in the context of a world where that market failure was the only market failure were markedly different from the consequences of removing a market failure in the context of a world in which there are multiple market failures (Lancaster and Lipsey, 1956; Meade, 1952). Much of the work in IAMs has omitted that lesson, or (implicitly) assumed that somehow government has remedied all market failures other than that associated with climate change.

5.7 Cost of mitigation

As we have noted in earlier sections, optimal policy in the IAMs entails setting the social cost of carbon (as derived from the intertemporal maximization problem) equal to the marginal abatement cost. If it is assumed that the latter is higher than it is in fact, again the "optimal" policy entails a higher long-run temperature. Implicit in at least many analyses is the assumption that innovation currently is optimal, so that welfare would be decreased by policies that enhance innovation. But, as section 3 emphasized, there are good reasons to believe that the levels of innovation, especially in the areas of concern, have been markedly suboptimal, and the mild measures to encourage innovation have already brought enormous benefits in terms of reduced costs of emission reduction. When there are large market failures which result in higher than efficient levels of emissions, interventions which address those market failures can lead to large reductions in emissions at low or negative costs- the marginal abatement cost is lower than if the greenhouse gas externality were the only market failure.

Moreover, as we have noted, with endogeneity of preferences and social norms, the social costs of changing behaviors in ways which reduce emissions may be far lower than implied by models which take preferences as fixed.

5.8 Powerful bias from assumptions in the IAMs

We have examined briefly here the key assumption within IAMs, showing how they all, on damages, on technology, on values and preferences, in the treatment of risk, distribution, and other market failures, tilt conclusions away from strong action on climate change and towards a low social cost of carbon. There is no mystery why Nordhaus concludes that stability at 4 degrees Celsius would be "optimal": he underplays damages, overplays costs of action and largely ignores the basics of moral philosophy on inter-temporal valuation, whilst specifying intertemporal values which have little foundation on ethics. Dietz and Stern (2015) show that adjusting just the first of these biases can have a profound effect on results. A range of other studies shows that mild modifications in the parameters put into the models yields markedly different results, more in accord with the international consensus. Seemingly, the models do not appear to be very robust. Even on their own terms, they are a weak basis for guiding policy and estimating social costs of carbon.

In our discussion here we have argued that the major part of the literature on IAMs is deeply flawed in the assumptions made, in leaving out market failures, distributional impacts, an adequate treatment of risk, and the limitations in government in correcting market failures and redistribution. Obviously, it is desirable to integrate economic and environmental analyses, and it is a task for future research to do that in a way that provides insights that are relevant for policy. While we have explained how some of these flaws and biases could be mitigated with different assumptions, and there have been some relevant contributions in the literature, there are deeper problems with the general approach of maximizing a social welfare function in the presence of extreme risk, as we argued in section 4. The next section briefly describes an alternative approach.

6. An alternative approach

There is an alternative strategy for designing policy in the face of the extreme risks presented by climate change: first, describe the likely consequences from climate change, under current arrangements; second, examine how the economy and emissions could be managed to give a good chance of stabilizing at different temperatures; and third, combine these two elements into a judgement on an approach to a temperature target. This is a consequentialist analysis of strategy towards immense risk. That analysis can then be followed by one that analyzes the consequences of setting different targets. By exposing explicitly the full consequences of different targets, including the risks which they entail, one provides a framework for better decision making, especially relevant in a world where different individuals may have different attitudes towards risks and/or different judgements about the probabilities of different scenarios, as we observed in section 4.

We don't need a full optimization model to make certain decisions, i.e. to obtain a partial ordering. If risk to well-being along a trajectory entailing an increase of 4 degrees Celsius is sufficiently below that with a 2 degree Celsius increase, it would "pay us" to spend the additional amounts required to limit climate change. If, as the Stern-Stiglitz Commission (2017) and others (Energy Transitions Commission, 2018; New Climate Economy, 2014; OECD, 2017) have estimated, it would take at most 2% of GDP[92] to limit temperature increase to 2 degrees Celsius, then if the value of the incremental (expected) loss from 4 degrees Celsius increase is greater than 2%, it would be socially desirable to make that investment. Indeed, it is even possible that these green investments might lead to a *higher* level of output, appropriately measured. With sufficient precautionary behavior, with sufficient risk aversion, it is understandable that the world wants to avoid the potential dire effects of 4 degrees—and one can make that judgment without a full optimization model.

[92] The investments embodied in this 2% can have very high social returns beyond reduced greenhouse gas emissions, including reduced air pollution, stronger biodiversity and so on. Thus, it is better to see these as investments rather than only as simply a "cost".

