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A GUIDE TO MACROECONOMICS AND CLIMATE CHANGE

Adrien Bilal
James H. Stock

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A Guide to Macroeconomics and Climate Change
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ABSTRACT

This paper analyzes the literature that links macroeconomics and climate change. We organize our paper into three categories: (i) loss and damage, which assesses long-run economic costs and non-market impacts from climate change; (ii) mitigation and the energy transition, which evaluates the macroeconomic consequences of shifting away from fossil fuels toward renewable energy; and (iii) adaptation, which explores the economic adjustments necessary to manage heat stress, more frequent severe weather events and rising seas. We discuss macroeconomic frameworks that incorporate these forces as well as empirical estimates that guide their calibration. We suggest areas in which macroeconomic research on climate is needed.

Adrien Bilal
Stanford University
Department of Economics
and NBER
adrienbilal@stanford.edu

James H. Stock
Harvard University
Department of Economics
and NBER
James_Stock@harvard.edu

1 Introduction

The world is experiencing increasingly severe physical consequences of climate change: flooding in 2022 that inundated one-third of Pakistan (Hong et al. 2023), temperatures exceeding 50°C in India (Mandal et al. 2025), and wildfires across Canada in the summer of 2023 that blanketed many United States cities in wildfire smoke for days (Jain et al. 2024). While no individual such event can be attributed solely to climate change, collectively these increasingly common and severe extremes are strongly consistent with climate models (National Academies of Sciences, Engineering, and Medicine 2016). Driven in part by such events and facilitated by sharply declining prices of renewable power, batteries, and electric vehicles, public and corporate support is broadening for decarbonizing broad swaths of economic activity and for adapting to the worsening physical damages of climate change to come. These trends will likely entail tens of trillions of dollars of redirected capital flows and change the daily lives and economic opportunities faced by billions of people.

The scale of climate change and the transition to a decarbonized economy raises important questions for macroeconomists and provides them with opportunities to meaningfully strengthen and improve the response to climate change, both by society and by those in charge of climate policy and traditional macroeconomic policy. Macroeconomists have long been involved in estimating the economic cost of climate change and in assessing optimal climate policy. Both streams date to the seminal work of Nordhaus (1992), who developed the first formal model to integrate climate and macroeconomics: the first integrated assessment model, or IAM. It enabled estimating the monetized damages from climate change, called the social cost of carbon or SCC, and linked the optimal Pigouvian tax on carbon to the social cost of carbon. Since then, and accelerating especially over the past five years, there has been an increasing amount of work at the intersection of climate change and macroeconomics. Parts of this literature are large and mature, in particular estimates of the social cost of carbon and the long-run macroeconomics of carbon taxes, while other parts are quite new, in particular the macroeconomics of adaptation.

This paper analyzes the literature on climate change and macroeconomics. Our aim is twofold: to provide an organizing framework for what can seem, to an outsider, a complex and interconnected topic that combines traditional macroeconomics with climate science and technology, and to suggest directions in which macroeconomic research on climate is particularly needed. As we discuss existing work, we put more weight where work is well-developed and less weight where work is scant.

We adopt a capacious definition of climate change that encompasses both the phys-

ical manifestations of climate change—heat stress, storms, floods, sea level rise, and so forth—and the human and institutional activities driving, experiencing, and responding to those physical changes. These risks occur over multiple time frames, ranging from quarters in the case of an energy price shock to centuries in the case of irreversible events such as ice sheet melting.

By contrast, our definition of macroeconomics is narrow, limiting attention to aspects of climate change that potentially have meaningful implications for macroeconomic aggregates and aggregate welfare, so that the tools of macroeconomic analysis are relevant. Our framework includes climate policy design to the extent that policy options have different macroeconomic consequences. It excludes much of the burgeoning literature on climate finance or natural capital. For space, we focus on work studying long-run macroeconomic outcomes and do not attempt to summarize the literature that analyzes the short-run, business-cycle macroeconomic implications of climate change or its fiscal implications. Importantly, our focus on long-run outcomes does not imply that we consider only phenomena that will only occur far in the future; we simply exclude those that tend to dissipate within a few years.

We structure our paper by expanding the familiar pair of physical risks and transition risks highlighted in Carney (2015)'s speech as governor of the Bank of England when assessing future risks facing the financial industry. We refine this classification into three categories: (i) loss and damage, (ii) mitigation and the energy transition; and (iii) adaptation.

Loss and damage encompasses Carney's "physical risk" and includes long-run economic damages, non-market damages, and physical tail risks—the focus of the social cost of carbon and its alternatives. The remaining two categories correspond to a broad definition of Carney's "transition risk" category. Mitigation encompasses the macroeconomics of energy use, the energy transition and innovation. Adaptation encompasses the macroeconomics of the transition to a warmer world with rising seas, more frequent and severe weather extremes, and their macroeconomic implications such as climate migration and adaptation policy. With continuous progress in the measurement of losses and damages, substantial price declines in renewable energy making broad mitigation potentially cost-effective, and the need to adapt to warming arising from past and near-term emissions, we view this three-pronged framework as the relevant one for our purposes.[1]

There are many excellent recent reviews of the economics of climate change (Dell et al. 2014; Dietz et al. 2021; Timilsina 2022; Bastien-Olvera and Moore 2022; Blanchard et al.

[1]While historical adaptation is implicitly part of the transmission mechanism in estimates of losses and damages, we include it as a separate section due to its importance going forward.

2023; Hassler et al. 2024; Moore et al. 2024; Burke et al. 2024; Desmet and Rossi-Hansberg 2024; Fernández-Villaverde et al. 2024). Each of these reviews focuses in depth on a specific aspect of the economics of climate change, for instance either the social cost of carbon, mitigation policies, or the spatial features of climate change. Our paper complements this work by drawing together loss and damage, mitigation and adaptation, thereby providing a comprehensive guide to the interested reader. We point to these complementary reviews in the relevant sections of our paper.

2 Loss and Damage

Climate change is a relevant question for macroeconomics because of the potential economic losses associated with a warming climate. Thus, the valuation of climate damages is an essential component of the economics of climate change, with the social cost of carbon as its centerpiece. The social cost of carbon is defined as the dollar valuation to society of the incremental damage from an additional ton of carbon dioxide emissions.

The social cost of carbon is a key guide to policy because it corresponds to the optimal Pigouvian tax on carbon emissions in many economic frameworks. Under standard cost-benefit analysis, emissions-reduction policies that are less expensive than the social cost of carbon should be implemented, while policies that are more expensive should not. Regardless of political practicality, carbon taxes provide a useful benchmark to understand cost-benefit analyses of most alternative policies.

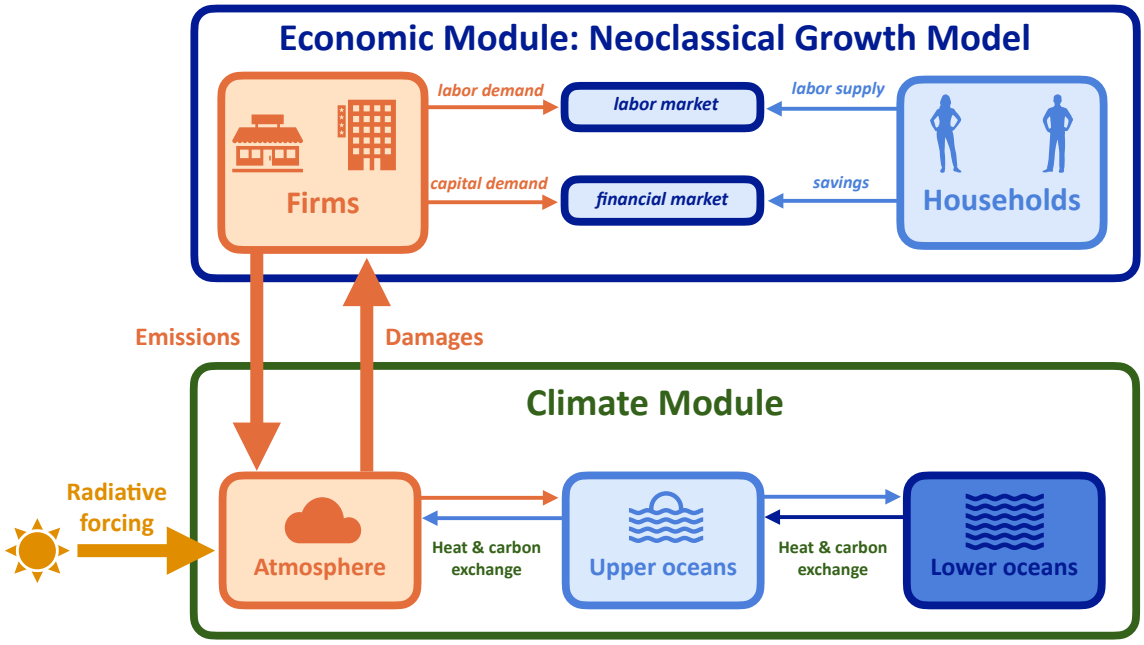
Thus, our first step is to develop a typology to classify macroeconomic frameworks that account for loss and damage and the social cost of carbon. We structure our discussion around the qualitative components of the social cost of carbon and provide quantitative evaluations and references at each step.

