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A TIME FOR ACTION ON CLIMATE CHANGE AND A TIME FOR CHANGE IN ECONOMICS*

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The case for action on climate change with urgency and at scale rests on the immense magnitude of climate risk, the very rapid emissions reductions which are necessary, and that there is a real opportunity to create a new and attractive form of growth and development. The analysis must be based on a dynamic approach to the economics of public policy, set in a complex, imperfect and uncertain world. The economics of climate change, and further, economics more broadly, must change to respond to the challenge of how to foster rapid transformation. It is time for economics and economists to step up.

1. Purpose and Plan

The address was, and this paper is, about the analysis of policy towards immense risks, the management of which necessitates rapid and fundamental change in our economies. The focus is on action with urgency and at scale, and the logic of that action. If we are to harness our subject effectively, with relevance, and in real time, we must understand and articulate the problem defined by the science and then marshal, develop and apply our economics around the issues and challenges that are at the core of the problem. In so doing, we must avoid trying to force a huge and non-standard challenge into a narrow and standard framework, however convenient it might appear to be to try to use familiar 'workhorses'.

Accordingly, this analysis begins with the urgency and scale of the climate crisis. Then the paper examines the twin crises of climate and COVID, together with the difficulties of the decades leading up to COVID, and explains why we must tackle these crises together. It will be innovative investment that can drive us out of the COVID-related economic disruption and on to a much better and sustainable growth path. The case for such investments, and how they can be fostered, forms the subject matter of Part I. I will also reflect on what we have learned since the Stern Review of 2006 and why the lessons strengthen the case for the action proposed.

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I shall also argue that these new investments and innovations present a great opportunity, with many benefits beyond the fundamental rewards associated with reducing the risks from climate change. But strong action to foster and finance these investments will be crucial if they are to come through, and the radical nature of the changes will inevitably involve dislocation, the management of which is central to equitable and successful action.

The case for action with urgency and at scale rests, in large measure, on the immense magnitude of climate risk and the very rapid emissions reductions which are necessary to create an acceptable chance of avoiding the worst of the risks. Tackling the problem in a coherent and effective way requires providing an analysis that identifies: the investments and innovations we need and the policies, institutional structures and finance that can draw through and support these investments and innovations. I will argue that these investments and innovations can deliver a new and attractive form of sustainable, resilient and inclusive growth. That argument can play a critical role in policy discussion, decision-making and creating coalitions for action.

It is surely clear that such analysis must be based on a dynamic approach to the economics of public policy, set in a complex and uncertain world. Policies focused on change are of the essence; and the analysis must be grounded in and reflect a world where there are many market imperfections, where there are increasing returns to scale, where risk is central, and where the distribution of income and welfare is a crucial issue. And where time is of the essence; urgency is intense. This is an economics of public policy which is rather different from the bulk of work in economics in this area, but it is, in my view, an economics forced by the logic of the problem.

In Part II of the paper, I will argue that the economics of climate change, and, further, economics more broadly, must change to respond to this challenge of how to foster rapid transformation. There is nothing more important or exciting than this problem. It requires and opens up a tremendous amount of economics. There is so much in the richness of our subject that we can and must put to work. But there is more that we must create. The task requires expertise ranging across the entirety of our subject and, indeed, collaboration with other disciplines. And an engagement by our profession in a way beyond what we have seen so far. It is time for economics and economists to step up.

Part I

2. Urgency, Scale and Opportunity

2.1. *The Science of Climate Change and the Role of Targets*

We must start with the science.[1] The Intergovernmental Panel on Climate Change (IPCC) has been in existence since 1988 and has produced a series of assessment reports, published every few years, about the current state of knowledge on climate change. Each one of those assessments has been more worrying than the last. The first one, published in 1990, was extremely worrying, but the outlook has only worsened as the evidence has become ever stronger of effects coming through more quickly and with greater intensity than we expected. The latest report (the Sixth Assessment Report) published in August 2021 has demonstrated even more clearly that we are under intense time pressure if we are to be able to hold temperatures at levels which manage the most extreme risks (IPCC, 2021).

[1] I am very grateful to scientist friends, particularly Brian Hoskins and John Schellnhuber, for discussions of the science over the last two decades. Any misunderstandings are my own responsibility.

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Global mean surface temperature is already 1.1°C above that of the end of the nineteenth century, our usual benchmark. This puts us on the edge of the temperature of the Holocene epoch; the benign period starting 10,000–12,000 years ago, during which our current civilisations emerged, following the end of the last ice age. It was during this period of fairly stable climate and temperature that many human cultures transitioned to a lifestyle based on sedentary agriculture. This is when we turned grasses into grains and stayed in one place as we nurtured crops until harvests; we built villages; we generated surpluses and used storage, thus creating opportunities for activities and services outside agriculture. With 1.1°C of temperature rise, on the borderline of the temperatures of that period, we are already seeing very intense effects: fires associated with heat and drought; severe flooding; hurricanes and typhoons; storm surges; sea level rises; local temperatures at levels dangerous to human life, and so on. In the summer of 2021, northern California and western Canada experienced temperatures close to 50°C, unprecedented and causing extensive loss of life and severe wildfires. And flooding, on a scale never previously experienced, occurred from Germany to China. There could be much worse to come. Our current emissions pathway implies that we are headed for temperature increases of more than 3°C (UNEP, 2020).[2] The science is clear that such temperatures could carry grave risks to humankind and the planet as a whole. As a world, we have not seen 3°C or more for around 3 million years, and at that time sea levels were 10 to 20 metres higher than now. The range of extreme climate impacts from sea levels to droughts to hurricanes/cyclones to floods to intense heat and beyond would radically change lives and livelihoods across the globe. Many parts of the world could become uninhabitable. Under a business-as-usual scenario, one of the most densely populated regions in the world, the North China Plain, would likely experience deadly heatwaves later this century with 'wet-bulb' temperature exceeding the threshold defining what people can tolerate while working outdoors (Kang and Eltahir, 2018). Similar heatwaves could also occur in other densely populated parts of the world, such as north India. Hundreds of millions, possibly billions, would have to move,[3] likely resulting in severe and extended conflict. It is quite possible on current paths that we could see 4 or 5°C of temperature rise 150 years or so from now; temperatures which the world has not seen for tens of millions of years. That would be absolutely devastating. The stakes we are playing for are immense.

So, what do we have to do? To stabilise temperatures, we have to stabilise the concentrations of greenhouse gases in the atmosphere.[4] To stabilise the concentrations of greenhouse gases, the flow of greenhouse gases into the atmosphere must be net zero. The earlier we stabilise the concentrations of greenhouse gases in the atmosphere, that is, the earlier we go to net zero, the lower the temperature at which we stabilise. One can fine-tune the climate science, and the path to net zero matters, but that is the underlying, basic physics and the logic of the net zero target. If we want to stabilise at 1.5°C (see below), we have to go to net zero CO_2 by mid-century. Figure 1 shows the emissions pathways (in terms of CO_2 equivalent, where the warming effect

[2] Following plans and commitments associated with UNFCCC COP26 in Glasgow, November 2021, we may be, if they are delivered, headed in a direction of a little above 2°C of warming. Such plans and commitments are linked to an increasing understanding of the dangers.

[3] Empirical estimates range substantially, from 50 million to 1 billion migrants associated with the effects of climate change during this century (Ferris, 2020). We should remember that we have been forced consistently over the last few decades to bring forward in time our estimates of when serious impacts can occur and revise estimates of their magnitudes upwards. And most models do not embody the tipping points that we think may occur at higher temperature which could generate dangerous feedback loans (e.g., collapse of Amazon forest, thawing of permafrost, melting of polar ice sheets). Thus the numbers having to move could be badly underestimated in these analyses.

[4] Greenhouse gases are those whose molecules oscillate at a frequency that interferes with the infra-red energy reflected from the earth's surface, thus preventing its escape and causing warming. CO_2 is the most important and is long-lived.

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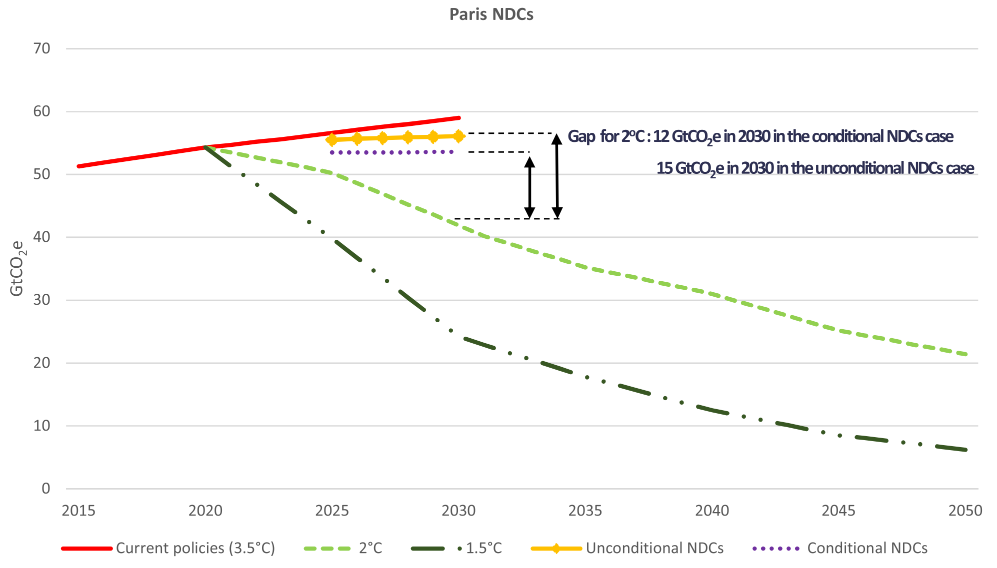

Fig. 1. *Stylised Emissions Pathways for 1.5°C and 2°C and the Gap to Emissions Trajectories Based on Paris NDCs.The vertical axis represents emissions in CO_2e, that is CO_2 plus the effects of other greenhouse gases.*
Source: Trajectories based on UNEP (2020).

of other greenhouse gases is included) that we need to follow if we are to stabilise at 1.5 or 2°C of temperature increase.