Indeed, such “full optimization” does not accord either with the way individuals or societies make decisions. In the presence of these extreme uncertainties, contemplating what the full range of possibilities might be, the likelihood that they might occur, and how well-being would be affected takes enormous effort; indeed, a full analysis is impossible. As individuals go about making decisions (or evaluating alternative public policies) they do not attempt to create a full ordering or indeed a full description. This helps explain the methodology for which we just argued: they could assess that at, say, 3 degrees Celsius there is a sufficient risk of very bad outcomes that if the probability of such an outcome can be greatly reduced at reasonable cost (say 2% of GDP per year) by setting a commitment not to exceed 2 degrees Celsius, it is desirable to do so. With these understandings, and with the knowledge that one can limit global warming to 2 degrees Celsius (with “reasonable probability”) at a cost that is less than 2% of GDP p.a, they do not have to enquire further, e.g. into how much they would be willing to pay. There might be a follow-on question: comparing 1.5 degrees and 2 degrees in a similar way. This is a structured, consequentialist dialogue which individuals could have with themselves (and with each other). It keeps a complex question simple but gets to the heart of decision-making.[93] And this is especially so if there are perceived to be certain threshold levels, as in the analysis of section 2.

A partial integration of the two approaches could be found by modifying the framework of section 2 by adding to the Hamiltonian an additional constraint, that the temperature (modelled as a function of the environmental state variables) never increase beyond 2 degrees C. (compared to pre-industrial levels). With this additional constraint in place, we can calculate, in terms of marginal damages, the social cost of carbon along a path where temperature is constrained below 2 degrees C[94].

The social cost of carbon calculated this way corresponds more closely to, but is not the same as, that provided by the Stern-Stiglitz Commission. They examined the prices of

[93] We do not provide here an axiomatic basis for this perspective. We note, however, that the individual realizes the deep uncertainties which are likely to overwhelm any fine-tuned calculations of his preferences. Moreover, individuals typically do not know their own preferences outside realms in which they regularly make choices—and this is an example well beyond individuals’ own experiences. In addition, individuals know that their preferences are endogenous (see the discussion below) and a major societal change such as climate change may well affect the evolution of preferences, but in ways which it is difficult for individuals to assess.

[94] See Dietz and Venmans (2019).

carbon that lead, over time, with markets *as they exist, modified by government climate interventions,* to achieve the goals of the Paris Agreement. Of course, the appropriate prices in this approach are highly dependent on these other policies, as the 2017 report of the international carbon pricing commission that we co-chaired emphasized. The prices we suggested in that report were, for 2030, $50-100 per ton. But since then ambitions have been strengthened (with targets at 1.5 degrees C rather than "well below 2", and net-zero emissions by 2050), and emissions have gone on rising. This would suggest that the top of that range would be relevant.

Given the physics of climate change, there is a close congruence between the formulation just described (with the 2 degrees constraint) and an alternative one, which, given the increasing recognition of the magnitude of the risks associated with climate change, is the one that the international community seems to be settling upon: adding to the Hamiltonian of section 2 the constraint of zero net neutrality by 2050.[95] A solution to this problem has been provided by Kaufman *et al (*2020), who come up with a SCC based on marginal damages around $125 per ton by 2030. The two approaches (as exemplified by Stern-Stiglitz and Kaufman et al) are different but in either case the numbers likely to emerge would be more in the region of $100 per ton by 2030 rather than the $50 per ton (in 2007 prices, $60 in 2018 prices) estimated by the Interagency Group in the Obama administration (with a 3 percent discount rate)[96].

7. Concluding remarks

We identified at the outset a set of major methodological flaws permeating the literature on the economics of climate change and in the subsequent analysis have examined some of the consequences, including a systematic bias towards reducing the strength of action on climate change, that results from underestimating the benefits and overestimating the costs of such action. In summary, these flaws: first, in the presence of extreme, for many

[95] The two problems are not identical. The international community may be excessively pessimistic about the ~~ability to take carbon out of the at~~mosphere, and so may be excessively aggressive in going to carbon neutrality. But the same risk aversion/precautionary behavior discussed with respect to going beyond 2 degrees C. may apply here: recognizing the uncertainties in technology, the international community does not want to face the risks imposed of a world which still has significant carbon emissions in 2050.