2.1 Monetizing Climate Damages: The Social Cost of Carbon

Nordhaus (1992) first integrates climate change into macroeconomic analysis. Many of the frameworks we discuss below, including other integrated assessment models, follow a similar structure. In these frameworks, the calculation of the social cost of carbon involves two modules that interact with each other.

The first module is an economic model that maps climatic phenomena to economic fundamentals such as productivity, amenities, capital depreciation or mortality rates. The economic module then maps individual decisions and policy into consumption, output, energy use, welfare, and emissions which feed back to the climate module. The second

Figure 1: Dynamic Integrated Climate Economy model diagram.



module is a climate model that maps greenhouse gas emissions into climatic outcomes. Figure 1 describes the typical integrated assessment model diagrammatically. Appendix A details the underlying mathematical structure.

Specifically, Nordhaus (1992) combines a 5-equation representation of the carbon cycle and greenhouse effect with an otherwise standard neoclassical growth model (Cass 1965, Koopmans 1963). In the neoclassical growth model, a representative household (or, equivalently, a unit measure of identical households) decides how much to consume and invest. A representative firm decides how much labor and capital to use. Production leads to emissions. Emissions feed back to temperature, which affects economic activity through productivity losses.

The resulting environment is an economic framework—the dynamic integrated climate economy (DICE) model—in which emissions, warming and economic activity are jointly analyzed. This model also features abatement costs that society can decide to pay to reduce emissions. This structure stands as the core foundation of the social cost of carbon and climate change policy analysis.

Of course, quantifying the social cost of carbon requires knowledge of both the economy and of the climate system together with empirical estimates of each of their components. Nordhaus (1992) calibrates his framework based on early damage measures from

Cline (1992) and obtains productivity losses of less than 1% per 1°C increase. As a result, he finds that optimal warming by 2100 exceeds 3°C. The social cost of carbon—which corresponds to the optimal Pigouvian tax—rises from $5 to $20 by 2100.

As with any modeling exercise, each module that enters the construction of the social cost of carbon is subject to modeling choices and estimation choices. These choices have sparked lively debate, both within the profession (Pindyck 2013; Pindyck 2017; Stern 2016; Stern et al. 2022) and between economists and natural scientists (Rising et al. 2022). The debate is not just over how to calculate the social cost of carbon, but whether it is even the right concept for a carbon price in a decarbonization effort driven not by cost-benefit analysis of marginal projects but by a temperature target (e.g., holding warming 2°C over pre-industrial temperatures) or a net-zero target date (e.g., 2050). In this paper we adopt the conventional view grounded in standard expected utility economic theory, which points to the social cost of carbon as the relevant concept to assess the impact of climate change from an incremental ton of emissions. Most aspects of the debate can be largely subsumed into the choice of an individual utility function, social welfare function, estimates of structural damage functions, and level of aggregation.

We now discuss how macroeconomics has built on Nordhaus (1992) and the ensuing debate to develop empirical and theoretical tools to continuously update the cost of carbon. Golosov et al. (2014) provide a useful benchmark to evaluate the choices involved in this process. They develop a representative agent framework building on Nordhaus (1992), in which they obtain a sharp formula for the social cost of carbon that is independent from the energy block of the economy. It is increasing in the structural damage function, household patience and initial output.[2] Thus, each of these objects feature prominently in our discussion. When no value of the social cost of carbon per se is reported, we report corresponding welfare or output losses. We discuss the economic module extensively, and include a shorter discussion of the climate module at the end of this section.

2.2 Damage Estimation in Representative Agent Frameworks

Damage functions. In representative agent frameworks such as Nordhaus (1992) and Nordhaus and Boyer (2000), damage functions that map climatic phenomena to economic fundamentals often take the form of a simple relationship between global mean temperature and productivity losses. This damage function can be calibrated to different types of

[2]Of course, the social cost of carbon also depends on the climate module through the persistence of carbon dioxide in the atmosphere and the climate sensitivity: how much carbon dioxide warms the atmosphere.

empirical moments, and ultimately feeds into the cost of carbon. We start by describing the typical range of the cost of carbon, before turning to how it depends on estimates of damage functions.

The National Academy of Sciences, Engineering and Medicine (2017) report provides a survey of the social cost of carbon, with a median value of \$42/ton. Moore et al. (2024) survey more recent estimates of the social cost of carbon, ranging from \$100/ton to \$240/ton.[3] Many studies rely on fully specified integrated assessment models to construct the social cost of carbon, as reviewed in Metcalf and Stock (2017) and Fernández-Villaverde et al. (2024). Over time, the social cost of carbon has been updated following improved measurement: accounting for persistent impacts and for a broader range of extreme events, either directly or through a focus on global mean temperature, with some recent values exceeding \$1,300/ton. We now turn to discussing specific progress in the measurement of damages in recent years.

The conventional approach is "top-down", whereby damage functions are directly calibrated to country-level estimates that regress country-level changes in output on changes in country-level temperature (Dell et al. 2012; Burke et al. 2015). Dell et al. (2014) provide a comprehensive review of the underlying panel econometrics which rely on transitory temperature fluctuations for identification. These estimates reflect the net effect of temperature, with possibly partially offsetting underlying mechanisms. These studies typically find that a transitory 1°C increase in a country's temperature reduces output by 1 to 3% in the medium run (e.g. 5 to 10 years).

In the medium run, it is difficult to disentangle whether these effects on output are transitory or permanent. The central question is then how to extrapolate these medium run output responses estimated off of transitory country-level temperature fluctuations to the long run. This question encapsulates the debate around "level" (transitory) vs. "growth" (permanent) effects. Over one century of climate change, this choice implies dramatically different evolutions.

Moore and Diaz (2015) and Kahn et al. (2021) calibrate damage functions in integrated assessment frameworks to the reduced-form impacts of temperature on output following Dell et al. (2012) and explore how assuming growth or level effects affects conclusions. Under growth (permanent) effects, Moore and Diaz (2015) find a social cost of carbon of \$220/ton and 2100 output losses that range from 10 to 40% across countries under 4.5°C warming, i.e. 2-10% per 1°C on average. When imposing level effects, the social cost of carbon is \$33/ton.

[3]Governmental reports such as U.S. Environmental Protection Agency (2023) and Council of Economic Advisers (2023) report similar estimates of economic damages from climate change.

Nath et al. (2024) clarify how to account for persistence by matching the full dynamic impulse response function of output to country-level temperature fluctuations in the data. They find that 4°C of warming implies a 7-12% decline in world output by 2100, i.e. 2-3% per permanent 1°C increase on average.

This conventional approach to estimating the impact of temperature on output relies on local, country-level temperature variation. While econometrically powerful, this approach relies on a source of variation that may not be entirely representative of climate change. Climate change materializes as an increase in global mean temperature, which then implies changes in local temperatures but also many other damaging climatic events that may not be correlated with local temperature, for instance tropical storms and hurricanes. Kotz et al. (2024) show that including extreme heat and rainfall further increases damages from climate change. The challenge is then to be able to enumerate, measure and estimate the impact of the full range of weather phenomena.

To address this challenge, Bilal and Känzig (2024) directly estimate the full impact of global temperature changes on world output in the time series. They find a social cost of carbon in excess of $1,300/ton, compared to just under $180/ton for local temperature. These costs correspond to 23% output losses per 1°C in the long run under global temperature, compared to 3% per 1°C under local temperature. They propose a geophysical interpretation for these differences: they find that ocean surface temperature and extreme weather events account for the majority of the gap between global and local temperature estimates.