It is important to note that the NDC scenarios (unconditional and conditional) shown in Figure 1 estimate the levels of GHG emissions projected as a result of the implementation of the mitigation actions pledged by countries in their Nationally Determined Contributions (NDCs) (UNEP, 2020). Most countries offer targets or ‘NDCs’, to 2030.

The differences between 1.5°C and 2°C are major. For example, the percentage of the global population exposed to severe heat at least once every 5 years would be 14% with 1.5°C of temperature rise, but 37% with 2°C of temperature rise (Dosio *et al.*, 2018). That is, the risk of being exposed to extreme heat every 5 years would be more than double for 2°C versus 1.5°C. Thus, when we consider the risks in a consequentialist way, the 2°C which we had earlier seen as dangerous to exceed, now itself seems very dangerous. That was the key lesson of the powerful and important IPCC report on 1.5°C of 2018, showing that the risks and dangers are still more serious than estimated previously. An examination of the risks in terms of potential consequences for humans and the planet as a whole suggests that it makes a lot of sense to try to hold the temperature rise down to 1.5°C. And it is an achievable goal if we move strongly and quickly. Further, we will argue that such a path can carry many ‘co-benefits’ beyond the reduced risks from climate change. It can be a much more attractive form of development.

We can think of setting a temperature target as a ‘guard-rail’ approach to extreme risk. That approach is a standard, indeed widely and understandably regarded as sensible, approach to great risks, particularly around human life. It is clearly a consequentialist approach, although not necessarily one arising from simple, indeed simplistic, optimisation of some standard welfare function from an underlying model. In my view, the risks, including the possibility of the loss of

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life of billions, extended and severe conflict, destroyed biodiversity, and profound loss of quality of life, livelihoods and well-being, are not well captured in narrow utility-based approaches. Neither the standard objective functions in economics, nor indeed the underlying models, capture the challenges at issue. Here, the governments and the people of the world, after thinking it through, and taking account of the feasibility, costs and attractiveness of paths that could achieve different targets, came to the targets in the Paris agreement at COP21 of the UNFCCC in December 2015, of holding temperature increases 'well below 2°C', with best efforts to 1.5°C. The IPCC report of 2018 on 1.5°C further underlined the importance of that target and pointed still more strongly towards a target of 1.5°C.

We should see the 1.5°C target as a balanced and consequentialist approach to immense risk. We can, of course, rig up expected utility models that give that conclusion but, in my view, they do not add significantly to the argument, particularly since such models are so sensitive to specification of structure, functional forms and parameters. Fairly modest model tweaks can give rather different results. I will expand on the flaws of these models in Subsection 6.2.

In a world of 4 or 5°C temperature rise, we risk loss of life in the hundreds of millions or billions, because we do not know what the 'carrying capacity' of that world might be. It could be much lower than the 9–10 billion or so expected towards the end of the century. It is hard to understand or put numbers on the potential devastation and agony around the process of loss of life that could be involved. It is difficult, in particular, to argue that an expected utility approach captures the issues at stake in a plausible way. In my view, a direct risk assessment looking across possible consequences and a guard-rail approach is more thoughtful, reasoned, broad-ranging and robust. And it is clearly seen as a reasonable and rational approach by large parts of the body-politic.

We know what kind of emissions paths we have to follow to achieve our target, i.e., holding warming to 1.5°C. But emissions are currently way off track for such paths. Global greenhouse gas emissions rose in 2019 for the third consecutive year, reaching a record high of 59.1 $GtCO_2e$ (including land use change) (UNEP, 2020). Although annual emissions decreased sharply in 2020 due to the global response to the COVID pandemic, global energy-related CO_2 emissions are projected to rebound and grow by 4.8% in 2021 (IEA, 2021a). Returning to Figure 1, we can see that, for 1.5°C, world emissions must start turning down now and continue to drop sharply. To get from current levels of close to 60 $GtCO_2e$ a year, down to net zero by mid-century, we have to change fundamentally the way we do things. And we have to do that everywhere, across all sectors, across all countries. We cannot be confident that there will be net negatives in large quantities,[5] so we must strive for net zero across the board.

2.2. *Urgency*

The next decade is critical. Choices made on infrastructure and capital now will either lock us in to high emissions, or set us on a low-carbon growth path which can be sustainable and inclusive. In the next 15–20 years infrastructure will roughly double; in the next 20–25 years the world economy will probably double; and in the next 40 years the urban population will likely double. If that new infrastructure, the new world economy, or the towns and cities we build look anything like the old, we will have no hope of meeting the objectives of the Paris Agreement.

[5] We can and should create negative emissions by building our natural capital, e.g., restoring degraded land and expanding our forests. And we should work intensively on possibilities for 'air capture' to bring down costs, and to examine potential for scale.

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The infrastructure we build in the next 15–20 years will be decided in the next few years. That is why we have to act quickly. A sense of urgency is absolutely critical in our decision-making.

2.3. *A New Form of Growth*

The necessary rapid change across the whole system, just described, can be a story of growth, indeed the only sustainable story of growth. In the shorter term, the necessary investments can boost demand in a world where planned savings exceed planned investments (with sluggish demand and low real interest rates). In the short and medium term it is an approach full of innovation, investment, discovery and new ways of doing things. It can be more efficient and much cleaner. It can create cities where we can move and breathe, and ecosystems which are robust and fruitful. It is potentially a very attractive, different way of doing things, relative to past dirty models, with so many gains across the different dimensions of well-being. But that does not mean that it is easy. It does mean that it is sensible, it does mean that it is attractive, and it is within our grasp. We have to change radically and, particularly, invest and innovate strongly to get there. That is the challenge. But there can be a real payoff in terms of a much better form of growth. We must also remember that there is unlikely to be a long-run growth story that is high carbon; it would likely create, the IPCC reports show, a physical environment so hostile as to derail growth and undermine living standards across the board.

Can it be done? The answer is 'yes' and in particular there are four forces at this current moment which are particularly favourable to moving quickly and on scale: low interest rates, rapid technological change (see Subsection 2.4), international understandings coming together (including the UNFCCC, COP21, the Paris Agreement of 2015 and more than 100 countries covering 61% of emissions committing to net zero by mid-century; Black *et al.*, 2021), and pressure from the young people of the world to change (for example, Fridays for the Future and strong activity in the universities of the world). Further, at COP26 in Glasgow in November 2021, we saw further progress, particularly around new targets set for themselves by private financial institutions, agreements on technologies, and new strategies from key countries (including India, South Africa and Vietnam).

2.4. *Rapid Technological Change*

Technology has changed very rapidly over the last 15 years or so. A whole range of low-emission technologies, that are already competitive with fossil fuel-based technologies without subsidy or a carbon price, have emerged. Capital costs for renewable electricity continue to fall much faster than those for conventional technologies and many electric vehicle technologies are now close to cost-competitive with their fossil fuel counterparts (see Figures 2 and 3). Electric vehicles are expected to reach sticker price parity with internal combustion engine vehicles by 2024, as lithium-ion battery prices continue to fall (ETC, 2021), and they have big relative advantages on running and operating costs.

The pace of these advances in technology and reductions in cost has been much faster than expected. For example, since 2001, the International Energy Agency (IEA) has consistently underestimated the rate at which the cost of solar photovoltaic (PV) would subsequently fall, in its World Energy Output (WEO) reports (Ives *et al.*, 2021)—see Figure 4. The costs of these new, cleaner technologies are falling rapidly and will likely continue to do so. In terms of the market,

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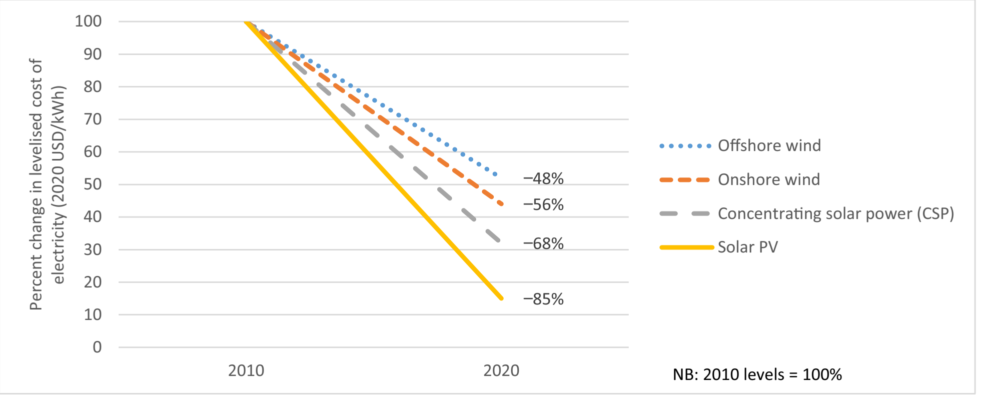

Fig. 2. *Renewable Power Technologies: Cost Decreases Since 2010.*
Source: IRENA (2021).

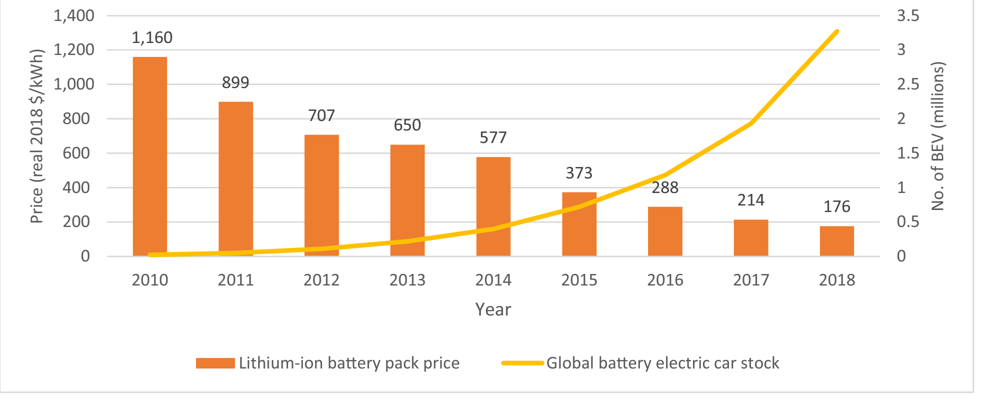

Fig. 3. *Lithium-ion Battery Pack Price Reduction and Global Battery Electric Vehicle Stock.*
Sources: BloombergNEF (2019), IEA (2020).

new technologies in the power sector have already passed tipping points and others seem to be approaching them (Systemiq, 2021).