[96] The Stern-Stiglitz approach produces prices that could guide private sector decisions. The Kaufman *et al* approach seeks to identify a shadow price for public decisions. The underlying models are rather different. But nevertheless it is reassuring that the numbers are in the same "ball park".

existential, risk, standard expected utility approaches are potentially deeply misleading. Second, assuming that all relevant markets are both present and perfect, except for the greenhouse gas externality, is a serious empirical and analytical mistake, and severely biases the analysis. Third, tackling the problem of climate change will require rapid and fundamental economic and technological transformation, which will involve dislocation, disequilibrium and deep systemic change and simple competitive equilibrium analysis, with full market clearing, severely distorts the design and assessment of policy. Fourth, the effects of climate change and the impact of policy vary greatly within populations; distribution has profound implications not only within but across generations- intertemporal values are central and their role warrants explicit examination- and across dimensions within a generation, including fundamental aspects of well-being broadly understood. Thus, in this context, aggregation into single individuals or single consumption goods can be particularly misleading.

As we have seen, the implications of these methodological flaws are fundamental. In the standard models, there is a close congruence between what the representative individual maximizes and the social optimization problem. The only disparity arises from the failure to internalize the environmental externality. We have shown that analyses based on that approach provide a poor description of the market economy, and accordingly cannot provide a sound foundation for policy and normative analyses. Analyses which embody these flaws, and the IAMs have, in large measure, embodied all of them, are biased against strong action. And they produce results, such as an “optimum” temperature trajectory that reaches 3.5 degrees Celsius of warming by 2100 and stabilizes at around 4 degrees Celsius which entail extraordinarily high levels of risk --with such risks either being explicitly ignored or marginalised--or with assumptions about the willingness-to-bear such risks buried inside the analysis. And they correspondingly lead to a too low social cost of carbon and a too narrow set of instruments to be employed in addressing climate change—more than price interventions are required.

Perspectives which take account of these flaws have pointed to an approach, such as embodied in the 2015 UNFCCC Paris Agreement, which sets a target designed to avoid and limit the risks, and which examines the achievement of targets in the best possible way from the perspective of well-being across and within generations. We have shown how a social cost of carbon can be estimated based on this alternative perspective; a price that will guide the economy and emissions towards the climate change target, a number that more realistically reflects perceptions of the risks of going beyond 2 degrees C.

The potential of new forms of growth and development

Underlying much of our analysis is the contention that, for a variety of reasons, market allocations may not be efficient or equitable and that climate change is not the only market failure. This has many implications. Most striking, it implies that growth, especially correctly measured, may actually be enhanced with stronger climate change policies. (By contrast, IAMs assume growth rates are exogenous, while our earlier analysis argued that accepting high levels of climate change will adversely affect well-being. Here we argue, by contrast, that strong climate action may have growth benefits.) There are three reasons, one discussed extensively here, two just hinted at.

The first is that the market is not in general efficient in either the direction or pace of innovation. Economies explore innovations near where they are. For two hundred years, technologies based on fossil fuel have been explored. Diminishing returns may have set in. Climate change has induced new searches in other parts of the technology frontier. Possible paces of innovation in these relatively unexplored areas can, at least for now, be markedly higher. This paper has presented evidence that that is in fact the case: the green economy may usher in a new era of high productivity growth.

The second is that the timing for climate action is coming just at the right moment in history, where the economy is going through a difficult economic transition from the manufacturing economy to a service sector, knowledge-based economy, with artificial intelligence, robotization, and globalization all leading to significant increases in inequality and the possibility of significant increases in unemployment. A transition to zero-carbon offers the possibility for the next thirty years of lower unemployment and inequality. And there would be stronger growth. Arguments on timing are reinforced by the necessity of recovering from the recession resulting from the response to the pandemic.

The third point (touched upon in sections 2 and 4) is that studies that have focused on impacts on aggregate consumption or GDP, as conventionally measured, are likely misguided: we care about living standards, broadly defined, not narrow aggregates which are a poor measure of well-being. Climate action can enhance well-being, both through the new ways of consuming and through the avoidance of immense risk.

Ways forward

Given that the strategic challenge, as we have set out in the opening section, is to avoid the extreme risks associated with large changes in climate, such as those that would likely occur were we to accept temperature changes beyond 2 degrees C, and given that to achieve that the world must move to a net-zero carbon economy within a few decades, the economics of policy can shed light on how to get there in ways that are efficient and equitable.

If the Biden Administration adopts the analyses of the standard IAMs, it is at risk of being put into the untenable position of employing models which reject the Paris Agreement and in which the social cost of carbon is estimated on the basis of accepting climate change of 3.5 to 4 degrees C. That is, almost surely, were the SCC associated with the standard models to be accepted, the US would be committing itself *not* to achieve the Paris goals. We have laid out in section 6 an alternative approach which is consistent with the Administration's stated position.

This paper thus provides a path towards the reconciliation between the perspectives of the broader scientific community, which has pushed for urgent and strong action (IPCC, 2018; Ripple et al., 2020) and a part of the economics community, using particular versions of Integrated Assessment Models, who have been skeptical of the need for such urgent action and have not only been tolerant of, but urged the acceptance, of higher levels of climate change. The intuitions of the scientific community may well be right: the simplistic models of the economists have simply not captured essential aspects of the societal decision problem, and when they do so, the disparities in perspectives may be closed, if not eliminated.