Discounting. The second critical object in representative agent frameworks such as Nordhaus (1992) as well in richer environments is the rate of time preference: individual or societal preferences for different time horizons. Climate damages occur largely in the future from any given initial period's perspective, implying back-loaded damages. Standard discounting arguments then imply that even small changes in the discount rate imply large shifts in the social cost of carbon because it is a stock variable. Welfare losses are less sensitive to the discount rate because they are a flow variable.

Quantitatively, Rennert et al. (2022) show that changing the discount rate from 3% annually to 2% annually shifts the social cost of carbon from $80/ton to $185/ton. Debates on discounting pervade the literature on climate change. The Stern (2006) review uses a near-zero pure rate of time preference, yielding a large social cost of carbon. Contemporaneous and subsequent work debates this choice (Weitzman 2007; Nordhaus 2007), ultimately settling on values closer to the risk-free interest rate. In this paper, we do not attempt to argue in favor of one or other value of the discount rate, but simply flag its

importance.

2.3 Heterogeneity

Representative agent frameworks have the virtue of simplicity and transparency. Estimation and simulation are straightforward. However, a key feature of climate change is that it has unequal impacts that may vary by region, sector/industry and type of household. Even if aggregate damages are equal to their representative agent value in a model that features heterogeneity, their welfare impact and the corresponding social cost of carbon may differ widely in the presence of heterogeneity. The next paragraphs discuss macroeconomic frameworks that feature heterogeneity relevant to the analysis of climate change loss and damage.

Geography. The impact of climate change varies dramatically by region. While Sweden will likely experience agricultural productivity benefits from additional warming, the opposite will presumably hold in Mali. Thus, taking spatial variation into account is key to account accurately for losses and damage from climate change.

Nordhaus and Yang (1996) extend the Nordhaus (1992) framework to a regional setting, the Regional Integrated Climate Economy (RICE) model, to assess climate impacts across countries. It mirrors the structure in Nordhaus (1992), but with multiple countries that may act as independent decision-makers or as cooperative agents. Countries do not interact through trade in goods or capital nor through migration: they only interact through the global climate, which is a function of all countries' emissions.[4]

Spatially disaggregated economic models can now be specified at much finer levels of spatial aggregation. In particular, they can be built at the level of spatial resolution of localized climatic shocks, allowing for a more accurate representation of climate impacts. A literature leveraged recent progress in modeling techniques for spatial economics—reviewed in Redding and Rossi-Hansberg (2017)—to construct macroeconomic models of climate change at a fine degree of spatial resolution: see for instance Desmet et al. (2021), Balboni (2025), Cruz and Rossi-Hansberg (2024), Krusell and Smith (2023), Bilal and Rossi-Hansberg (2023), and references therein. Collectively, these settings incorporate migration across a near-arbitrary number of locations, trade in goods and capital across these regions, and dynamic, micro-founded decision-making. They cover loss and damage channels such as labor productivity, amenities, slow-onset sea level rise, extreme heat and storms.

[4]See also Hassler and Krusell (2012) for a version with a continuum of regions and a closed form solution.

Desmet and Rossi-Hansberg (2024) provide an extensive review of the role of geography for climate damages and adaptation. They show that accounting for regional heterogeneity, for instance at the 1° x 1° latitude and longitude cell level, can double the social cost of carbon relative to a country-level or world-level representation.

Throughout this literature, damage functions affect varying subsets of productivity, amenities, and capital depreciation. Recent computational advances in large-scale dynamic spatial models allow to efficiently estimate these frameworks at spatial resolutions that mirror the resolution of empirical analysis, for instance by matching difference-in-difference estimates of the impact of weather extremes at the county level (Bilal 2023; Bilal and Rossi-Hansberg 2023). Depending on differences in targeted moments and modeling choices, the present welfare cost of moderate climate change ranges from 1% to 5%.

Sectors and Industries. Climate damages affect different sectors and industries differently.[5] Just as for geography, the economic model may also be specified at various levels of sectoral, or industrial, disaggregation.

Agricultural productivity losses feature prominently in the social cost of carbon literature (Moore et al. 2017; Rennert et al. 2022; Nath 2024), for two reasons. The first reason is that agricultural yields drop precipitously when temperature exceeds crop-specific thresholds and precipitation falls, making agriculture a sector that is particularly exposed to climate change. The second reason is that most low- and middle-income countries have large agricultural sectors, implying that over a quarter of the world's employment works in this highly exposed sector.

Blanc and Schlenker (2017) review the panel-based literature that studies the impact of climate change on agricultural productivity (Schlenker and Roberts 2009; Schlenker and Lobell 2010). There are substantial and nonlinear impacts of climate change on agricultural output. For instance, corn yields are largely unaffected until temperature reaches 25-30°C, and then drop by 2% for any additional day over 35°C. These estimates imply that moderate climate change is expected to reduce agricultural yields by more than 30% worldwide by 2100. These effects pervade high-income and lower-income, warmer countries (Lobell et al. 2011). Integrating these findings into an integrated assessment model, Rennert et al. (2022) find that worldwide agricultural losses account for a partial social

[5]In traditional economics jargon, "sectors" designate a classification of economic activity into agriculture, manufacturing, services, and so on. In the climate change literature, "sectors" sometimes take on a somewhat different definition that encompasses both market and non-market impacts, e.g. mortality, violent crime, civil conflict, as well as particular channels through which climate change affects society, e.g. sea-level rise, migration, as reviewed in Carleton and Hsiang (2016). Both definitions are of course valid, but their co-existence can sometimes lead to ambiguity. In this paper we use "sectors" in the traditional economics meaning.

cost of carbon of \$84/ton.

The country-level and world-level estimates in Dell et al. (2012), Burke et al. (2015) and Bilal and Känzig (2024) all point to impacts of climate change beyond agriculture. For instance, Cachon et al. (2012) find that productivity in the United States auto industry falls by 8% when temperature exceeds 90°F. Wilson (2017) finds broad-based damages from temperature across United States counties. Somanathan et al. (2021) find that an increase of 1°C in all days of the year lowers annual output by 2% in Indian manufacturing plants.

Consistent with these observations, Conte et al. (2021), Cruz (2024) and Rudik et al. (2022) include granular industrial composition in addition to regional heterogeneity and estimate industry-specific damage functions by matching reduced-form estimates. Collectively, these papers find that agriculture shifts away from equatorial latitudes and closer to polar latitudes, with little substitution to non-agricultural industries. Losses in agriculture appear to be three times larger than in non-agriculture.

A rapidly expanding literature in macroeconomics studies the role of input-output networks for aggregate economic activity, starting with Hulten (1978), Long and Plosser (1983), and further developed more recently by Baqaee and Farhi (2020). With very few exceptions (Zappala 2024), these analyses have not yet directly been used to evaluate the consequence of climate change, though they appear relevant.

Households. Within locations and industries, households with different characteristics may be exposed differently to climatic shocks. A strand of work explores the role of household heterogeneity for climate change impacts, concluding that heterogeneity tends to increase societal average effects to the extent that damages are more concentrated on poorer households because of concave utility (Anthoff and Emmerling 2019; Fried 2022; Benveniste et al. 2022; Fried 2024; Del Campo et al. 2024; Prest et al. 2024; Kubler 2024).

Relative to the vast literature in macroeconomics that incorporates household heterogeneity (see, among many others, Huggett 1993; Aiyagari 1994; Kaplan et al. 2018; Auclert et al. 2024), the literature on its implications for climate change is less developed. We hope that more work will assess the role of household heterogeneity in the future, empirically and structurally.

2.4 Natural Disasters and Weather Extremes

Some of the costliest manifestations of climate change are likely natural disasters and extreme weather. Examples include extreme heat, wind, precipitation, flooding, droughts, hurricanes, and so on. A broad empirical literature finds meaningful effects of extreme

events on economic outcomes (Hsiang 2010; Deschênes and Greenstone 2011; Hornbeck 2012; Deryugina 2013; Hsiang and Jina 2014; Geiger et al. 2016; Kruttli et al. 2024; Gourio and Fries 2020; Kim et al. 2022; Roth Tran and Wilson 2023). These studies sometimes find differences in sign, perhaps due to differences in controls for background demographic trends, governmental aid, and reconstruction efforts.