With falling costs of clean technologies, estimates of the ‘cost’ of the transition to net zero have been consistently reduced. The United Kingdom’s Climate Change Committee (CCC) has been producing estimates of the investments, costs and resource savings associated with the United Kingdom’s pathway to net zero. Their 2020 analysis suggests that the annualised resource cost[6] of reducing GHG emissions to net zero would be approximately 0.5% of GDP in 2050 (CCC, 2020). This is lower than the estimate the CCC produced in 2019, which put the annual cost of meeting the net zero by 2050 target at 1–2% of GDP in 2050. Further, the estimate they produced

[6] Annualised resource costs are estimated by adding up costs and savings from carbon abatement measures and comparing them to resources costs in an alternative scenario of no-further-climate-action (CCC, 2020).

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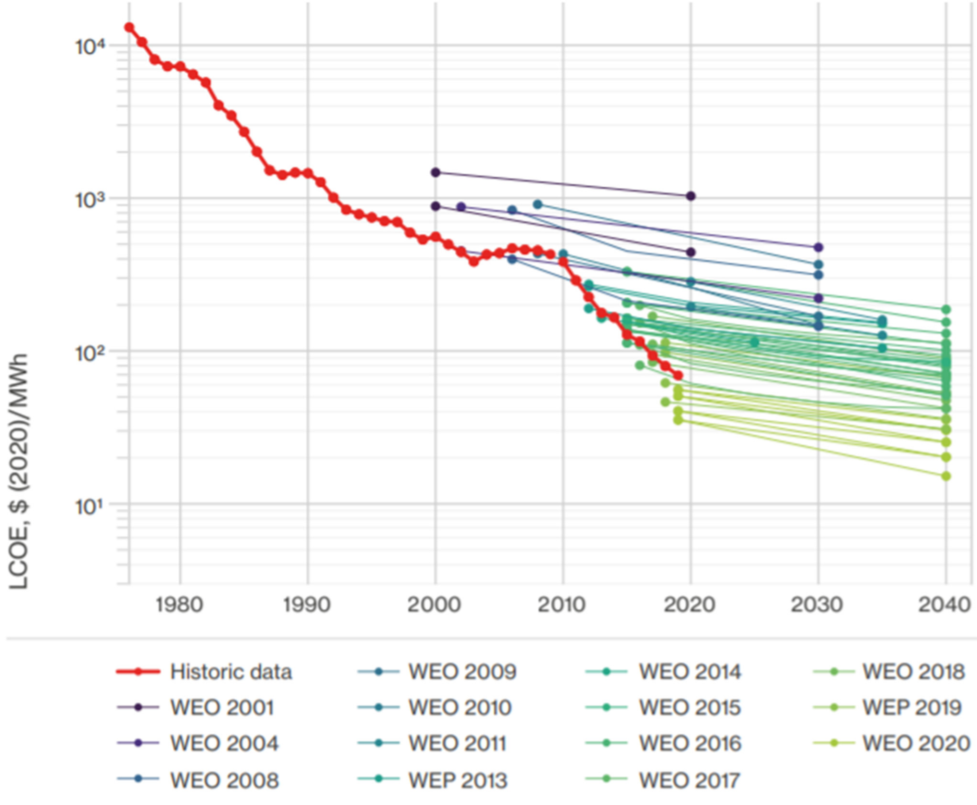

Fig. 4. *Actual Versus IEA projected LCOE of Solar PV.*
Source: Ives *et al.* (2021).

in 2008 put the annual cost of meeting a much weaker target, reducing emissions by 80% by 2050 (relative to 1990), at a similar 1–2% of GDP in 2050 (CCC, 2019).

At the time of the Stern Review (Stern 2006) we estimated costs of 1–2% GDP per annum for reducing emissions (globally) by 80% (comparing 1990 and 2050). It has been argued that, even with that target, the last few percent would be particularly costly; that is embodied, indeed forced by assumption, in the modelling of many integrated assessment models (IAMs). Now we have estimates (in the case of the United Kingdom) below 1% of GDP for going to *net zero* emissions by 2050. The changes in estimates reflect real changes in costs and fairly modest assumptions (in relation to experience) of future cost changes—technical progress continues rapidly. There are strong economies of scale in production and discovery, which, with clarity in policy direction, will drive change; that observation is crucial because many IAMs have diminishing returns and increasing marginal costs to climate action, and that assumption is key to many of their results.

We should note that the averaging of costs can conceal the strong upfront nature of the necessary investment. At the same time, we should also observe that the language of investment is in some ways a better description than the narrow term ‘cost’. ‘Investment’ reflects a more dynamic approach. Many of these investments will have powerful returns in productivity and efficiency,

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reduction of air pollution and so on as well as emissions reductions. We should nevertheless be clear that such investments will be substantial.

Low-carbon technologies are already competitive with fossil fuel-based alternatives in the power sector without carbon price or subsidy. In 2020, solar/wind was the cheapest form of new power generation[7] in countries representing over 70% of world GDP (Systemiq, 2020). And renewable energy technologies are expected to continue to decline in cost. Reductions in upfront capital costs will be driven by innovations around efficiency and new methods, more competitive global supply chains and economies of scale, while reductions in total levelised cost of electricity (LCOE) generation will be driven by increasing capacity factors and declining operational and financing costs (ETC, 2021). Low-carbon solutions could scale rapidly, become competitive, and push down emissions in sectors accounting for 90% of emissions by 2030 (Systemiq, 2021). This analysis indicates the possibility of tipping points in the adoption of new technologies, where the rise of the new technology is accelerating and moving in the direction of dominance. These possibilities were at the core of the Glasgow Breakthrough agreements on technology at COP26.

In the building sector, for example, reversible heat pumps are already at cost parity with a gas boiler plus air conditioning in some geographies. If the falling cost of this technology is coupled with incentives, it could achieve cost parity with the fossil fuel alternative by 2025 (Systemiq, 2021). In the food and agriculture sector, it is estimated that plant-based ‘meats’ could reach price parity with existing proteins between 2023 and 2025 and cultured meat by 2030–2 (CE Delft, 2021; Morach *et al.*, 2021). In addition to the adoption of low-carbon technologies, the IEA’s global pathway to net-zero emissions by 2050 projects that around 8% of emissions reductions will need to be achieved from behavioural changes and materials efficiency. The absence of behavioural changes to reduce energy demand in transport, buildings and industry, would increase the costs and difficulty of achieving net zero by 2050 substantially (IEA, 2021b).

Further, there are immense benefits beyond the fundamental contribution of radically reducing the risks of climate change. As we have noted, these include cities where we can move and breathe and be more productive, and ecosystems which are robust and fruitful. We can find, and are finding, great advances in resource (including energy) efficiency. And, crucially, we can strongly reduce deaths and damage to health from air and other pollution—around 15% of world deaths in 2018 were linked to air pollution associated with the burning of fossil fuels (Vohra *et al.*, 2021).

In summary, in this section I have explained why we have to change, the degree to which we have to change, why it is feasible, and the very attractive new form of growth and development that this change could bring. Management of that change at the pace we need, including associated dislocations, will be crucial to both welfare and political feasibility.

3. The First Decades of this Century, the COVID Crisis, and the Climate Crisis

We are at a very special moment in history, facing two crises: the COVID crisis that we are experiencing right now (December 2021) and the climate crisis, which embodies risks and challenges that are bigger, deeper and longer lasting even than the tragic COVID crisis. There are powerful arguments that we have to tackle these crises in a similar way; with strong, innovative investment, to drive a recovery and create a new form of development and growth (Stern and Bhattacharya, 2020).

[7] Based on the levelised cost of electricity (LCOE). LCOE is the average offtake price needed across a project lifetime for a developer to meet its equity hurdle rate of return (BloombergNEF, 2020).

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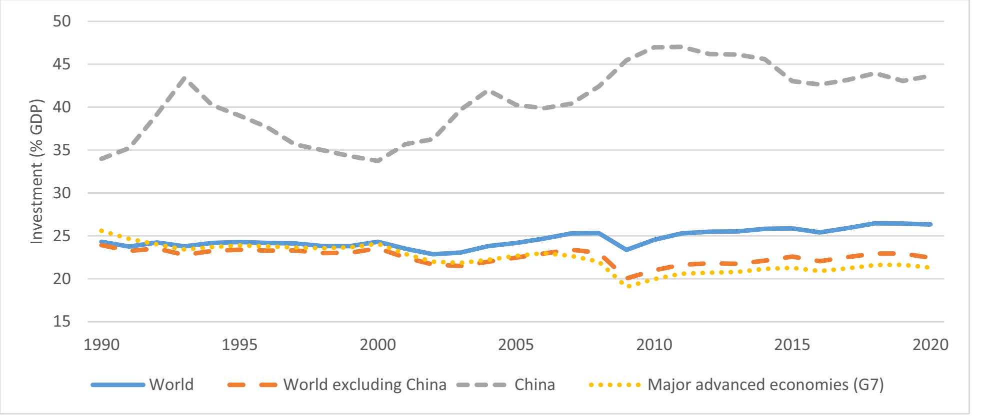

Fig. 5. *Investment Rates in the Decades Before COVID.*
Source: IMF (2021).

3.1. *The Decade Before COVID*

The COVID crisis has underlined the dangers, weaknesses and fragilities that had been building in the world economy. Broadly speaking, the economic and social conditions across the world during the decade before the COVID pandemic were troubling. Growth rates and investment rates plunged across the world during the global financial crisis (2007–9) and, for the most part, had not, in the second decade of this century up to COVID, recovered to the levels of 2000.[8] This pattern of lower investment rates (see Figure 5) and lower growth (see Figure 6) was important background to the challenges of social cohesion and populism (Tabellini, 2019), which emerged during the 2010s. There was also some faltering, particularly under President Trump, of internationalism. This was in addition to rising emissions and severe loss of biodiversity (Dasgupta, 2021).