References

Acemoglu, D., Aghion, P., Barrage, L., & Hemous, D. (2019). Climate Change, Directed Innovation, and Energy Transition, The Long-Run Consequences of the Shale Gas Revolution.

Ackerman, F., Stanton, E.A., & Bueno, R. (2010). Fat tails, exponents, extreme uncertainty, Simulating catastrophe in DICE. Ecol Econ, 69(8),1657–1665.

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., & Van Reenen, J. (2016). Carbon Taxes, Path Dependency and Directed Technical Change, Evidence from the Auto Industry. Journal of Political Economy, 124, 1-51.

Anthoff, D. & R.S.J., Tol (2014). The Climate Framework for Uncertainty, Negotiation and Distribution (FUND), Technical Description, Version 3.9. http://www.fund-model.org/documentation/

Arrow, K.J. (1951). Social Choice and Individual Values. Wiley.

Arrow, K.J. (1965). Aspects of the Theory of Risk-Bearing. Yrjö Jahnssonin Säätiö.

Arrow, K.J., Cline, W.R., & Maler, K.-G. (1996). Intertemporal equity, discounting, and economic efficiency. In: Bruce, J.P., Lee, H., Haites, E.F. (eds) Climate Change 1995: Economic and Social Dimensions of Climate Change – Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 125–144.

Atkinson, A., & Stiglitz, J.E (1969). A New View of Technological Change. The Economic Journal, 79(315), 573-578.

Atkinson, A.B., & Stiglitz, J.E. (1976). The Design of Tax Structure, Direct versus Indirect Taxation. Journal of Public Economics, 6 (1–2), 55–75.

Battiston, S., Delli Gatti, D., Gallegati, M., Greenwald, B., & Stiglitz, J.E. (2012) Liaisons Dangereuses, Increasing Connectivity, Risk Sharing, and Systemic Risk. *Journal of Economic Dynamics and Control*, 36(8), 1121-1141.

Battiston, S., Caldarelli, G., May, R.M., Roukny, T., & Stiglitz, J.E. (2016). The Price of Complexity in Financial Networks. *PNAS,* 113(36), 10031-36.

Battiston, S., Mandel, A., Monasterolo, I., et al. (2017). A climate stress-test of the financial system. Nature Clim Change, 7, 283–288.

Bosello, F., Carraro, C., & De Cian, E. (2010). Climate Policy and the Optimal Balance between Mitigation, Adaptation and Unavoided Damage. Climate Change Economics, 1, 71–92.

Cai, Y., Lenton, T.M., & Lontzek, T.S. (2016). Risk of multiple interacting tipping points should encourage rapid CO 2 emission reduction. Nature Climate Change, 6(5), 520.

Carleton, T.A., & Hsiang, S.M. (2016). Social and economic impacts of climate. Science, 353, aad9837.

Catanzaro, M., & Buchanan, M. (2013). Network opportunity. Nature Phys 9, 121–123.

Chichilnisky, G., Hammond, P., & Stern, N. (2020). Fundamental utilitarianism and intergenerational equity with extinction discounting. Social Choice and Welfare, 54, 397–427.

Ciscar, J.C., Rising, J., Kopp, R.E., & Feyen, L. (2019). Assessing future climate change impacts in the EU and the USA: insights and lessons from two continental-scale projects. Environmental Research Letters, 14, 084010.

Cline, W.R. (1992). The Economics of Global Warming. Institute for International Economics, Washington DC.

Coalition for Urban Transitions (2019). Climate emergency, urban opportunity: how national governments can secure economic prosperity and avert climate catastrophe by transforming cities. World Resources Institute (WRI), Ross Centre for Sustainable Cities and C40 Cities Climate Leadership Group, London, UK.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., & Turner, R.K. (2014a). Changes in the global value of ecosystem services. Global Environmental Change, 26, 152-158.

Costanza, R., Kubiszewski, I., Giovannini, E., Lovins, H., McGlade, J., Pickett, K.E., Ragnarsdóttir, K.V., Roberts, D., De Vogli, R., & Wilkinson, R. (2014b). Development, Time to leave GDP behind. Nature, 505, 283–285.

Czupryna, M., Franzke, C., Hokamp, S., & Scheffran, J. (2020). An Agent-Based Approach to Integrated Assessment Modelling of Climate Change. Journal of Artificial Societies and Social Simulation, 23(3).