A nascent literature incorporates extreme events in structural models (Fried 2022; Cantelmo et al. 2023; Bakkensen and Barrage 2021; Jia et al. 2022; Phan and Schwartzman 2024; Rudik et al. 2022; Castro-Vincenzi 2024). For instance, Bilal and Rossi-Hansberg (2023) use county-level estimates of extreme heat and coastal storms to estimate their productivity, amenity and capital depreciation impacts in a structural model of the United States at the county level. They find that coastal storms are at least as important as heat stress for the United States and thus double climate damages relative to an analysis that would only focus on heat.

2.5 Risk and Uncertainty

Traditionally, deterministic scenarios have been used to project the impacts of future climate change, without incorporating uncertainty about future emissions, the climate sensitivity, tail events and other aspects of the framework. In practice, the risk involved is considerable. To assess scenario or estimation uncertainty, existing work sometimes samples parameters from the relevant empirical distribution, but conditional on a given draw, agents in frameworks behave as if all parameters were known.

In this section we discuss how to incorporate risk and uncertainty consistently with agent expectations. We henceforth refer to risk in the traditional sense: a known probability distribution over warming scenarios, the climate sensitivity, damage functions, etc. We refer to uncertainty as an unknown probability distribution over these same variables.

With risk-averse individuals, risk may translate into larger perceived damages than under a median deterministic scenario, as highlighted in Weitzman (2009) and Weitzman (2014). In fact, the cost of carbon can become infinite when risk has thick enough tails.

Cai and Lontzek (2019) quantify the effect of risk on the social cost of carbon in simulations in an integrated assessment model, and Van den Bremer and Van der Ploeg (2021) derive analytical formulas in an integrated assessment economy that delivers a risk adjustment to the social cost of carbon. Both studies find that the sign of the impact of risk critically depends on the Elasticity of Intertemporal Substitution (EIS). Risk increases the social cost of carbon if and only if the EIS is above 1, due to the semi-elasticity structure of damage functions. Both studies find that risk can double (or halve) the social cost of

carbon depending on parameter values.[6]

All these papers use dynamic decision-making models that resemble those typically used in asset pricing, and distinguish between the elasticity of intertemporal substitution and risk-aversion (Epstein and Zin 1990). Consistently with asset pricing logic, Dietz et al. (2018b) highlight that the valuation of risk depends on the correlation between climate damages and consumption. Much more work is required to incorporate a quantitatively accurate role for risk into the social cost of carbon.

Most of the probability distributions of climate damages are not known with certainty (for instance the speed of the West Antarctic ice sheet melting and ensuing coastal flooding). The presence of such uncertainty may justify using ambiguity-averse decision-making setups that have deep roots in decision theory (Gilboa 1987; Hansen and Sargent 2001; Maccheroni et al. 2006). Barnett et al. (2023) and Barnett et al. (2024) find an important role for ambiguity aversion under climate change. Additional work is needed at least as much for uncertainty as for risk.

2.6 Non-Market Outcomes and Welfare

Climate change impacts not only market outcomes typically included in integrated assessment models such as output, investment and consumption, but also non-market outcomes that have critical importance for welfare: the amenity valuation of various locations, mortality, violent crime, civil unrest and migration. These outcomes directly affect individual well-being, but do not directly appear in output.

A large empirical literature evaluates the impact of rising temperature on mortality. Deschênes and Greenstone (2011) find that each additional day above 32°C increase mortality rates by 0.1% in the United States. Burgess et al. (2017) find that this impact is six times larger in developing countries. Carleton et al. (2022) and Rennert et al. (2022) find that the global mortality-induced (partial) social cost of carbon ranges from \$36/ton to \$90/ton. Health co-benefits from reducing emissions, which can be substantial, are frequently overlooked in social cost of carbon calculations. Dell et al. (2012), Ranson (2014) and Hsiang et al. (2017) find significant effects of temperature on crime, violence, and political instability.

Originally, integrated assessment models have not included non-market impacts of climate change (Nordhaus 1992; Nordhaus and Yang 1996). Over time, social cost of

[6] A burgeoning literature incorporates climate risk in firm decision-making in the context of supply chain decisions (Castro-Vincenzi 2024; Castro-Vincenzi et al. 2024; Balboni et al. 2024). These papers find that firms shift their supply chains to safer grounds in the face of heightened climate risk, leading to higher costs and consumer prices.

carbon assessments have incorporated some of these channels using standard monetization methods. For instance, Rennert et al. (2022) find that mortality damages account for about half of their social cost of carbon value of $185/ton. Crime and political instability are more difficult to monetize without more structure but may account for some of the costliest consequences of climate change. More research is needed in these areas.

2.7 The Climate Module

For space, we focus on the economic module in the construction of the social cost of carbon and only briefly discusses the climate module. The National Academy of Sciences, Engineering and Medicine (2017) report, Dietz et al. (2021) and Folini et al. (2024) provide extensive reviews of the climate science and how it interacts with the economic module.

Most economists use small-scale, simplified climate models when paired with an economic model because large-scale models are extremely computationally intensive even on their own. If paired with the typical but additional fixed point problem involved in finding an equilibrium in an economic model, the problem would become computationally intractable.

However, for many applications of interest, simplified climate models that relate worldwide emissions to global mean temperature together can suffice. When regional impacts are needed, statistical downscaling that projects local weather on global mean temperature can often provide a useful first pass, as in Krusell and Smith (2023), Bilal and Rossi-Hansberg (2023) and Cruz and Rossi-Hansberg (2024).

3 Mitigation

Faced with the possibility of climate damages, one strategy is to reduce emissions and limit the economic impacts of a warming climate. Because neither households nor firms internalize the effect of their greenhouse gas emissions on the rest of the economy, policy intervention has an important role to play.

Throughout the twentieth century and for at least the first ten years of this century, there were few economical alternatives to the use of fossil fuels for energy, so the main way to reduce emissions of carbon dioxide was simply to use less energy. For this reason, until very recently, the goal of reducing carbon emissions essentially reduced to encouraging energy conservation. Unsurprisingly, economists naturally gravitated to carbon taxation which introduced a Pigouvian tax that internalized the carbon externality. Nordhaus (1977) introduced carbon taxation as a way to address global warming. In Nordhaus

(1992), the optimal carbon tax equals the social cost of carbon. Building on this result, there is now an extensive literature on carbon taxes and their cousins, cap-and-trade systems, which together are generally referred to as carbon pricing mechanisms.

The situation now is very different than it was a decade ago: wind and solar generation, paired with storage to address intermittency, are now competitive with fossil thermal generation in many parts of the world, and battery electric vehicles are already cost-competitive with internal combustion engine vehicles on a full cost of ownership basis for several vehicle classes. Those developments, driven by inventions, learning-by-doing, and scale economies, highlight the importance of other policies: research and development policies, standards, green demand subsidies, and supply-side subsidies (green industrial policy).

This section discusses macroeconomic frameworks that are well-suited to analyze the impact of energy policy. We start with a brief overview of energy resource management. Next, we discuss carbon pricing, innovation towards cleaner technology, and their implications for factor markets.

3.1 Energy Use

A long tradition in economics models the dynamics of exhaustible resources such as fossil fuels (Hotelling 1931; Dasgupta and Heal 1974; Solow 1974; Stiglitz 1974; Stiglitz 1976; Nordhaus 1982; Salo and Tahvonen 2001; Fröling 2011). While standard exhaustible resource models predict that the price of the resource eventually rises precipitously as reserves run out, this literature emphasizes that technical change and increasing returns can offset these effects and allow the economy to sustain economic growth in the long run (for instance, in the context of energy, the fracking boom or improvements in offshore drilling).[7]

In fact, Hassler et al. (2021) demonstrate that technological progress is stimulated and directed by rising prices. They develop an endogenous growth model with innovation that dynamically offsets gradual depletion of fossil fuels. Even when the static elasticity of substitution between energy and other factors is close to zero, technical change implies that the long-run elasticity of substitution between fossil fuels and other factors is unity.

A parallel line of work provides rich representations of energy systems, consumption and emissions, that studies optimal or constrained decarbonization pathways (Edmonds and Reilly 1983; Clarke et al. 2007; Calvin et al. 2019). Jebaraj and Iniyan (2006) review

[7]Depending on the structure of property rights and other production distortions, there can be under- or -over-extraction (Bohn and Deacon 2000; Copeland and Taylor 2009; Asker et al. 2019).

the earlier stage of this body of work. This line of work shares many features with integrated assessment models in the tradition of Nordhaus (1992), with particular emphasis placed on granular representations of energy types and uses, and a detailed climate and environment module.