Despite these challenges in the decade prior to COVID, there was growing momentum towards a more sustainable economy. There had been major advances in international commitment and agreement (e.g., the Paris Agreement and adoption of the Sustainable Development Goals (SDGs) in 2015); improved understanding of a new sustainable, inclusive and resilient approach to growth and development (Stern, 2015; NCE, 2018; OECD, 2018); growing commitment to net zero emissions by the private sector (Black *et al.*, 2021); and engagement by economic policymakers (e.g., via the Network on Greening the Financial System—central banks—and the Coalition of Finance Ministers on Climate Action).

3.2. *Tackling the COVID and Climate Crises and Creating a New Internationalism*

Tackling the two crises—COVID and climate change—requires a new and shared understanding of how to reconstruct our economies and societies and the meaning of ‘build back better’. Rebuilding in a different way will involve substantial investment and innovation; and the global nature of the challenges demands international collaboration.

[8] China was the exception where investment rates have been fairly steady in the second decade of this century, up to the COVID crisis, although China’s growth rate was substantially lower in the 2010s, relative to the 2000s.

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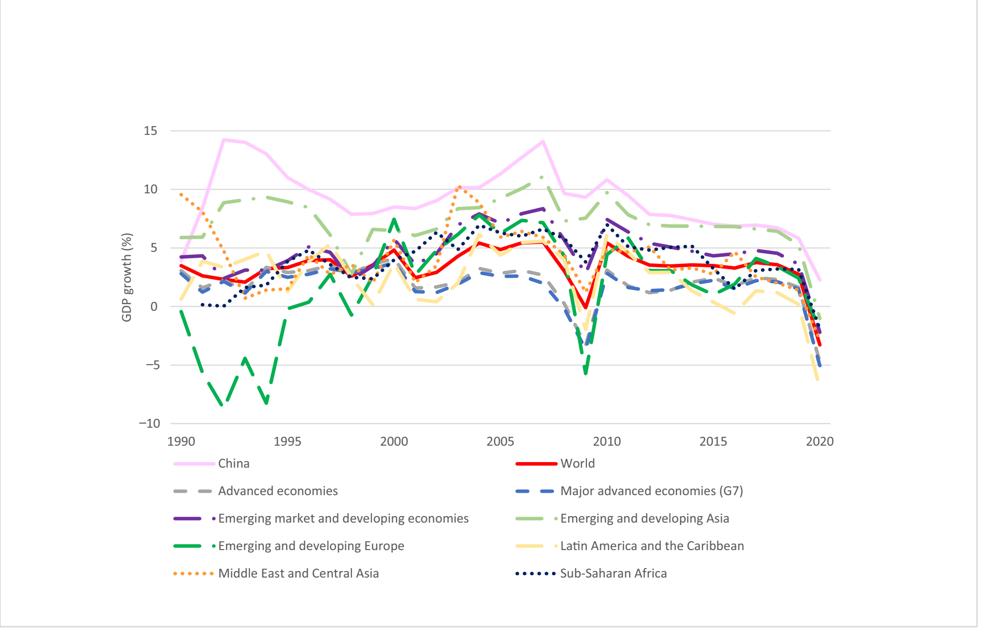

Fig. 6. *GDP Growth in the Decades Before COVID.*
Source: IMF (2021).

There have always been arguments for internationalism; in our current circumstances they are extraordinarily powerful. The returns to collaboration in current circumstances can be expressed in terms of four wins. The first is that we have seen sluggish demand in many countries of the world over the last decade. From a macro perspective, planned saving exceeds planned investments and we have very low real interest rates. We need to expand world demand. Expanding demand in countries simultaneously has a much more powerful effect than expanding demand in just one country, because increasing demand in one country spills over to boost demand and employment in others. Second, we have to reset expectations, not only for growth but also for a different kind of growth. If we reset those expectations together around the world, then investors will know that the investments they are considering are of a kind that are going to be in harmony with the movement of demand around the world. A third win is that if there is a shared understanding of the direction of new technologies then we will create increasing returns to scale in production and discovery. We have already seen (see Section 2) that very powerfully in the way in which costs of solar and wind power have been driven down; the same is happening now with batteries; and electric vehicle costs are going to fall very quickly. The overall scale of technology deployment, achieved by acting together, can generate big returns. The fourth win comes from climate and biodiversity being global public goods. If we emit less greenhouse gases in one country, then all other countries gain from that drop in emissions: similarly protecting and regenerating biodiversity benefits us all. Working together is, therefore, of fundamental importance, perhaps now more than any time in history (Stern and Bhattacharya, 2020). The private sector, the multilateral development banks and international financial institutions, and the ministries of finance and the central banks all have central roles.

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4. Realising Investment for a Strong and Sustainable Recovery

4.1. *Investment*

In Section 3, I explained why strong, internationally coordinated investment should be at centre stage, right through from recovery from the COVID pandemic to transformational growth and the drive to a net zero economy. What kind of orders of magnitude of investment do we need to make? To bring through the new ways of doing things and the new technologies required, we have to increase investment by around 2–3 percentage points of GDP across the world, relative to the previous decade—more in some places, less in others—as well as change the composition of investment (in China, however, it is not a question of raising investment rates but changing the composition of investment). Many of these new technologies involve pulling capital increases forward, along with investing in different ways. Renewable electricity, for example, requires upfront investment whereas fuel cost savings are realised once the renewable technologies are operational. Importantly, these investments should not be seen narrowly in terms of extra costs from going 'clean'; many of them have substantial returns in terms of greater efficiency, cleaner air, better health and more. But an increase in the investment rate by 2–3 percentage points of GDP is needed to realise these gains, to recover sustainability and to put us on a new path.

This estimate of the magnitude of the necessary boost to global investment can be arrived at from a number of different perspectives. First, for the world excluding China, it would take us back to the level of investment seen three or so decades ago (Figure 5; see also IMF, 2021) and help to restore growth rates and productivity improvements. Second, there has been a persistent gap in infrastructure spending in both developed and developing economies, in terms of what is necessary to support growth and development, that has been estimated at 2–3% of global GDP (NCE, 2016; Bhattacharya *et al.*, 2019). Third, we can examine the specifics of the needs and significant opportunities for scaling up the sustainable investments necessary to accelerate the transition to a low-carbon and climate-resilient economy, and restore natural capital. These investments are examined and quantified in a number of recent reports (ETC, 2021; IEA, 2021b; Stern, 2021). These three approaches are not additive, they are different ways of looking at the issue, but they all point to numbers in a similar range.

At the country level, the necessary increase in investment will vary according to level of development and circumstances. For the G7 countries, a 2 percentage point step up in investment, relative to the past decade, would partly reverse earlier declines, driven in part by cuts in public investment. More detail on an investment programme for green recovery and transformational growth, that can be driven by G7 countries, is provided in Stern (2021). For many emerging market and developing countries (EMDEs), the necessary increase in investment will likely be higher than 2 percentage points, given the range of investments, particularly around infrastructure, required to meet development goals. More detail on the magnitude and types of investment needed in EMDEs other than China, and a strategy for financing those investments, is provided in Bhattacharya (2022). For China, as noted, the main challenge will be to change the composition rather than the level of investment.

Such an investment programme could overcome the secular stagnation that has been experienced around the world over the last decade or so. From a basic Keynesian macro perspective, this was associated with planned investment being too small in relation to planned saving. The obvious solution, then, is to increase planned investment, in the light of the urgent requirements we have described. From this perspective, we can overcome secular stagnation by investing in

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new, and environmentally necessary, ways of doing things, thereby not only restoring demand but also charting a much more attractive form of growth.

4.2. *Policy*

These increases in investment will require strong policy and a positive investment climate, including the functioning of relevant governmental institutions. Further, the many relevant market failures (see Section 7) and the urgency of change indicate the necessity of a whole range of policy instruments. Carbon pricing will be important, but alone it will not be enough. Complementary policies, including city design, regulation and standards, and investments in R&D, will also be needed.

Investment seeks returns over the medium and long term and requires clear and credible signals. However, circumstances change and learning occurs, and that means policy will be revised; but it should occur in ways that are 'predictably flexible'. Thus, policy revisions, as lessons are learned, systems change and technologies advance, must be carried through in ways that people understand, and which can be anticipated. For example, it can be announced that an emerging technology will be supported initially but as it moves out, or 'diffuses', into the productive world, or as the cost of the new technology falls, its supporting subsidy will be reduced. Predictable flexibility has been a principle of monetary policy for some time, but it should be applied across the board; otherwise confidence in policy is undermined, policy risk is seen as pervasive, and investment is discouraged. Government-induced policy risk is one of the major deterrents to investment worldwide, particularly around infrastructure (World Bank, 2004; WEF, 2014; Baker *et al.*, 2015; OECD, 2015; World Bank, 2020; World Bank, 2021).

4.3. *Finance*

Investment and innovation inevitably involve a certain amount of risk. Strong and rapid increases in investment might be seen as particularly risky, especially around infrastructure where early stage risk can be severe and the reliability of long-term revenue streams can be problematic. The necessary investment can be realised only with the right kind and cost of finance, on the right scale, in the right place, at the right time, which can help reduce, share and manage risk. Across the world there is great investment potential and aggregate savings are strong. But there are important difficulties in turning opportunities into real investment programmes; good policies and social institutions are of basic importance.

Further, getting the right kind of finance, in the right place, at the right time is not easy. Mobilising private sector finance, at scale, will be critical. But there will also be a need for development finance and concessional finance to support the activities that do not quickly generate strong revenue streams or have high risks. The international financial institutions, especially the multilateral development banks, and including the IMF, have a crucial role to play. This is a moment—with the crises of COVID and climate, the criticality of raising investment, the centrality of rapid change, and the importance of internationalism—to expand and strengthen our international financial institutions. In doing so, we should expect them to ramp up their support for fostering and developing investment programmes, expand their finance for investment, and expect them to ramp up and reorient their activities towards sustainability. It would be a 'grand bargain' with great potential rewards for the world.[9]

[9] For more on these issues, see Stern (2021) and Bhattacharya (2022).