David, P. (2001). Path dependence, its critics and the quest for 'historical economics'. In: Garrouste, P., & Ioannides, S. (Eds.). Evolution and Path Dependence in Economic Ideas, Past and Present. Edward Elgar Publishing.

Davila, E., & Korinek, A. (2018). Pecuniary Externalities in Economies with Financial Frictions. The Review of Economic Studies, 85(1), 352–395.

de Bruin, K.C., Dellink, R.B., & Tol, R.S.J. (2009). AD-DICE: An Implementation of Adaptation in the DICE Model. Climatic Change, 95, 63-81.

DeFries, R., Edenhofer, O., Halliday, A., Heal, G., Lenton, T., Puma, M., Rising, J., Rockström, J., Ruane, A., Schellnhuber, H.J., Stainforth, D., Stern, N., Tedesco, M., & Ward, B. (2019). The missing economic risks in assessments of climate change impacts. London, UK, Grantham Research Institute on Climate Change and the Environment.

Delli Gatti, D., Gallegati, M., Greenwald, B.C., Russo, A., & Stiglitz, J.E. (2012). Mobility constraints, productivity trends, and extended crises. Journal of Economic Behavior & Organization, 83(3), 375-393.

Díaz, J., García, R., Velázquez de Castro, F., et al. (2002). Effects of extremely hot days on people older than 65 years in Seville (Spain). from 1986 to 1997. Int J Biometeorol, 46, 145–149.

Diaz, D., & Moore, F. (2017). Quantifying the economic risks of climate change. Nature Climate Change, 7, 774–782.

Dietz, S. (2011). High impact, low probability? An empirical analysis of risk in the economics of climate change. Climatic Change, 108, 519–541.

Dietz, S., & Stern, N. (2015). Endogenous Growth, Convexity of Damage and Climate Risk, How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions. Econ J, 125, 574-620.

Dietz, S., & Venmans, F. (2019). Cumulative carbon emissions and economic policy: In search of general principles. Journal of Environmental Economics and Management, 96, 108-129.

Dixit, A., & Pindyck, R.S. (1994). Investment Under Uncertainty. Princeton University Press.

Drupp, M.A., Freeman, M.C., Groom, B., & Nesje, F. (2018). Discounting Disentangled. American Economic Journal Economic Policy, 10(4), 109-34.

Dumitru, O.A., Austermann, J., Polyak, V.J., et al. (2019). Constraints on global mean sea level during Pliocene warmth. Nature, 574, 233–236.

Energy Transitions Commission (2018). Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors. Energy Transitions Commission.

Eurostat (2020). Europe 2020 indicators - R&D and innovation. https://ec.europa.eu/eurostat/statistics-explained/pdfscache/50448.pdf

Evans, D. (2005). The Elasticity of Marginal Utility of Consumption, Estimates for 20 OECD Countries. Fiscal Studies, 26(2), 197-224.

Farhi, E., & Tirole, J. (2012). Collective moral hazard, maturity mismatch, and systemic bailouts. Am. Econ. Rev., 102(1), 60-93.

Fleurbaey, M., & Zuber, S. (2015). Discounting, risk and inequality, A general approach. Journal of Public Economics, 128, 34-49.

Food and Land Use Coalition (2019). Growing Better: Ten Critical Transitions to Transform Food and Land Use.

Geanakoplos, J.D., & Polemarchakis, H.M. (1986). Existence, regularity, and constrained suboptimality of competitive allocations when the asset market is incomplete. In Heller WP, Starr RM, Starrett DA (eds.). Uncertainty, Information and Communication, Essays in Honor of K. J. Arrow, Vol. III, 65 - 96. Cambridge University Press.

Gerlagh, R., & Liski, M. (2018a). Carbon prices for the next hundred years. The Economic Journal, 128(609), 728–757.

Gerlagh, R., & Liski, M. (2018b). Consistent climate policies. Journal of the European Economic Association, 16(1), 1–44.

Gilboa, I., & Schmeidler, D. (1989). Maxmin expected utility with non-unique priors. Journal of Mathematical Economics, 18(2),141–153.

Gillingham, K., Nordhaus, W., Anthoff, D., et al. (2018). Modeling Uncertainty in Integrated Assessment of Climate Change, A Multimodel Comparison. Journal of the Association of Environmental and Resource Economists, 5(4), 791-826.

Gollier, C., & Hammitt, J.K. (2014). The Long-Run Discount Rate Controversy. Annual Review of Resource Economics, 6(1), 273-295

Golosov, M., Hassler, J., Krusell, P., & Tsyvinski, A. (2014). Optimal Taxes on Fossil Fuel in General Equilibrium. Econometrica, 82, 41-88.

Greenwald, B.C., & Stiglitz, J.E. (1986). Externalities in Economies with Imperfect Information and Incomplete Markets. The Quarterly Journal of Economics, 101(2), 229–264.