3.2 Carbon Pricing Frameworks

Regardless of the particular path of fossil fuel resources, the Pigouvian approach to align private and socially efficient emissions is carbon pricing. Carbon pricing is typically achieved through one of two instruments: carbon taxes or cap-and-trade systems. Stiglitz et al. (2017) provide a broad overview of the goals and means of carbon pricing. Timilsina (2022) comprehensively surveys the literature on carbon taxes. We complement their survey by categorizing the economics of carbon pricing through the lens of economic frameworks.

3.2.1 Carbon Taxes vs. Cap-and-Trade

Optimal cap-and-trade and carbon taxes are equivalent under certainty in a static model. Both instruments provide contemporaneous incentives to reduce emissions, based on their price: the tax rate or the price of tradeable carbon allowances. When there is risk, a classic result by Weitzman (1974) shows that quantity instruments perform better than price instruments if and only if marginal benefits of the regulated good are more concave than marginal costs.

In practice, cap-and-trade systems, intensity standards, and portfolio standards have been implemented more broadly than carbon taxes. All are implicit carbon pricing schemes although that term is commonly used only for carbon taxes and quantity-based cap-and-trade.

3.2.2 The Impacts of Carbon Pricing

The results in Golosov et al. (2014) indicate that the optimal carbon price does not depend on the economy's reliance on energy. However, economic mitigation costs do depend on the effect of carbon pricing on energy use and thus emissions, as well as on output and employment. We first discuss estimates of the elasticity of emissions to carbon prices, and next discuss estimates of the elasticity of economic activity to carbon prices.

Carbon pricing and emissions. How elastic are carbon emissions to carbon pricing in practice? Metcalf and Stock (2023) use country-level panel techniques across European

Union countries and find that a country-level $40 per ton carbon price leads to cumulative emissions reductions of 4 to 6% when 30% of the economy is covered, amounting to a 13 to 20% reduction within the covered sector. Using matched difference-in-differences design at the firm level, Colmer et al. (2024) find similar elasticities for the European Emissions Trading System prices: 14-16% emissions reduction for $20-40 carbon prices.

Carbon pricing and economic activity. Declines in emissions due to a carbon tax that raises energy prices could be accompanied by adverse effects on output and employment. How costly is abatement for the economy? Shapiro and Metcalf (2023) study this trade-off in a model with green energy, highlighting that substitution towards green energy is key in mitigating the possible adverse effects of rising carbon prices.

The empirical literature finds limited evidence of such adverse effects. Metcalf and Stock (2023) and Colmer et al. (2024) find that even substantial increases in carbon taxes lead to little to no losses in output or employment growth in the context of the European Union. Using a country-level panel approach, Konradt and Weder di Mauro (2023) find no evidence of effects of carbon taxes on aggregate inflation, though some evidence on energy price increases. Using high frequency time series methods based on regulatory updates for the European Union Energy Trading System, Känzig (2023) finds evidence of a starker trade-off between carbon pricing and economic activity, possibly because this approach accounts for general equilibrium effects of carbon pricing. Pisani-Ferry (2021) discusses additional reallocative costs of the energy transition which may take place for deeper decarbonization than those seen historically. While much of the available research has focused on developed countries due to data availability, more research is needed in the context of developing countries.

These estimates can be put in perspective with work estimating the impact of energy price fluctuations on economic activity. While this literature is too vast to be summarized here, we point to a few recent papers and reference therein. Using time series methods and OPEC announcements as an external instrument for energy price changes, Känzig (2021) suggests that output reacts somewhat less to energy price changes than to carbon prices. Similarly, Moll et al. (2023) and Chiacchio et al. (2023) show theoretically and empirically that the energy price spikes that followed Russia's invasion of Ukraine led to only moderate economic losses, if any at all. These estimates highlight the importance of substitution through technology and openness to trade.

Risk. Carbon pricing risk can affect these conclusions beyond the reasons highlighted in Weitzman (1974). Because the price of the tradable allowances fluctuates—for exam-

ple, in 2023-2024 the price of emissions permits under the European Emissions Trading System ranged from 54 euros/ton to 102 euros/ton—tradable allowance systems provide less certainty about payoffs of expensive low-carbon projects. This risk can discourage investment as they provide different dynamic investment incentives, as indicated by standard investment theory (Dixit and Pindyck 1994) and modeled in the context of tradeable emissions projects by Aldy and Armitage (2022) and broad mitigation policy risk by Fried et al. (2022).

3.2.3 First-Best vs. Second-Best Policy

In standard cost-benefit analysis, carbon taxes or equivalent emission trading systems implement the first-best allocation. They can also be used to achieve what would be a second-best objective from the perspective of standard cost-benefit analysis: for instance, achieve a given climate path to stay under a predetermined temperature target.

The European Union tends to operate under a precautionary principle and uses a temperature ceiling: avoid warming above 2°C. This second-best temperature target approach amounts to an optimal use of the finite resource of the carbon budget—that is, implicit Hotelling pricing—adjusted to take into account increasing marginal abatement costs and, in principle, endogenous technical change in green technologies.

Nordhaus (1992) and Nordhaus and Boyer (2000) compare carbon pricing to emissions and temperature targets in integrated assessment models, finding that the latter imply larger mitigation costs than the former. Lemoine and Rudik (2017) show theoretically that temperature targets achieve lower mitigation costs than emissions targets because of warming lags inherent to the climate system. Fitzpatrick and Kelly (2017) study how temperature targets interact with risk in integrated assessment models.

Other instruments can also be used to reduce emissions. Dietz et al. (2018a) study corporate targets around the world, and Levinson (2019) shows that energy efficiency standards can be more regressive than energy taxes.

3.2.4 International Coordination

Pricing carbon is challenging in practice because of two coordination failures. The first one is the free-riding problem: any given country bears only a fraction of the consequences of its carbon emissions, and thus may not find it beneficial to engage in unilateral decarbonization. The second coordination failure is carbon leakage: carbon pricing in a country leads emissions-intensive economic activity to relocate to other countries. We discuss both coordination failures in turn.

The free-riding problem. Nordhaus and Yang (1996) analyze a multi-region integrated assessment model and finds that non-cooperative carbon policy leads to substantially lower carbon prices than global cooperation, although the resulting difference in emissions is moderate under their calibration. Bilal and Känzig (2025) show that ambitious unilateral decarbonization—more than 80% of the economy—becomes cost-effective for large economies such as the United States or the European Union as a block when climate damages and the resulting cost of carbon are calibrated to global temperature rather than local temperature. Of course, a cooperative carbon policy would be even more ambitious also under global temperature damages.

Trade policy is often viewed as a partial solution to the free-riding problem: it is a possible enforcement mechanism to influence other countries in a non-cooperative setting. The idea originates in Markusen (1975), who uses a simple trade model to show that tariffs can be used to reduce other countries' production of a globally harmful externality such as carbon dioxide.

Building on Markusen (1975), Nordhaus (2015) formalizes the idea of a "climate club", where countries in the club would impose high carbon prices and countries outside the club would be incentivized to participate through trade policy. This climate club concept addresses the free rider problem. In this static framework with a limited number of regions, Nordhaus (2015) finds that large climate clubs are sustainable only if the social cost of carbon remains low enough, which in his calibration turns out to be $50. At a higher level, trade sanctions on defecting members become too costly for remaining club members, and the club disintegrates.[8]

Carbon leakage. In an international setting, carbon pricing in a given country or climate club leads emissions-intensive production to relocate to third party countries. The emissions-intensive goods may then be imported back into the country who initially imposed the carbon price. The resulting allocation negates any emissions benefits of carbon pricing, while relocating economic activity away from the country pricing carbon. The leakage problem can compound with the free-riding problem by exacerbating the costs of trade sanctions necessary to keep a climate club in place.

Carbon border adjustments or other trade-based policies can solve the leakage problem. Carbon border adjustments impose tariffs on carbon-intensive imports to the same degree as domestic carbon prices, thereby nullifying the incentives to shift emissions-intensive production abroad and import it back to the pricing country.

[8]See also Harstad (2012) and Battaglini and Harstad (2016) for the role of commitments in dynamic games in sustaining first-best allocations.