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5. What We Have Learned Since the Stern Review

In the light of the policy analyses and arguments set out above, it is interesting to ask how issues and understanding have moved on since the publication of *The Economics of Climate Change: The Stern Review* (Stern, 2006) in October 2006. Fifteen years on, the review's core finding—that the costs of inaction on climate change are much greater than the costs of action—which was compelling then, in my view, is now still stronger. First, the *science* is ever more worrying. Greenhouse gas emissions have continued to rise. There is evidence that the impacts of climate change are happening faster and with greater intensity than expected. We can see ever more clearly that there are significant risks of major areas in the world, with currently large populations, becoming unliveable; thus the risks of mass migration and conflict look increasingly severe. Each IPCC report over the last three decades has looked more worrying. The IPCC 2018 report showed how much more dangerous 2°C of warming would be than 1.5°C. And the Sixth Assessment Report of the IPCC on the physical science, published in August 2021, paints a still more difficult picture; time is running out for strong and decisive action if we are to hold temperature increases to 1.5°C.

Second, clean energy *technologies* have been developing at pace, with costs falling further and faster than expected. Any reasonable estimate of the costs of inaction would be still higher and the costs of action lower than in 2006.

Third, the *politics*, have sometimes moved forward strongly (e.g., UNFCCC, COP21, Paris Agreement in 2015) and sometimes backwards (e.g., the election of Presidents Trump and Bolsonaro). The global financial crises of 2008 and 2010 reduced 'bandwidth' for climate change. More recently there have been strong positives politically, for example, China's commitment to carbon neutrality by 2060, the intensification of action in the European Union and in the United States following the election of President Biden. The private sector has started to engage strongly. And COP26 in Glasgow in November 2021 was a significant step forward.

Fourth, *analytically* our understanding and focus have moved to emphasise still more strongly the dynamics of change (Acemoglu *et al.*, 2012; Aghion *et al.*, 2016; Van der Meijden and Smulders, 2017; Systemiq, 2020; Ives *et al.*, 2021). We can now point to new and much more attractive paths or models of development than were followed in the past. We can look to a new story of growth, indeed the drive to net zero can be the sustainable, inclusive and resilient growth story of the twenty-first century. The deeper understanding of the problem, in terms of dynamics of development and of the nature and breadth of potential benefits, implies that we have to deepen our economic analysis. This is the subject of Part II of this paper.

Part II

6. How Economics Must Change

An assessment of what the current situation demands of us, particularly for this decade, in terms of action was set out in Part I. That requires changing our ways of producing and consuming, rapidly and fundamentally, and creating the investment, innovation, sets of policies, and the finance that could foster and support the change. How can we bring our economics to bear in a way that informs those very real and urgent problems? How can we use economic analysis to tell us as much as it possibly can about why to do this, how to do this, and the methods and policy instruments we should use? In this section I will focus, in terms of broad analytical

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approaches, on where we are in the economics discipline on climate change and argue that it is time for change in the economics of climate change and, in some respects, economics generally. In Section 7, I will argue that our subject does have much to offer in applying our existing tools and in developing new perspectives and analyses, but we must be innovative and, as a profession, engage much more strongly on this, the biggest issue of our times.

6.1. *Some History of the Economics of Climate Change*

A natural starting point is the important set of insights of economists Alfred Marshall and Arthur Pigou. At the end of the nineteenth century, Marshall (Marshall, 1890) drew attention to the potential difference between marginal private cost and marginal social cost. Thirty years later, Pigou (Pigou, 1920) argued for a tax, equal to the difference between the marginal private cost and the marginal social cost, to correct for an externality, where that is the source of the difference.[10]

Around 60 or 70 years ago, Ronald Coase began considering these concepts in a different way, emphasising institutional arrangements (Coase, 1960). He spoke of allocating property rights and establishing markets so that there could be trade in externalities. James Meade—his work *Trade and Welfare* (Meade, 1955) was a landmark—also wrote very insightfully about the theory of externalities, including integrating externalities into the theory of reform, bringing in distributional issues and looking at general equilibrium in multi-good models. Coming forward further, and looking at applications 30 or so years ago, David Pearce, for example, was writing *Blueprint for a Green Economy*, emphasising how the Pigouvian idea could be implemented (Pearce *et al.*, 1989).

This is all a very important and valuable part of our intellectual history in economics. Then climate change came along with an explicit and very large problem. The IPCC was established, as a result of initiatives from scientists, in 1988, and climate change started to become a more active subject in discussions of policy. There was growing recognition that climate change could be disruptive, but at that time the common belief was that our emissions of greenhouse gases would cause only small perturbations at some point in the future. The modelling of climate change began with Bill Nordhaus's important and admirable paper 'To Slow or Not to Slow?', published in the *Economic Journal* in 1991 (Nordhaus, 1991) and Bill Cline published his book *The Economics of Global Warming* in 1992 (Cline, 1992). Nordhaus's question, recognising that there could be potential dangers from climate change and that emissions arose from activities around producing and consuming, was 'should we grow a little less fast than we might have envisaged before we thought about climate change?'. He proceeded in a sensible way, taking an emerging problem and applying the standard tools of economics: first the Pigouvian story of marginal social costs, marginal private costs, and taxing for the externality; second on growth, he used the framework of a standard exogenous growth model and considered the impact of climate change largely in terms of small perturbations around the underlying growth path(s). That was a sensible and valuable early contribution for the economics of climate change.

Over the following 10–15 years, it became more and more clear that climate change is not a marginal problem. We are dealing with a challenge involving huge potential disruptions. Further, rising to that challenge requires very radical changes in our production systems and ways of consuming. This challenge cannot sensibly be examined by simply picking up a fairly standard underlying model of exogenous growth and, within that model, portraying climate change in terms

[10] There could be other sources, such as monopoly power, missing markets, asymmetric markets, market failures in other markets, and so on.

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of marginal damages of just a few percent of GDP. Nordhaus's DICE model (dynamic integrated model of climate and the economy) launched a major literature on integrated assessment models (IAMs), which integrate economy and climate with similar approaches to that of DICE. Their scope has been expanded, but the basic underlying features of optimisation of explicit, calibrated social welfare functions, of underlying exogenous growth and of aggregation (usually to one good) impose severe limitation on their ability to illuminate *two basic questions*. The first is how to approach analytically the challenge of managing immense risk, which could involve loss of life on a massive scale. The second is how to chart and guide a response to this challenge which will involve fundamental structural change across a whole complex economy. These two issues are at the core of economic policy on climate. The basic structure of IAMs, I shall argue, even with the many advances and mutations that have been offered, is not of a form which can tackle these two questions in any satisfactory way.

There is a problem in the profession, which goes beyond the way IAMs are structured and specified, associated with an inability or unwillingness to move much beyond the static Pigouvian or twentieth-century approach to externalities in analysing the challenges of climate change. Many discussions of policy suggest that 'economic theory says' that policy should be overwhelmingly about a carbon price. A carbon price should indeed be at centre stage, but we need so much more in terms of policy and perspectives, and understanding of the issues. However, we must be clear that the suggestion that 'theory says' that the carbon price is the most effective route is simply wrong and involves a number of mistakes.

The first mistake is the failure to incorporate a whole collection of market failures and market absences which are of great relevance and are beyond the greenhouse gas externality (see Section 7). The second is that under the temperature target or guard-rail approach (see Subsection 2.1), the choice of carbon prices is focused on its role, in combination with other policies, in incentivising paths which achieve the overall target (such as net zero emissions by mid-century to fit with the temperature target) with as much economic advantage as possible. Such prices are not simply the marginal social cost as in Pigou (see discussion of Stern–Stiglitz Commission below, this section). Third, where the risks of moving too slowly are potentially very large and there are increasing returns to scale, fixed costs and uncertainties in key industries, then standards and regulations can help reduce uncertainty and bring down costs (e.g., Weitzman, 1974). Fourth, many consumers, producers, cities, and countries, recognise the obligation to act, and are not blinkered, narrow optimisers with a view of utility focused only on their own consumption. Fifth, much of the challenge of action is how to promote collaboration and act together. This poses a whole set of important questions around institutions and actions for mutual support. Putting all this together constitutes a major analytical and practical challenge concerning risk, values, dynamics and collaboration, and the narrow Pigouvian model of the one greenhouse gases (GHG) market failure, useful though it is, is very far from the whole story.

6.2. *Some Problems with IAMs*

To explain my argument concerning the failures of IAMs in relation to the *two basic questions* highlighted above, I will set out, in broad terms, some of the basic structure and specifications in standard IAMs. There is an underlying one-good growth model where emissions depend on output, where accumulated emissions cause temperature increase and climate change, and where emissions can be reduced by incurring costs. However, much of this literature, which has dominated so much work on the economics of climate change, has been misleading and biased

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against strong action, because climate damage specifications are implausibly low and costs of action both implausibly high and subject to diminishing returns. For example, a recent version of the DICE model estimates losses of 8.5% of current GDP at a global temperature rise of 6°C (Nordhaus, 2017). If this were plausible, there would be little cause for concern about climate change because 6°C of warming will not be reached, even with bad luck, probably for over 100 years, by which point, with a modest amount of economic growth, losing less than 10 percentage points of GDP would be of minor significance in relation to GDP which had more than doubled (at say an underlying growth rate of 1% per annum). But a 6°C temperature rise would likely be deeply dangerous, indeed existential for hundreds of millions, or billions, of people. It could be a world that could support a far lower population, and we could see deaths on a huge scale, migration of billions of people, and severe conflicts around the world, as large areas, many densely populated currently, became more or less uninhabitable as a result of submersion, desertification, storm surge and extreme weather events, or because the heat was so intense for extended periods that humans could not survive outdoors. It is profoundly implausible that numbers around 10% of GDP offer a sensible description of the kind of disruption and catastrophe that 6°C of warming could cause. We cannot be sure of the probabilities of different scales of catastrophe, but it would seem deeply unwise, indeed reckless, to assume that catastrophe of immense proportions would not be associated with temperature increases of this magnitude.