Groom, B., & Maddison Pr., D. (2019). New Estimates of the Elasticity of Marginal Utility for the UK. Environ Resource Econ, 72, 1155–1182.

Grossman, S. (1981). The Informational Role of Warranties and Private Disclosure about Product Quality. The Journal of Law & Economics, 24(3), 461-483.

Grossman, S., & Stiglitz, J.E. (1980). On the Impossibility of Informationally Efficient Markets. *American Economic Review*, 70(3), 393-408.

Grubler, A., Wilson, C., Bento, N., et al. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat Energy, 3, 515–527.

Guzman, M., & Stiglitz, J.E. (2020). Towards a Dynamic Disequilibrium Theory with Randomness. NBER Working Paper No. w27453.

Hajat, S. (2017). Health effects of milder winters, a review of evidence from the United Kingdom. Environ Health, 16, 109.

Hänsel, M.C., Drupp, M.A., Johansson, D.J., et al. (2020). Climate economics support for the UN climate targets. Nature Climate Change, 10(8), 781-789.

Hassler, J., & Krusell, P. (2012). Economics and climate change: Integrated assessment in a multi-region world. Journal of the European Economic Association, 10(5), 974–1000.

Hassler, J., Krusell, P., Olovsson, C., & Reiter, M. (2018). Integrated assessment in a multi-region world with multiple energy sources and endogenous technical change. Working Paper.

Hendricks, D., Kambhu, J., & Mosser, P. (2006). Systemic Risk and the Financial System, Background Paper. Federal Reserve Bank of New York.

Howard, P.H. (2014). Omitted damages, what's missing from the social cost of carbon. The Cost of Carbon Pollution Project.

Hurd, M.D., & Smith, J.P. (2002). Expected Bequests and Their Distribution. RAND, Labor and Population Program Working Paper Series 03–10.

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 [Masson-Delmotte, V., Zhai, P., Pörtner, H. –O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., & Waterfield, T. (eds).]. In Press.

Iverson, T., & Karp, L. (2017). Carbon taxes and commitment with non-constant time preference. Working Paper.

Karp, L. (2005). Global Warming and Hyperbolic Discounting. Journal of Public Economics, 89, 261–282.

Karp, L. (2017). Provision of a public good with altruistic overlapping generations and many tribes. The Economic Journal, 127(607), 2641–2664.

Kaufman, N., Barron A.R., Krawczyk, W., Marsters, P., & McJeon, H. (2020). A near-term to net zero alternative to the social cost of carbon for setting carbon prices. Nature Climate Change, 10, 1010–1014.

Korinek, A., & Stiglitz, J.E. (2008). Political Economy in a Contestable Democracy, The Case of Dividend Taxation. 2008 Meeting Papers, Society for Economic Dynamics.

Kreps, D.M. (1979). A Representation Theorem for ‘Preference for Flexibility. Econometrica, 47(3): 565–577.

Lamperti, F., Dosi, G., Napoletano, M., et al. (2018). Faraway so close: coupled climate and economic dynamics in an agent-based integrated assessment model. Ecological Economics, 150, 315-339.

Lebègue, D. (2005). Révision du taux d’actualisation des investissements publics. Rapport du Groupe d’Experts, Commisariat Général du Plan.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., & Schellnhuber, H.J. (2008). Tipping elements in the Earth's climate system. Proceedings of the National Academy of Sciences, 105(6), 1786-1793.

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

Lipsey, R., & Lancaster, K. (1956). The General Theory of Second Best. The Review of Economic Studies, 24(1), 11-32.

Maskin, E. (1979). Decision-Making under Ignorance with Implications for Social Choice. Theory and Decision, 11, 319-337.

McKinsey (2020). Purpose: Shifting from why to how. McKinsey Quarterly.

Meade, J.E. (1952). External economies and diseconomies in a competitive situation. Economic Journal, 62, 54-67.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., & Stouffer, R.J. (2008). Stationarity Is Dead, Whither Water Management?. Science, 319, 573-574.

Moore, F.C., & Diaz, D.B. (2015). Temperature impacts on economic growth warrant stringent mitigation policy. Nature Climate Change, 5(2), 127.

Neelin, J.D., Bracco, A., Luo, H., McWilliams, J.C., & Meyerson, J.E. (2010). Considerations for parameter optimization and sensitivity in climate models. Proceedings of the National Academy of Sciences, 107(50), 21349-21354.

New Climate Economy (2014). Better Growth, Better Climate. The New Climate Economy Report.

Newbery, D., & Stiglitz, J.E. (1982). The Choice of Techniques and the Optimality of Market Equilibrium with Rational Expectations. Journal of Political Economy, 90(2), 223-246.