Carbon border adjustments in a given country can also incentivize its trading partners to adopt their own carbon pricing system. Indeed, trading partners may find it preferable to impose a carbon pricing mechanism and retain its revenue rather than letting the country imposing the carbon border adjustment collect the proceeds. Weisbach et al. (2023) and Weisbach and Kortum (2023) derive jointly domestically optimal domestic carbon taxes and carbon tariffs to influence the rest of the world and control carbon leakage in a two-country setting. Cicala et al. (2023) show theoretically how to design tariffs on carbon-intensive imports to maximize adoption of carbon-saving technologies abroad. In line with this body of work, the European Union has started rolling out a Carbon Border Adjustment Mechanism, that imposes a tariff on the carbon content of imports (European Commission 2021). Linsenmeier et al. (2022) emphasize that carbon policy adoption is associated with adoption in neighboring countries.

Farrokhi and Lashkaripour (2025) compare climate clubs and carbon border adjustment mechanisms in a quantitative trade model. They find that climate clubs can be more effective than carbon border adjustment mechanisms because most emissions are not embedded in traded goods. Clausing et al. (2025) assess quantitatively the impact of the European carbon adjustment mechanism. They find that it improves competitiveness and limits leakage without penalizing low-income countries. In practice, trade policy is far even from these second-best benchmarks. Shapiro (2021) shows that tariff rates are lower on carbon-intensive industries. More work is needed to evaluate its effect on European Union emissions and spillover effects on its trading partners.

International spillovers of carbon policy can also occur through other channels than trade, for instance general equilibrium fossil fuel price adjustments. Sinn (2008) argues that demand-side policies such as carbon pricing enacted by a subset of countries are ineffective if supply does not react strongly to demand. In the extreme, if fossil fuel supply is fixed, a demand reduction by some countries is exactly offset by an increase in demand from other countries due to falling prices.

3.3 Innovation and Technological Progress

When there is the possibility of technological progress in green energy generation, innovation policy is a powerful complement to carbon pricing. From a first-best perspective, carbon pricing is necessary regardless of the presence of innovation. But innovation in green or intermediate carbon-intensity technologies requires an additional set of policies. Blanchard et al. (2023) and Bistline et al. (2023) review how green innovation policies complement carbon pricing.

3.3.1 Directed Innovation

A long tradition in economics develops theories of innovation (Romer 1990; Grossman and Helpman 1991; Aghion and Howitt 1992). Knowledge is a public good, so firms can only capture a fraction of the benefits that innovation brings to society in the form of research and development or learning by doing. Therefore, market forces may provide insufficient incentives for innovation. Under-investment in innovation is a generic feature of innovation, and applies just as well to the energy transition. A carbon price that is too low further worsens innovation in clean energy. But under-investment remains even if the carbon price is set right. See Newell (2010) for a review.

Just as for any market activity, innovation flows towards sectors where marginal returns are highest: technical change is directed, but the allocation across sectors needs not be efficient (Acemoglu 2002). Goulder and Schneider (1999), Goulder and Mathai (2000), Van der Zwaan et al. (2002), and Popp (2004) analyze endogenous technological change in integrated assessment models. Relative to models without directed technical change, they tend to find modest emissions reductions and lower carbon prices because directed technical change in emissions-scarce industries substitutes for abatement.

Acemoglu et al. (2012), Acemoglu et al. (2016), and Hassler et al. (2021) propose tractable theories of directed technical change with two types of energy: clean (low-emissions) and dirty (high-emissions). Collectively, these papers obtain the following four implications. First, optimal policy features both carbon taxes and green innovation subsidies. Second, when clean and dirty energy sources are sufficiently substitutable, policy intervention needs only be transitory to permanently redirect innovation to green energy and reduce long-run emissions. Third, fossil fuel scarcity contributes to directed technical change. Fourth, a higher elasticity of substitution between green and carbon-intensive energy sources implies lower optimal carbon taxes.

Energy sources with intermediate carbon intensity have more nuanced implications: they can either increase or lower emissions along the energy transition. Acemoglu et al. (2023) analyze the shale gas boom in the United States with a model of directed technical change. They find that despite short-run reductions in emissions, the United States is pushed into a fossil fuel trap in which innovation is directed away from renewables.

Additional margins affect the direction of innovation. Aghion et al. (2023) show that the environmental concerns of consumers direct innovation towards greener energy use in the automobile industry. Arkolakis and Walsh (2023) provide a spatial theory of clean growth and emphasize the importance of local comparative advantage in renewable potential together with electric grid transmission costs. Despite large heterogeneity and lower tradability, they find that renewable-induced price declines have large beneficial

effects for households.

Empirical evidence confirms that carbon-saving innovation is directed by market forces. Popp (2002), Aghion et al. (2016), Moscona and Sastry (2022), Dugoua and Gerarden (2023) find that green technical change responds to energy prices or market needs.[9] Farmer and Lafond (2016) show that green technology prices decline similarly to Moore's law. Wiser et al. (2021) and Way et al. (2022) find that renewable cost declines have consistently outperformed expectations.

3.3.2 Diffusion of Technology

Knowledge and technology do not remain confined within regional, country or industry borders (Eaton and Kortum 1999; Keller 2004; Sampson 2016; Buera and Oberfield 2020). They diffuse across countries and industries, making green technological progress a powerful instrument to reduce carbon emissions across the globe.

Pigato et al. (2020) provide an extensive review of green technology diffusion with an emphasis on developing countries. Hémous (2016) demonstrates that green innovation subsidies alleviate environmental degradation in the presence of international diffusion. Barrett (2021) shows quantitatively in a multi-region integrated assessment model with green innovation and diffusion that international diffusion can halve long-run warming. Gerarden (2023) proposes a related analysis specifically for solar panels. Donald (2024) develops a framework of green technology diffusion in production networks within countries. More work is needed in this area to quantify the importance of technological diffusion for emissions reductions.

3.4 Factor Market Reallocation

In most frameworks discussed so far, the reallocation of production inputs—labor, capital—is assumed to occur frictionlessly between green and carbon-intensive industries. In practice, large factor market reallocation can be difficult and protracted. For instance, the rise of Chinese import penetration in the United States has left many communities persistently exposed to joblessness (Autor et al. 2013). Given that the green transition implies a comparable change in the comparative advantage of industries, it may well share some of these features.

[9] See also Fischer and Newell (2008), Gerlagh et al. (2014), Fried (2018), Chateau et al. (2024) for quantitative assessments.

3.4.1 Labor

Potentially millions of jobs are in industries reliant on high emissions-intensity activity in the United States. These jobs are concentrated in just a few states (Hanson 2023). A large literature in economics evaluates the consequences of frictional labor reallocation in the face of industrial or spatial shocks. For instance, Dix-Carneiro (2014), Traiberman (2019) and Caliendo et al. (2019) propose rich structural models to assess labor market adjustments to trade liberalizations. Grossman and Rossi-Hansberg (2008) and Acemoglu and Restrepo (2022) propose frameworks to evaluate the reallocation of workers across production tasks in response to trade and automation shocks. Originating with Hopenhayn (1992) and Hopenhayn and Rogerson (1993), a long tradition of papers has studied the reallocation of workers across firms.[10]

This structural literature is less developed when it comes to the energy transition. Hafstead and Williams (2020) review the key trade-offs associated with the energy transition. Shapiro and Metcalf (2023) evaluate the general equilibrium impacts of a carbon tax in a framework with unemployment and find that long-run effects depend on green technology adoption. Conte et al. (2022) develop a quantitative framework to study the spatial consequences of carbon taxes in the presence of agglomeration externalities. They find that carbon taxes can improve the spatial allocation of workers by correcting agglomeration externalities: places that are under-sized are also less carbon-intensive.

Walker (2011) and Walker (2013) empirically estimates the displacement effects of plant-level contractions on workers due to the enforcement of the Clean Air Act. He finds worker-level impacts consistent with conventional estimates of displacement effects, but that these costs are small compared to the benefits from regulation. Much more work is needed to assess the impact of the energy transition on workers and labor market reallocation.

3.4.2 Capital

Fossil fuel intensive energy generation tends to be heavily capital intensive. More generally, capital tends to be specific to given energy technologies (machines, equipment, vehicles) and may only adjust slowly along the energy transition. Motivated by these observations, a rapidly expanding literature assesses how green capital investment shapes the energy transition. Bistline et al. (2023) propose an organizing framework to assess the role of subsidies on green capital investment. Varga et al. (2022), Hinterlang et al. (2023) and Coenen et al. (2024) develop quantitative models with green and carbon-intensive

[10] See for instance Bilal et al. (2022) for a more recent example.

capital and a rich nesting structure to evaluate institutional climate targets.