Most standard IAMs also embody diminishing returns to scale and increasing marginal costs of action to reduce emissions, plus modest rates of technical progress (relative to those experienced in the last decade or so). These features are very problematic because we have already seen how important increasing returns to scale and very rapid change in technology are in this context. Costs of solar power and LEDs have plummeted as the world has scaled up investment and innovation in cleaner technologies (as we saw in Section 2). The same is happening with batteries and electric vehicles, and is likely to happen with hydrogen. By embodying diminishing returns and modest technical progress, the IAMs systematically overstate the costs of climate action. Further, they distort the theory of policy which is much more complex when we have increasing returns to scale; particularly in the context of risk. Standard optimising policy models which focus on 'marginal cost equals marginal benefit' are far more tractable with diminishing returns and increasing marginal costs to action. By choosing model assumptions primarily for tractability and convenience, and which badly distort, or indeed omit, the key issues, we risk severely undermining the ability of the policy analysis to make a relevant contribution to the discussion at issue.

Some of the flaws and biases described above and embodied in the standard IAMs can be mitigated with different assumptions, and there have been some valuable and relevant contributions in the literature. This is not the place for a literature review but some relevant and useful references to elaborations of IAMs are given in the footnote.[11]

[11] Dietz and Stern (2015) show that if the DICE model is modified to take more strongly into account three essential elements of the climate problem—the endogeneity of growth, the convexity of damage and climate risk—optimal policy comprises strong controls. 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 stabilises 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

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However, and this point is crucial, there are deep problems with the general approach of maximising a social welfare function, in particular based on expected utility, in the presence of extreme risk; problems which cannot plausibly be corrected by adjusting functions and parameters within that framework. The stakes we are playing for with respect to climate change are absolutely immense. The challenges of immense risk to life itself for many, point towards the need for alternative strategies for building theories and models. Impacts which can involve deaths of billions are not easily captured in the standard social welfare functions, which are used in most IAMs (and more broadly), involving aggregation of individual utility functions. Indeed, as Weitzman argued (Weitzman, 2009, 2012) standard approaches quickly run into problems of utility functions going to minus infinity. There can be arbitrary 'fixes', for example, by putting bounds on utility. But model outcomes would be extremely sensitive to such bounds, for which the empirical and ethical foundations would be very shaky. These problems constitute an indication that the model has lost touch with the issues at hand.

Just as with the social welfare function aspect of IAMs, there is a set of deep questions on the production side of the modelling. The policy challenge, as we have seen, involves generating rapid and major change in key complex systems, including energy, transport, cities and land, over a very short period. Simple 'cost' functions for emissions reductions, even if made more realistic, do not get to grips with the real policy challenges of how to make these changes. IAMs generally embody simple equilibrium on the production side. The problems of rapid change, dislocation, increasing returns, system change, and rapid innovation that are of the essence here are therefore very hard to capture in standard IAMs. We cannot expect one simplistic equilibrium framework to get to grips with the range of issues at the core of the challenges of transformation. We are likely to need a collection of modelling approaches and analyses. The IAMs could be one of these, but they should not be the central method for all the reasons advanced in this paper.

In Stern and Stiglitz (2022) we further develop these and other criticisms of the IAMs and conclude that the standard IAMs do not provide a framework suitable for the design and evaluation of the broad collection of policies required for the necessary transformation of our economies. In that paper, our criticisms of IAMs are presented under three categories:

A) Those problems that IAMs cannot address, and for which alternative approaches are necessary:
  - (*i*) the assumption of deep uncertainty, where the outcomes which (with associated probabilities) cannot be fully described;
  - (*ii*) the failure to deal with extreme risk (different from deep uncertainty–fat tailed distributions involving catastrophic outcomes), as Weitzman has emphasised (Weitzman, 2009), where expected utilities may not be defined (as highlighted above);
  - (*iii*) endogenous preferences, where welfare functions of the standard kind, based on fixed utility functions, are not defined.

B) Those problems where there has been some—in some cases, considerable—progress (a more extensive discussion of some of this literature is provided in Stern and Stiglitz, 2022), but which require deeper treatment if the results of IAMs are to carry weight in policy discussion:
  - (*i*) intragenerational distribution, vested interests and political economy;

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 (Hassler and Krusell, 2012; Golosov *et al.*, 2014; Rezai and Van der Ploeg, 2016; Iverson and Karp, 2017; Karp, 2017; Gerlagh and Liski, 2018a,b; Hassler *et al.*, 2018; Traeger, 2018) and agent-based IAMs (Lamperti *et al.*, 2018; Czupryna *et al.*, 2020).

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(*ii*) climate damage functions, where impacts can be immense, and there are large irreversibilites (the importance of which is limited in the absence of uncertainty), non-linearities, and complex feedback effects, giving rise to tipping points.

C) Those problems that IAMs could perhaps in principle address, but with extreme difficulty, and which would transform the nature of the modelling—they typically have not been addressed. Many of these problems relate to a flawed description of the underlying economy. And these flaws carry powerful biases in the results. If the underlying descriptive model is flawed,[12] normative analyses based on that model are an unreliable guide for interventions. These flaws include:

(*i*) The assumption, that there are no limitations in government ability to redistribute incomes and, effectively, that the government, in fact, has actually done so, indeed optimally in relation to the social welfare function.

(*ii*) Ignoring multiple and major market failures, beyond the greenhouse gas externality. These failures can give rise to discouragement or distortion of investment and innovation, transition risks, dislocation, and adjustment costs. Their recognition points to the employment of a wider range of instruments (see next section).

(*iii*) Failing to consider the major systemic changes that would be necessary and adopting a narrow focus on marginal analysis.

(*iv*) A narrow, simplistic and conservative approach to technological change. This is an area in which markets are never optimal, and in this context of transformational change the deficiencies in simplistic ‘market solutions’ are amplified by possibilities of increasing returns to scale in both action and discovery, and for which path dependency is crucial.

These failures of the standard approach embodied in IAMs led us to argue, see Subsection 2.1, that the sensible, consequentialist approach to such immense risk and the need for radical change is to put in place targets or guard rails (e.g., temperature increase of 1.5°C) and then examine how best to manage the transitions necessary to keep within them. This was the approach taken within the Paris Agreement in 2015 (UNFCCC, COP21).

How we aggregate disparate preferences and beliefs has been a long-standing question in economics and political science (see Arrow, 1951). But, as noted in Subsection 2.1, the consensus across more than 190 countries embodied in the Paris 2015 UNFCCC agreement did not require full agreement on the utility function to be maximised, the correct damage function, discounting or the probabilities of outcomes. Instead, as it became clear, and broadly accepted, that with temperature rise over 2°C there was a significant probability of extremely bad outcomes, and that those outcomes could be avoided at moderate costs, there emerged consensus that we should act strongly to try to avoid them. The collective understanding that significant reductions in the immense potential risk can be achieved if temperature rise is kept well below 2°C, and in particular below 1.5°C, is based on findings from the physical science of climate change (e.g., IPCC, 2018). It should be noted that it is this understanding that has led the international community to focus on achieving net zero emissions by around 2050, not the recommendations of economists based on IAMs.[13]

[12] Of course all models are simplifications but to quote Dani Rodrik (2015, p.213), ‘Unrealistic assumptions are ok; unrealistic critical assumptions are not ok’.

[13] From a dynamic programming perspective we could suggest that a state of affairs which implies that temperatures above 1.5°C are likely, is associated with a state valuation function which is at or beyond a cliff edge of minus infinity.

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The Stern–Stiglitz Commission looked at the implementation of a target-based approach, in that it examined price profiles of carbon that could lead, over time, using markets and a range of government climate interventions, to achievement of the goals of the Paris Agreement. The 2017 report of the commission suggested CO_2 prices of \$50–100 per tonne for 2030 (Stern and Stiglitz, 2017).[14] These are prices which guide production decisions rather than prices based on marginal damages. In simple, perfectly competitive models which are fully optimised, the prices to guide production would be equal to marginal damages. But we are in a world with many market imperfections, with major risks, basic distributional challenges, requiring fundamental systemic change, and where optimisation is difficult to define, let alone achieve. Thus, such equality cannot plausibly be assumed to be a general feature of appropriate policy. As Stern–Stiglitz emphasise (and see Section 7), the kind of change we require will need a whole range of complementary policies if it is to deliver the necessary change in a satisfactory way.

6.3. *Discounting*

A further challenge for the economics of climate change, that is not just an issue for the IAMs, but which arises as a key question in formulating approaches to major, intertemporal problems, is discounting. The discussion of discounting around climate change has been, in my view, somewhat weak and often not well founded in basic theory. It is important to focus on discounting, which concerns the relative valuation of future costs, benefits and lives, relative to now. Unfortunately, economists (and others) leap too quickly to 'discount rates', which constitute a derived concept within discounting rather than the central notion.

In this context, the important concept to consider in discounting is the social discount factor. To keep things simple let us suppose that we have chosen a unit of account and that we define the social discount factor, λ, as the relative social evaluation of an extra unit of account (e.g., consumption) in the future, relative to an extra unit now. In economics we generally use relative prices, here shadow prices, to guide choices, decisions or trade-offs. The social discount factor corresponds to this idea. The proportional rate of fall of the social discount factor is the social discount rate.

We can illustrate the applications of this basic approach and concept, in a simple aggregative framework without uncertainty, and where social welfare is defined as an integral of discounted utilities over time (essentially one consumer or with 'optimal' unconstrained intragenerational distribution). The social discount factor, λ, can then be described by

$$\lambda = u'(c)e^{-\delta t},$$

and the social discount rate $(-\dot{\lambda}/\lambda)$ by the Ramsey equation,

$$-\dot{\lambda}/\lambda = \eta g + \delta,$$

where social utility, $u(c)$, is a function of consumption, η is the elasticity of social marginal utility with respect to consumption, g is the growth rate of consumption and δ is the pure-time discount rate. The definition of pure-time discounting is the attaching of a lower weight to individuals and

[14] A related approach is taken by Kaufman *et al.* (2020), who estimate the CO_2 prices needed in the near term for consistency with a net zero CO_2 emissions by 2050 target. They arrive at estimates, in their model based on marginal damages, of US\$34–US\$64 per tonne in 2025 and US\$77–US\$124 in 2030. The IMF have proposed \$75 per tonne by 2030 (IMF, 2019). More recent work looks at the possibilities of price differentials across different countries (IMF/OECD, 2021).