NOAA (2020). U.S. Billion-Dollar Weather and Climate Disasters. National Centers for Environmental Information (NCEI). https://www.ncdc.noaa.gov/billions/.

Nordhaus, W.D. (1991a). To Slow or Not To Slow: The Economics of the Greenhouse Effect, Economic Journal 101(407), 920–937.

Nordhaus, W.D. (1991b). The Cost of Slowing Climate Change: A Survey, The Energy Journal 12(1), 37–66.

Nordhaus, W.D. (2017). Social cost of carbon in DICE model. Proceedings of the National Academy of Sciences. 114 (7), 1518-1523.

Nordhaus, W.D. (2018). Climate Change: The Ultimate Challenge for Economics. Nobel Lecture in Economic Sciences.

Nordhaus, W.D. (2019). Climate Change: The Ultimate Challenge for Economics. American Economic Review, 109 (6): 1991-2014.

OECD (2017). Investing in Climate, Investing in Growth. OECD Publishing.

Oreskes, N., & Conway, E. (2010a). Merchants of doubt, How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming. Bloomsbury Press.

Persson, T., & Svensson, L.E.O. (1989). Why a Stubborn Conservative Would Run a Deficit, Policy with Time-Inconsistent Preferences. Quarterly Journal of Economics, 104(2), 325–345.

Pratt, J.W. (1964). Risk Aversion in the Small and in the Large. Econometrica, 32, 122-36

Pycroft, J., Vergano, L., Hope, C., Paci, D., & Ciscar, J.C. (2011). A tale of tails, uncertainty and the social cost of carbon dioxide. Economics, The Open-Access, Open-Assessment E-Journal.

Ramsey, F.P. (1928). A Mathematical Theory of Saving. Economic Journal, 38(4), 543–559.

Rawls, J. (1971). A Theory of Justice. Belknap Press of Harvard University Press.

Rezai, A., & van der Ploeg, F. (2016). Intergenerational Inequality Aversion, Growth, and the Role of Damages: Occam's Rule for the Global Carbon Tax. Journal of the Association of Environmental and Resource Economists, 3(2), 493-522.

Ripple, W.J., Wolf, C., Newsome, T.M., Barnard, P., & Moomaw, W.R. (2020). World Scientists' Warning of a Climate Emergency. BioScience, 70(1), 8–12.

Salter, W.E.G. (1960). Productivity and Technical Change. Cambridge University Press.

Samuelson, P. (1965). A theory of induced innovation along Kennedy–Weizsäcker lines. The Review of Economics and Statistics, 47(4), 343–56.

Sandmo, A. (1975). Optimal Taxation in the Presence of Externalities. The Swedish Journal of Economics, 77(1), 86-98.

Schumacher, I. (2018). The Aggregation Dilemma in Climate Change Policy Evaluation. Climate Change Economics, 09, 03.

Schweitzer, F., Fagiolo, G., Sornette, D., Vega-Redondo, F., Vespignani, A., & White, D.R. (2009). Economic networks, the new challenges. Science, 325(5939),422-5.

Sen, A. (2009). The Idea of Justice. Belknap Press of Harvard University Press.

Shiller, R. (1981). Do stock prices move too much to be justified by subsequent movements in dividends? American Economic Review, 71(3), 421–436.

Stern, N. (1977). Welfare weights and the elasticity of the marginal valuation of income. In: Artis, M., & Nobay, R. (eds.). Proceedings of the Aute Edinburgh Meeting of April 1976. Basil Blackwell.

Stern, N. (2007). The Economics of Climate Change: The Stern Review. Cambridge University Press.

Stern, N. (2014a). Ethics, Equity and the Economics of Climate Change Paper 1: Science and Philosophy. Economics and Philosophy, 30(3), 397-444.

Stern, N. (2014b). Ethics, Equity and the Economics of Climate Change Paper 2: Economics and Politics. Economics and Philosophy, 30(3), 445-501.

Stern, N. (2015). Why Are We Waiting? The Logic, Urgency and Promise of Tackling Climate Change. MIT Press.

Stern, N., & Stiglitz, J.E., et al (2017). Report of the high-level commission on carbon prices. World Bank.

Sterman, J.D. (2011). Communicating climate change risks in a skeptical world. Climatic Change, 108, 811.

Stiglitz, J.E. (1975). Incentives, Risk and Information: Notes Towards a Theory of Hierarchy. Bell Journal of Economics, 6(2), 552-579.

Stiglitz, J.E. (1982). The Rate of Discount for Cost-Benefit Analysis and the Theory of the Second Best. *Discounting for Time and Risk in Energy Policy*, Lind, R. (ed.), Resources for the Future, 151-204.