A large literature studies the reallocation of capital across firms with or without financial frictions (Khan and Thomas 2008; Winberry 2021). With a few exceptions discussed below, there is comparatively less work using these frameworks to evaluate capital reallocation across firms and sectors in the face of the energy transition. However, the potential costs may be high. Semieniuk et al. (2022) suggests that stranded fossil fuel assets under 2060 net zero policies represent $1.4 trillion globally, with over half in OECD countries.

The losses associated with stranded assets and the speed of the energy transition depend on whether capital is tightly tied to a particular type of energy. This idea corresponds to the classic concept of vintage capital. Capelle et al. (2023) document vast heterogeneity in emissions-intensity across firms and develop a firm dynamics framework with capital vintages to analyze its implications for mitigation policy. They find that policies that incentivize firms to upgrade their capital vintages can lead to long-lasting economic and emissions gains. Lanteri and Rampini (2023) propose a similar analysis in the context of shipping. Abuin (2024) builds a model of capital investment in shale gas production and exports to analyze the expansion of liquefied gas export infrastructure in the United States. Similarly to directed technical change, an increase in United States shale gas export capacity can lock the world economy away from renewables in the long run. More work is needed to assess the impact of the energy transition on capital market reallocation.

4 Adaptation

With more than 1°C of warming already sunk in past emissions and modest progress in mitigation to date, societies will likely need to adapt to climate change. Countries vary not only in their exposure to climate change, but also in their economic and institutional capacity to adapt. This adaptation can be reactive or proactive.

Macroeconomics has started studying climate change adaptation only recently, but it is a topic of increasing importance. Technological improvements, changes in individual behavior, the ability of trade to insure against climate risk, movements of labor away from exposed areas, reallocation of capital, and climate-related insurance, all constitute forms of adaptation. Yet, estimates of adaptation costs representative of all sectors of the economy are still scarce (Crimmins et al. 2023) and much more work is needed in this area. Burke et al. (2024) provide a recent review of empirical estimates of the degree of adaptation along various economic margins.

4.1 When Does Adaptation Matter?

A common criticism of the canonical damage approach is that it uses short-run weather variation to identify the impact of long-run, slow-moving changes in the climate. These impacts may differ for multiple reasons: they may reflect fundamentally different changes in the climatic system, and society may adapt differently to temporary and permanent changes in the climate.

Deryugina and Hsiang (2017) formalize this "weather vs. climate" debate. Using a simple envelope argument, they show that adaptation is irrelevant for welfare—and thus for the cost of carbon—to first order: to the extent that households or firms are already balancing marginal costs and benefits of adaptation, the additional valuation of adaptation is zero in response to a change in the climate. Under these conditions, estimates that do not account for adaptation in fact coincide with the cost of climate change inclusive of adaption.

Of course, this result relies on small change and interior adaptation prior to the change in the climate. Adaptation may still matter more for larger shocks for which a first-order approximation does not hold, or for slow-onset adaptation that materializes as large, fixed cost investments such as levies or storm surge barriers.

Empirically, the evidence on whether adaptation to climate change impacts is taking place is mixed. Barreca et al. (2016) find a strong decline in the heat-mortality relationship in the United States that they attribute to the adoption of air conditioning. Kahn (2005) shows that mortality in richer countries is less responsive to natural disasters, and Carleton et al. (2022) find that richer countries display smaller heat-mortality sensitivities. All papers interpret their results as evidence of adaptation.

Using a related approach that assesses whether the sensitivity of outcomes to temperature changes over time, Burke et al. (2024) obtain different results. They find limited evidence of adaptation across a wide range of outcomes (output, mortality, conflict, and so on). Much more work is needed to unpack whether and why adaptation may have been limited historically, and whether it may become more prevalent as climate change progresses and becomes more salient.

4.2 Reallocation of Production

In areas exposed to climate change, a natural way to adapt is to shift activity to sectors that suffer less from climate change. This shift can occur with or without trade.

Changes in sectoral specialization. Shifting economic activity away from agriculture is a particularly relevant example, but the literature finds mixed results. Costinot et al. (2016) develop a high-resolution model of crop switching and find that agricultural losses from climate change are three times larger if farmers cannot adapt by switching crops. By contrast, Burke and Emerick (2016) use a panel approach to compare the impact of long-run changes in the climate to short-run heat fluctuations on agricultural productivity in the United States across locations. They find similar impacts and conclude that long-run adaptation to extreme heat is likely weak in agriculture.

Changes in agricultural productivity can further hamper the reallocation of labor to other sectors. Combining a structural model and global firm-level data, Nath (2024) shows that non-homothetic food demand limits the reallocation of workers away from agriculture in the face of climate stress: relative demand for food rises as the economy shrinks due to climate change, leading to more, rather than less, specialization in agriculture.

Trade. Given the specialization of locations in particular sectors, changes in sectoral comparative advantage across space imply that trade acts as potential adaptation mechanism. Building on an earlier literature (Reilly and Hohmann 1993; Rosenzweig and Parry 1994; Hertel and Randhir 2000), Costinot et al. (2016) find that trade in agricultural products is less important than crop switching.

Conte et al. (2022), Rudik et al. (2022) and Cruz (2024) develop multisector models of economic activity that incorporate the adaptation benefits from sectoral switching and trade for the broader economy. Without sectoral comparative advantage, Cruz and Rossi-Hansberg (2024) find only a moderate role for trade as an adaptation mechanism. By contrast, Conte et al. (2022) find a larger role for trade when incorporating changing comparative advantage across a broader range of sectors than agriculture.

Trade itself further interacts with the economic environment in the presence of climate change. First, trade leads to emissions due to national and international transportation. Cristea et al. (2013) document that emissions related to trade are non-trivial, yet Shapiro (2016) finds that the gains from trade are substantially larger than climate damages associated with trade-related emissions.

Second, trade policy may react to climate shocks. Hsiao et al. (2024) collect measures of trade policy around the world and show empirically that they respond to climate shocks. Governments protect domestic consumers and producers of agricultural goods. These interventions may distort domestic and international prices, and limit private incentives to reallocate production to less exposed sectors.

4.3 Reallocation of Labor and Migration

When adaptation in place to climate change and extreme weather through sectoral switching or trade is too costly, out-migration is another option to adapt. Of course, whether households in exposed areas can migrate out depends on available resources to do so as well as migratory barriers.

Whether migration responds to climate change is not a settled question. Empirically, there is some evidence that migration responds to climate shocks within developed countries (Leduc and Wilson 2023; Bilal and Rossi-Hansberg 2023). Across countries however, the evidence is more mixed and depends starkly on the demographic characteristics of would-be migrants (Cattaneo and Peri 2016; Missirian and Schlenker 2017; Benveniste et al. 2024). More work is needed to understand empirical relationship between migration and climate change.

Perhaps to fill this relative paucity of data, the literature has taken a more structural approach that models migration within and across countries as responding to migration costs and idiosyncratic preferences, as well as to income and amenities that can be influenced by climate change (Desmet et al. 2021; Krusell and Smith 2023; Bilal and Rossi-Hansberg 2023; Cruz and Rossi-Hansberg 2024; Balboni 2025). Collectively, these papers find moderate adaptation benefits from migration, that can offset up to one third of the direct impact of climate change.

4.4 Reallocation of Capital

Climate change affects the comparative advantage of locations not only for labor, but also for capital. There is little direct evidence on how capital is reallocated following climate change. Perhaps for this reason, the literature is scarce and largely structural.[11]

Fried (2022) develops an incomplete market model with storm risk to assess the impact of climate change and federal insurance policies on capital accumulation and adaptation with a small number of locations. She finds that the negative moral hazard effects of federal disaster aid offset the positive effects of adaptation investment aid. Bilal and Rossi-Hansberg (2023) model and estimate local capital investment responses to heat and storm shocks with rich spatial heterogeneity at the county level. They find that investment and capital ultimately reallocate away from the South-East Atlantic coast of the United States

[11]The empirical literature on capital and equipment reallocation tends to focus on specific policies or mechanisms rather than a broad definition of capital. Barreca et al. (2016) show that adoption of air conditioning lowers the sensitivity of mortality to heat stress in the United States. Fowlie et al. (2018) show that home weatherization programs have much lower energy savings benefits than previously thought, explaining the low take-up among households.

which is exposed to more frequent coastal storms.

Conte et al. (2021) and Desmet et al. (2021) emphasize a different type of capital accumulation. They develop dynamic spatial structural frameworks to study the reallocation of knowledge capital across locations under climate stress due to heat or sea level rise. They find that knowledge capital tracks changing comparative advantage and concentrates in favorable locations.