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their associated utility simply because they occur in the future; it is the discounting of individuals or utilities because they occur later (and not because of any assumption about consumption levels). Here $e^{-\delta t}$ is the social discount factor and δ is the pure-time discount rate. Pure-time discounting is essentially discrimination by date of birth.

Other than the possibility of extinction (for example, from an asteroid crashing into the earth), which is something that you can, at least in principle, build directly into the analysis, there is no serious ethical argument in favour of pure-time discounting (see Stern, 2015, chs 5 and 6, for an extended discussion of the issues and key references; also the pair of articles in the *Journal of Economics and Philosophy*, Stern, 2014a,b).[15,16]

It is the social discount factor, λ, the relative shadow price, that is the important concept to focus on. The essence of intertemporal valuation is embodied, on the margin, by this relative shadow price. Under most, or many at least, systems of value, how much you judge the value of units of consumption or income in the future, relative to now, depends on how well off you think those in the future will be then. That is *endogenous* because how well off they will be depends on what we do now. This relative shadow price depends on our decisions and is not exogenous to them. This is of particular importance in this context, because if we act recklessly on climate change, future generations could be much poorer than ours.

We should note that the social discount factors (and here also social discount rate) would depend on the good chosen as numeraire, on the individual (where individuals differ), on time and on the state of nature. Thus, using the language of 'the' discount rate can be misleading and the use of the definite article is often associated with confusion in the underlying concept.

Finally, on discounting, we must note that there is little point in looking for ethical values relevant to social discounting in capital markets, because capital markets: (i) do not reflect ethical social decisions; (ii) they embody expectations and views about risk that are hard to identify; and (iii) they involve many imperfections. Nevertheless, one often seems to hear the mistaken argument that social preferences can be derived from these markets.

The above arguments are fairly simple and basic and it is disappointing that many discussions of discounting by economists fail to start with the underlying concept and then make a series of mistakes.[17]

7. New Approaches to the Economics of Climate Change

I have tried to explain the limitations of the IAMs in tackling the big questions at issue: the understanding and management of extreme risk and of rapid structural change. What would sound and constructive approaches to the economics of climate change look like? Can economics rise to the nature, magnitude and urgency of the challenge? We are going to need an array of different models, a variety of perspectives, and a collection of different ways of understanding different parts of the problem. And then wisdom and good judgement in putting all these pieces together.

Economic analyses of policy and action towards climate change must first capture *extreme risk*, including possible large-scale and unforeseeable consequences. Second, they should recognise

[15] For a rather mathematical account of some relevant issues, see Chichilnisky *et al.* (2020).

[16] Note that this work draws on perspectives from moral and political philosophy and emphasises the importance of considering these perspectives in assessing policy and action on climate change.

[17] For example, Nordhaus (2007) has sometimes seemed to think that empirical answers to questions of ethical discounting lie in the capital markets.

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Table 1. *Six Market Imperfections Relevant for Tackling Climate Change.*

Market failure	Description	Policy options
Greenhouse gases (GHGs)	Negative externality because of the damage that emissions inflict on others.	Carbon tax/cap-and-trade/regulation of GHG emissions (standards).
Research, development and deployment (R,D & D)	Supporting innovation and dissemination.	Tax breaks, support for demonstration/deployment, publicly funded research.
Imperfection in risk/capital markets	Imperfect information assessment of risks; understanding of new projects/technologies.	Risk sharing/reduction through guarantees, long-term contracts; convening power for co-financing; phaseout dates for dirty technologies.
Networks	Coordination of multiple supporting networks and systems.	Investment in infrastructure to support integration of new technologies in electricity grids, public transport, broadband, recycling. Planning of cities.
Information	Lack of awareness of technologies, actions or support.	Labelling and information requirements on cars, domestic appliances, products more generally; awareness of options; product standards.
Co-benefits	Consideration of benefits beyond market rewards.	Valuing ecosystems and biodiversity, recognising impacts on health; agricultural subsidy reform.

Note: The policy options in the third column are not exhaustive. I have set out these six market imperfections in a number of contexts, see e.g., Stern (2015, pp. 97–9).

that many key markets have *critically important failures* (beyond that of the GHG externality), that crucial markets may be absent, and that there are limits on the ability of government to 'correct' these market failures or absences. Third, they should embody *rapid technical and systemic change*, often in very large and complex systems such as cities, energy, transport, and land use, and allow for *increasing returns to scale*. Fourth, they should examine rapid changes in (endogenously determined) *beliefs and preferences*; and fifth, take into account *distributive impacts* and risks, both at a moment in time and over time, and including those associated with structural change. All of this will unavoidably involve explicit analysis and discussion of *value judgements*. These components, or sets of questions, are difficult to incorporate in standard integrated assessment modelling, but are at the core of the issues around understanding policy towards climate change. We must deepen our economic analysis to incorporate them. We should also recognise that questions embodied in, or similar to, these components arise in many other parts of economics, where major risks and fundamental change are at the core of the challenge under examination. Thus, the issues we are raising here on understanding policy towards major challenges concern economics as a whole, and not just the economics of climate change.

It is not possible in the space here to develop arguments around all the areas just described. By way of example, and an important one, I will delve a little deeper into market imperfections. Table 1 outlines six important failures that policy design must take into account. These different market failures point to the use of different instruments, but the collection should be mutually reinforcing. These failures interact.

Across these market failures and associated policies, theories of instrument design and implementation are likely to be helpful, for example, in the design of carbon markets, standards and regulations, layouts of cities, policies to encourage the change of gas boilers, prizes for breakthrough discoveries, and so on.

There are also important *absent* markets. We cannot trade fully, over long horizons, on future carbon. We cannot easily trade over possible new technologies because we do not know, or

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have rather limited knowledge of, what breakthrough technologies lie in the future. As a matter of basic theory, a competitive equilibrium with some absent markets cannot be assumed to be Pareto efficient. Such absences mean that expectations, and how they are formed, are crucial for investment. They can and should be shaped by public strategy and action, including by the key public policy and financial institutions which set direction.

At the same time, there are difficult issues around knowledge of, or confidence in, future policies, in terms of their possible effects in relation to market participants. That issue is of real relevance to the shaping of expectations. The more that governments can build in predictability about how policy will change as learning occurs, the greater will be the confidence underpinning investment, innovation and future commitments. That is why I have emphasised (Subsection 4.2) 'predictable flexibility'. Part of confidence is based on track records which, unfortunately in the context of climate change, have seen chopping and changing (Stroebel and Wurgler, 2021).

Further, given that governments are made up of complex compromises and coalitions, are limited in information and capabilities and are not necessarily long lasting, we must recognise in our analysis that there are limits on their ability or willingness to 'correct' for market failures and absent markets. Governments cannot fully commit to future actions in a credible way. They may have short time horizons, they may have narrow objectives, and they face major administrative and political constraints. In thinking about public policy, we have to put all these considerations together and take into account how policies are constrained, might shift and can go wrong. And we can ask how to build strong institutions, which can survive across different parties in power and pressures of vested interests, to help reduce uncertainty about future directions and policies.

These considerations underlie the rationale for the climate change legislation and the carbon budgets in the United Kingdom. The Climate Change Act and the Climate Change Committee, with its carbon budgets,[18] are good examples of where the law and institutions can play a valuable role. Indeed, the law is beginning to play a strong role in other countries too. In April 2021, Germany's Constitutional Court upheld a claim challenging the constitutionality of certain provisions of the German Climate Protection Act, in the sense that the measures in the Act were too weak. The court ruled that Germany's legal requirement to meet the overall goals of the Paris Agreement, together with insufficiently strict 2030 emissions reduction targets, imply a rate of emissions reductions after 2030 that places an unreasonable burden on future generations (Setzer and Higham, 2021). This decision prompted the German Cabinet to approve a bill that raises the ambition of the emissions reduction targets enshrined in the Climate Protection Act (Boldis and Lütkehaus, 2021). And in the Netherlands, the District Court of The Hague ruled in May 2021 that Royal Dutch Shell must cut its global carbon emissions by 45% compared to 2019 levels by 2030, due to an 'unwritten standard of care' that Shell owes to Dutch residents under the Dutch civil code (Grimmitt, 2021).

The GHG failure is top of our list of market failures. And carbon pricing has a critical role to play in tackling that market failure. However, we can see, from thinking about different aspects of market and government failures, that the policy question is much richer and more complex in substance than can be handled by carbon pricing alone. If we consider the very real circumstances of increasing returns to scale on mitigation action, strong risk, and worries about what government might do, we could argue that regulatory policies, such as the phase out of internal combustion engine (ICE) vehicles, have a strong role to play. The British government has set a date of 2030

[18] The Climate Change Act became law in the United Kingdom in November 2008. It sets out emission reduction targets to which the governments must comply. The Act also provides a system of carbon budgeting; a series of five-year carbon budgets that set a pathway for the United Kingdom to meet its targets.

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(and the EU 2035), beyond which ICE vehicles can no longer be sold. That provides a very clear and strong signal, which gives car firms the confidence to pursue the major fixed costs around the development of alternative technologies and moving to scale. The banning of incandescent light bulbs is a powerful example of how new and much better technologies can be developed and driven to low cost by regulation, and how the move to scale of new technologies can be fostered by the clarity regulation can bring. This regulation did not specify technologies to replace the incandescent bulbs, but required their phase out because they were so wasteful. Before long the far superior LED system came through and costs were driven down. Thus, in the case of incandescent lightbulbs and ICE vehicles, the policy does not pick winners; it is about regulating out the harmful. These policies should also be subject to periodic evaluation, but that evaluation would need to be broader than standard marginal cost–benefit analysis.