Stiglitz, J.E. (1988). Economics of the Public Sector. W. W. Norton & Company.

Stiglitz, J.E. (1994). Whither Socialism? MIT Press.

Stiglitz, J.E. (1998). The Private Uses of Public Interests, Incentives and Institutions. Journal of Economic Perspectives, 12(2), 3-22. (Originally presented as Society of Government Economists Distinguished Lecture on Economics in Government, ASSA meetings, January 4, 1998).

Stigliltz, J.E. (2002). Information and the Change in the Paradigm in Economics. Abbreviated version of Nobel lecture. American Economic Review, 92(3), 460-501.

Stiglitz, J.E. (2006). Samuelson and the Factor Bias of Technological Change. In Szenberg, M., et al. (eds.). Samuelsonian Economics and the Twenty-First Century, 235-251. Oxford University Press.

Stiglitz, J.E. (2010). Freefall, America, Free Markets, and the Sinking of the World Economy. W.W. Norton.

Stiglitz, J.E. (2014). Unemployment and Innovation. NBER Working Paper 20670.

Stiglitz, J.E. (2018). Pareto Efficient Taxation and Expenditures, Pre- and Re-distribution. Journal of Public Economics Special Issue in Honor of Sir Tony Atkinson (1944-2017), 162, 101-119. In: Luttmer, E., & Kleven, H. (eds.).

Stiglitz, J.E. (2019). Addressing climate change through price and non-price interventions. European Economic Review, 119, 594-612.

Stiglitz, J.E., Abernathy, N., Hersh, A., Holmberg, S., & Konczal, M. (2015). Rewriting the Rules of the American Economy, An Agenda for Growth and Shared Prosperity. W.W. Norton.

Stiglitz, J.E., & FEPS (2020). Rewriting the Rules of the European Economy. W.W. Norton

Stiglitz, J.E., Fitoussi, J., & A. Sen, M. (2010) *Mismeasuring Our Lives: Why GDP Doesn't Add Up*. The New Press.

Stiglitz, J.E., Fitoussi, J., & Durand, M. (2018). Beyond GDP: Measuring What Counts for Economic and Social Performance. OECD Publishing.

Stiglitz, J.E., & Greenwald, B. (2003). Towards a New Paradigm in Monetary Economics. Cambridge University Press.

Stiglitz, J.E., & Greenwald, B. (2014). Creating a learning society, A new approach to growth, development, and social progress. Columbia University Press.

Systemiq (2020). The Paris Effect: How the Climate Agreement is Reshaping the Global Economy.

Thaler, R.H. (1992). The Winner's Curse, Paradoxes and Anomalies of Economic Life. Princeton University Press.

Traeger, C.P. (2018). ACE – Analytic Climate Economy (with Temperature and Uncertainty), (December 1, 2018).

Trisos, C.H., Merow, C., & Pigot, A.L. (2020). The projected timing of abrupt ecological disruption from climate change. Nature, 580, 496–501.

Vicedo-Cabrera, A.M., Guo, Y., Sera, F., et al. (2018). Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios. Climatic Change, 150, 391–402.

Wealth Economy (2019). Measuring wealth, delivering prosperity'. Wealth Economy Project, Natural and Social Capital. Interim Report to LetterOne. Bennett Institute for Public Policy.

Weitzman, M.L. (1974). Prices vs. Quantities. Review of Economic Studies, 41, 477-91.

Weitzman, M.L. (2009). On modeling and interpreting the economics of catastrophic climate change. Review of Economics and Statistics, 91(1), 1-19.

Wilhelm, M.O. (1996). Bequest Behavior and the Effect of Heirs' Earnings, Testing the Altruistic Model of Bequests. The American Economic Review, 86(4), 874-892.

Wolff, E.N., & Gittleman, M. (2014). Inheritances and the distribution of wealth or whatever happened to the great inheritance boom?. J Econ Inequal, 12, 439–468.

World Economic Forum (2020). Measuring Stakeholder Capitalism: Towards Common Metrics and Consistent Reporting of Sustainable Value Creation. World Economic Forum.

Xu, C., Kohler, T.A., Lenton, T.M., Svenning, J.-C., & Scheffer, M. (2020). Future of the human climate niche. Proceedings of the National Academy of Sciences, 117(21), 11350-11355.

Yumashev, D., Hope, C., Schaefer, K., Riemann-Campe, K., Iglesias-Suarez, F., Jafarov, E., Burke, E.J., Young, P.J., Elshorbany, Y., & Whiteman, G. (2019). Climate policy implications of nonlinear decline of arctic land permafrost and other cryosphere elements. Nature Communications, 10, 1900.