Although there are only few papers linking climate change with capital reallocation, there is a large literature on housing and the allocation of capital in macroeconomics (Piazzesi et al. 2007; Kaplan et al. 2020). We believe that the frameworks and insights from this literature can be fruitfully brought to shed light on the reallocation of private capital and housing in response to climate change. Much more work is needed in this area.

4.5 Policy-Driven Adaptation

Public policy is a key margin of adaptation (Analytical Perspectives—Office of Management and Budget 2022, Council of Economic Advisers 2023), with the same economic rationale as for any local public good. Infrastructure investment is one of the most salient margins that governments can leverage to adapt to climate change. Because large infrastructure projects are rare, it is challenging to evaluate their costs and benefits purely empirically. Thus, the literature is mostly structural.

Balboni (2025) uses a quantitative spatial framework to study public infrastructure investment in flood-prone coastal areas, and finds that they can have substantial costs by keeping economic activity exposed to floods. Hsiao (2023) develops and estimates a spatial model of Jakarta and shows that time-inconsistency problems can lead governments to respond inefficiently with defensive investments such as a sea wall.

One exception to the structural approach is Benetton et al. (2025), who evaluate the effect of Venice's sea wall activation on property prices by leveraging differential exposure of properties to flood protection depending on elevation. They find that sea wall costs just balance benefits at conventional discount rates. This result suggests that the envelope argument of Deryugina and Hsiang (2017) may also apply approximately to large infrastructure projects.

Governmental post-disaster transfers can complement protective investments, and are likely to rise in magnitude with climate change. Deryugina (2017) shows that automatic stabilizers such as unemployment insurance and medical insurance pay out larger sums than direct disaster aid after hurricanes. Henkel et al. (2022) document that post-hurricane transfers are more generous in election years.

5 Conclusion

The length of the sections of this paper speak for themselves: the literature on macroeconomic damages and mitigation is well-developed and still undergoing important progress. The literature on adaptation is comparatively less developed, particularly from a macroeconomic perspective. It remains unclear how much societies will manage to adapt to climate change impacts. We hope that adaptation to climate change will keep growing as a topic and take a prominent place within the field of macroeconomics.

Adaptation involves a host of individual and institutional decisions at various levels of aggregation: households and firms; local, state and federal governments; and groups of countries. We hope that future work will make the most of detailed, large datasets that can inform the behavior of these agents. Many detailed datasets on exposure are constructed by institutions and private businesses (e.g. flooding risk by the First Street Foundation, or property values by CoreLogic), but can have varying degrees of verifiability (Schubert et al. 2024). We expect that fruitful collaborations between these institutions, governmental agencies and academics will improve the quality of available datasets.

Assessing the impact of climatic events unfolding over decades is necessarily challenging because, by definition, data is available only for the past. While creative data collection efforts are continuously improving the information available to researchers, we view the combination of the best possible data with structural models as the most promising avenue to evaluate the macroeconomic implications of climate change.

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A The DICE Model

A.1 Economic Module

The economic module of the DICE model resembles the neoclassical growth model. The main differences are the inclusion of climate damages (similar to productivity shocks) and of abatement costs. Gross output at time t is $Y_t = A_t K_t^{\alpha} L_t^{\alpha}$, where A_t denotes total factor productivity, K_t is the capital stock and L_t is the stock of labor. $\alpha \in [0, 1]$ is the capital share in production. The paths of A_t, L_t are exogenously given.

Output net of climate damages and abatement costs then writes: $Y_t^{\text{net}} = (1 - \Omega(T_t))Y_t - \Lambda(\mu_t)Y_t$. $\Omega(T_t)$ is the damage function that depends on temperature. $\Lambda(\mu_t)$ is the abatement cost function expressed as a share of output, and depends on the fraction of emissions abated μ_t, with $\Lambda(0) = 0$.

Capital accumulates according to $K_{t+1} = (1 - \delta_K)K_t + I_t$, where I_t denotes investment and δ_K is the capital depreciation rate. Aggregate consumption is then $C_t = Y_t^{\text{net}} - I_t$. Households have standard time-separable preferences with flow utility function U and discount factor β.

A.2 The Climate Module

Emissions are given by $E_t = \sigma_t(1 - \mu_t)Y_t + E_t^{\text{land}}$, where land emissions E_t^{land} are exogenously given. The first component $\sigma_t (1 - \mu_t) Y_t$ represents emissions from economic activity and is proportional to gross output Y_t, the fraction of unabated emissions $(1 - \mu_t)$, and the exogenous emissions intensity of production σ_t. A secular decline in σ_t can capture technological progress in low-emission energy sources.

The standard climate module posits: $M_t = (\text{Id} + B)M_{t-1} + E_t$, where $M_t = \left[M_t^{\text{AT}}, M_t^{\text{UO}}, M_t^{\text{LO}}\right]$ is the vector of carbon masses in the three main reservoirs (the atmosphere, the upper oceans, and the lower oceans). Here, Id denotes the 3×3 identity matrix, and B is a 3×3 matrix that represents carbon mass transfer between the reservoirs, with $\sum_j B_{ij} = 0$ by mass conservation.

Radiative forcing takes the form $F_t = F_0 \log\left(M_t^{\text{AT}}/\overline{M}\right) + F_t^{\text{EX}}$, where F_0 is the climate sensitivity, $\overline{M}$ is the long-run mass of atmospheric carbon absent anthropogenic emissions, and F_t^{EX} is exogenous forcing.

Temperatures in the atmosphere and the oceans then follow: $T_{t+1}^{\text{AT}} = T_t^{\text{AT}} + c_1\big(F_t - \lambda\, T_t^{\text{AT}} - c_2(T_t^{\text{AT}} - T_t^{\text{OC}})\big)$, and $T_{t+1}^{\text{OC}} = T_t^{\text{OC}} + c_3\big(T_t^{\text{AT}} - T_t^{\text{OC}}\big)$. The coefficients c_1, c_2, c_3 capture heat exchange between the atmosphere and the oceans, and λ represents radiative feedback.

A.3 Decision Problem

Planning problem. A world planner chooses the optimal path of investment and abatement to solve:

$$\max_{\{\mu_t, C_t\}_t} \sum_{t=0}^{\infty} \beta^t L_t U\left(\frac{C_t}{L_t}\right),$$

subject to: (1) $C_t + K_{t+1} = [1 - \Omega(T_t) - \Lambda(\mu_t)] A_t K_t^{\alpha}\, L_t^{1-\alpha} + (1-\delta_K) K_t$,

(2) the climate module,

where $\Omega(T)$ represents climate damages, $\Lambda(\mu)$ represents abatement costs, A_t is productivity, δ_K is the depreciation rate, and β is the discount factor.

Decentralized equilibrium. In the decentralized equilibrium, dynasties of households and firms make individual decisions. Firms earn zero profits due to constant returns to scale. Because households are atomistic and do not internalize the benefits of decarbonization, they always set $\mu_t = 0$. Households then choose:

$$\max_{\{C_t\}_t} \sum_{t=0}^{\infty} \beta^t L_t U\left(\frac{C_t}{L_t}\right),$$

subject to: (1) $C_t + K_{t+1} = w_t + r_t K_t + (1-\delta_K)\, K_t$

(2) given the paths of w_t, r_t.

In addition: $r_t = \alpha[1 - \Omega(T_t)] K_t^{\alpha-1} L_t^{1-\alpha}$, and $w_t = (1-\alpha)[1-\Omega(T_t)] K_t^{\alpha} L_t^{-\alpha}$,

T_t is given from the climate module.

Functional forms. Common functional forms include:

$$U(c) = \frac{c^{1-\gamma} - 1}{1-\gamma}, \quad \Omega(T) = 1 - \frac{1}{1 - \Omega_1 T - \Omega_2 T^2}, \quad \Lambda(\mu) = \Lambda_0 \sigma_t \mu^2.$$

Interpretation. Our discussion of loss and damage in Section 2 corresponds broadly to various specifications and parametrizations of the damage function $\Omega(T)$. Our discussion of mitigation in Section 3 corresponds broadly to various specifications and parametrizations of the abatement cost curve and technological progress $\Lambda(\mu), \sigma_t$. Our discussion of adaptation in Section 4 amounts to adding more choices and margins to the planner or the representative households in the decision problem.