In these circumstances of increasing returns and risk, alongside other market failures, such regulatory policies, alongside carbon pricing, could be more efficient and effective than carbon pricing alone. It is surprising therefore that some economists assert that economics says that the most efficient policy instrument is carbon pricing, and that we pursue others simply because this may be politically difficult. That is a theoretical mistake of real practical significance.

Much of structural change will be around the functioning of major systems, including: energy, cities, transport, land. Clean power is at the centre of the transition to net zero emissions. A number of estimates suggest that the global electricity supply will need to quadruple over the next three decades, given the likely dependence of much of transport and heating/cooling on electricity (ETC, 2021; IEA, 2021b), if we are to achieve net zero emissions by mid-century. And that electricity will all need to be zero carbon by 2040.

By 2050, around two-thirds of the world population is projected to live in cities, up from 55% in 2018 (United Nations, 2019). The choices made in cities on transport, infrastructure, buildings, and energy use, as they grow rapidly over the coming decades, will, in large measure, determine whether the world can both manage climate change and realise the benefits of low-carbon growth.

A recent estimate has suggested that transformation to reduce the current ‘hidden costs’ of food and land use systems across the world could generate economic gains to society of $5.7 trillion annually by 2030 and $10.5 trillion annually by 2050 (FOLU, 2019). These systems are currently dysfunctional along key dimensions, so we have much to gain from managing them better as we work to cut emissions. Indeed, in all too many cases, the structure of incentives embodied in agricultural policies and subsidies lead to land degradation, the poisoning of rivers and oceans, and the destruction of forests. Further, often the financial or other returns to such policies are captured by richer enterprises and individuals.

Progress in *digital and artificial intelligence (AI) technologies* continues to move very rapidly, and these technologies will be enormously helpful in improving the management of systems. In this way, we are fortunate that these new technologies are moving so fast at exactly the moment we have to make major systemic changes.

7.1. *Research Agenda*

The need for new approaches to the economic analysis of climate change raises an enormously rich research agenda. At the same time, action on scale is urgent. The transformation must be accelerated; we have to act strongly now. Thus we must think hard in real time about what we do now and its basis in current evidence, theory and judgement, whilst we simultaneously pursue vigorously the most critical lines of research. That statement is true in general for those who

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have to make or advise on policy, but it applies particularly sharply here where both urgency and rapid change are of the essence.

I have emphasised throughout this paper that managing climate change requires fundamental transformation of our economies: and it requires conceptual and evidential frameworks that can guide the policies and actions that can shape such transformations. A collection of conceptual, theoretical, empirical and modelling approaches, and not just a single grand model, will be needed; there are several important questions to answer. These include the following: What instruments should we utilise? If we use prices as guidance, what could be, and how do we understand, the social cost of carbon, and what prices might guide the production side to net zero emissions by mid-century? What are the key large structural and systemic changes that will be required as part of the green transition? How should we foster innovation and R&D? A model, or analytical approach, designed to help answer one of these questions may be less helpful in answering others. It will be necessary to assemble microeconomic, structural, technological, and macroeconomic analyses of change for countries and communities across the world. Suitably improved IAMs may play a role on the more aggregative end of the spectrum in this collection of analyses and models. My arguments here are not that they have no role to play but that we should be clear that it should not be the dominant role, because of their inherent limitations on the key challenges of risk and change.

These analyses will have to take account of the varying circumstances, difficulties and opportunities they face. And, as ever in economics, we need nuanced and measured judgements in blending the different analyses, each with its focus, into policy decisions in real time. For a more detailed discussion of promising modelling approaches that can contribute to such analyses see Section 7 in Stern and Stiglitz (2022). Below I highlight some key areas for future research, which can provide important insights relevant to these analyses.

Changes in the *behaviours* and values of consumers, workers, shareholders, managers and voters are key to driving change in business and policy decisions, while business and policy decisions can also have a powerful influence on consumer behaviours. Understanding the *political economy*, and associated instabilities, constraints and opportunities, shaping the transition to net zero emissions will be important both for creating effective policy frameworks to decarbonise at pace and to accelerate the deployment of clean technologies across the economy. There has been a huge amount of progress in the literature in economics on behaviour, institutions and political economy over the last 20–30 years. This includes fruitful collaboration with other social sciences, for example, research at the intersection of economics and political science relating to polycentric governance of public goods (e.g., Ostrom *et al.*, 1999). Interesting work on changing values in the context of climate is emerging (see e.g., Besley and Persson, 2019).[19] Important areas for continued research include: behaviour change in the face of adjustment costs and missing information; and incentives and nudges.

We must analyse how to support a *just transition* which recognises the problems of dislocation. Some jobs will disappear; others will change radically. Some locations may be particularly affected. There will be many new opportunities. Managing change so that all have a chance of benefitting will be not only an issue of justice, but also of political feasibility. Much of this will involve investment in people and places. And in some cases, direct income support.

The necessary transformation of the economy relies critically on changing key systems: energy, cities, transport, land use. These large and complex systems cannot be changed by fiddling with

[19] See also the important work of David Halpern and the Behavioural Insights Team (e.g., The Behavioural Insights Team, 2020).

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just one parameter; a whole set of policies will be required to foster change. For example, you would not sensibly attempt to redesign a city to reduce congestion and pollution via only a carbon price, even though a carbon price would be of great relevance. Understanding how to foster change at the system level will be vital. Part of that will be around sequencing. For example, much of transport and heating will depend on electricity so that, if they are to be decarbonised, then electricity will have to be expanded quickly and itself be decarbonised.

The interactions of systems (including energy, transport, cities) and of systemic regulation (grids, buildings and land use, transport) will be crucial issues. So, too, the systemic management of change. This is a 'whole economy' transition and the economy-wide story requires strong central coordination from those ministries—prime ministers and finance ministries especially—which cover the whole economy. Implementation which relies only on line ministries would likely run into major difficulties.

We are going to need to understand *innovation* in a much deeper and stronger way, because it is at the heart of the transition to net zero. The necessary innovation will go far beyond one particular technology, in one particular industry; it will be innovation across the whole range of ways of doing things. Thus, more work is needed to understand the complementarities between different features of the innovation system, as well as between different types of innovation (Stern and Valero, 2020). It would be good to look still more deeply into how new technologies enter a market and how they can accelerate towards and beyond market tipping points, to eventually become the dominant technology. And in the spirit of Schumpeter, we can expect these technologies, in time, to be themselves disrupted.

These processes, always of central interest to growth and development, are vital to the fundamental transformation required in the next two or three decades. Thirty or so years ago the economics profession would, on the whole, have emphasised an approach which left the directions of investment and innovation largely to the market. The market will still be at the heart of action and the big majority of innovation and investment will be private. But we now have a story which is different in two key respects: *a clear environment and climate purpose; great urgency*.

Efficiency is something we will have to scrutinise much more carefully than we have done in the past. The simplistic perspective that 'all that exists is efficient because if it is not efficient it would not exist' is less than convincing at the best of times, but is thoroughly unconvincing in this case. There are all kinds of inefficiencies that exist in our economies and we must try to understand their nature and origins and how to overcome them. Energy efficiency is, of course, central, but the challenges of better resource use go way beyond that. Ideas around the circular economy, and resource efficiency more generally, will be of fundamental importance.

The functioning and role of *financial institutions and 'de-risking'*, particularly in terms of the nature and scale of investments and activities they finance, will play a core role in climate action. There are important issues around financial regulation and the role of central banks (Dikau *et al.*, 2021; Robins *et al.*, 2021).

And, finally, *biodiversity*. The Dasgupta review on the economics of biodiversity, published in 2021, is an important piece of work, which provides a valuable framework for looking at the issue of biodiversity loss. Though the climate and biodiversity crises are not the same thing, there are key dimensions of the two which do overlap and interweave, and we are going to have to tackle climate change and biodiversity loss together. A changing climate threatens biodiversity and loss of biodiversity, including through release of carbon, exacerbates climate change. Many forces, particularly the use of fossil fuels, undermine them both. Of course, biodiversity loss comes also from over-exploitation of our natural world, beyond climate change.

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The integration of '*nature-based solutions*' into climate policy provides real opportunities both for carbon removal and for promoting biodiversity. We should seek 'nature-based solutions' that can promote diverse, intact natural ecosystems for preserving forest carbon sinks in the face of climate change (Sakschewski *et al.*, 2016) and supporting human adaptation to climate change (Lavorel *et al.*, 2015). At the same time, we should avoid monocultures (Hulvey *et al.*, 2013; Seddon *et al.*, 2019) which may be problematic both for biodiversity and long-term carbon storage. There is great potential in restoring degraded land which can be good for all of mitigation, adaptation and development. There is important research needed here on how to examine the mix of policies and the role of institutions that would help us to tackle these interrelated challenges and realise the great potential in enhancing our natural capital. We have been damaging and destroying it over the last decades with severe consequences, both for climate and biodiversity and for our environment and ecosystems more generally.

8. Responsibility, Opportunity, Collaboration and Leadership

The strategic challenge is to move to a net zero carbon economy within a few decades. The economics of action must be focused on the achievement of fundamental economic change at real pace, where time matters (Stern, 2018). That will involve, as I have stressed, looking at, inter alia, innovation, behaviour change, political economy, and the dynamics of all those elements. And we will need all of our economics to take on these problems: international, industrial, labour, health, education, environment, energy, economic history and more. We should not be narrowly focused on a sub-discipline within economics if we are going to take on big problems of this kind; we should be economists. And we must work with other social scientists, scientists and engineers. For example, designing the policies and institutions that can tackle the interrelated challenges of biodiversity loss and climate change will require economists to work together with ecologists, while understanding the nature and magnitude of the investments required to create a zero-carbon power system and developing strategies to finance these investments will require economists to work together with engineers. Though we may have our specialities, we have to recognise that most elements of economics come into the challenge of climate change. There has never been anything more important, there has never been anything more fascinating, and we have so much to offer from our existing set of ideas and tools if we put them to use. And we must develop new analyses and perspectives. The key issues are *risks and change*. That is why I think it is time for change in economics.

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