1 Understanding Deep Decarbonisation over the Long Run

1.1 INTRODUCTION

Economists use theoretical models to understand which mechanisms drive an economy. Models, be they economic or otherwise, are simplified representations of the world. The art of modelling consists in deciding which aspects of the world can be ignored in order to focus on the main mechanisms of interest. With the exception of a specific subfield, most economic models have assumed that the interaction between the economy and the broader natural environment is of secondary importance. One notable exception stands out. A specific field of large computational models, so-called Integrated Assessment Models (IAMs), emerged in the 1990s to challenge the view that the greenhouse gas (GHG) emissions resulting from economic activity do not matter (Nordhaus, 1992). The researchers in this field set out to quantify the trade-off between economic activity and environmental degradation, in particular global warming resulting from GHG emissions.

This chapter presents the main structure of IAMs and discusses the lessons that have emerged from this literature. These models have been used to address two broad types of questions. The first consists in describing an optimal path of GHG emissions over multiple decades. The second seeks to quantify the impact of achieving a given path of emissions on economic activity. This second exercise has given rise to some clear recommendations concerning which policy options deliver on emissions targets at the lowest possible cost to the economy.

Finally, we present the main theoretical limitations of this field of research. They highlight important economic trade-offs and call for additional analytical tools found in other branches of economics. First, we argue that the nature of the climate change crisis has considerably shrunk the timescale left to address the problem of GHG emissions. Hence, in addition to considerations around a smooth long-term transition to a carbon-free economy, a number of short-run transitory effects are likely to become more relevant. Second, we argue that IAMs make unsatisfactory assumptions about the nature of technological progress and about the ability of economies to allocate resources. Finally, these models completely abstract away issues of policy credibility and fairness considerations, which are nevertheless key components of the success of a decarbonisation strategy.

1.2 HOW ECONOMISTS HAVE THOUGHT ABOUT DECARBONISATION

Starting with the seminal Dynamic Integrated Climate Economy model of William Nordhaus (1992), a prolific field of economics has emerged to link economic activity to the resulting GHG emissions and the feedback of climate conditions on the economy. This class of models adds three elements to a standard model of the economy.

1. **An emissions module** describes how economic activity generates GHG emissions, often offering a very detailed breakdown of which sectors are responsible for emissions. For example, they can separate fossil fuel-based electricity production from renewables, or carbon-intensive manufacturing, such as steel, cement and paper, from the rest of the manufacturing sector. They make use of databases that measure the flows of goods and services between sectors of the economy, so-called Input–Output Tables. These models can also easily integrate trade considerations. They are particularly useful to identify the extent of sectoral reallocation implied by decarbonisation and its distributional consequences.
2. **A climate module** draws on climate science to map how the level of emissions translates into environmental damage, especially global temperature increases.

3. **A damage module** describes the feedback mechanism whereby climate change will impose costs on economic activity through, for example, the destruction of economic assets from extreme weather events or the loss of productivity from heatwaves. This damage module builds on a diverse literature quantifying the costs of climate and weather events on economic activity (see Box 1.1 for a detailed overview).

BOX 1.1 The impact of climate change on economic activity

Developments in empirical studies documenting the effect of climate change on the economy are well summarised in Carleton and Hsiang (2016) and Dell et al. (2014). Some studies focus on the whole economy, while others focus on specific dimensions of the economic system. In either case, temperature is by far the most used metric to represent climate change across studies. Other less used metrics include precipitation, used in the literature analysing the impacts on agriculture, and extreme weather events, used in the studies focusing on the impact on the financial sector.

Regarding economic output, consensus seems to emerge regarding the negative effect of temperature on output and the uneven impact of climate change on different regions across the globe. For example, Dell et al. (2012) find that temperature rises have a negative effect on economic growth for poor countries – namely a 1°C rise in temperature in a given year reduces economic growth by 1.3 percentage points on average – while the results for rich countries are not statistically significant. Using a larger sample, Acevedo Mejia et al. (2018) estimate that for the median low-income country a 1°C increase from a temperature of 25°C lowers growth in the same year by 1.2 percentage points.

Burke et al. (2015) argue that higher temperatures affect both poor and rich countries, especially because the evidence does not seem to suggest any significant differences in adaptation between the two groups of countries. Nonetheless, given that poorer countries are predominantly located in regions with warmer climate, they are still the ones most affected by increases in temperature. Kahn et al. (2021) support the view that both poor and rich countries are affected by increases in temperature and argue that by 2100 gross domestic product (GDP) per capita of all countries will suffer in the absence of climate change mitigation policies. This is mainly because both persistent increases in temperatures and the degree of climate variability affect economic growth. Kahn et al. provide estimates for the global economy by 2100 under three different scenarios: (i) the absence of mitigation policies and an average increase in global temperature; (ii) the absence of mitigation policies combined with country-specific variability of climate conditions; and (iii) compliance with the 2015 Paris Agreement objective. For the three scenarios, the reduction in world GDP per capita would be 7 per cent, 13 per cent and 1 per cent, respectively, highlighting the crucial role of climate action in reducing the negative long-run economic effects.

Labour productivity is frequently analysed alongside other key economic variables. Evidence of reduced productivity as a result of temperature increases also highlights the importance of climate adaptation. Kjellstrom et al. (2009) quantify the impact of climate warming on labour productivity, for several regions, assuming a trend towards less labour-intense work but no adaptation to climate change under two scenarios: (a) a moderately high emissions scenario and (b) a scenario that assumes reduced GHG emissions. By the 2080s, the increase in the percentage of workdays lost could be as high as 27 per cent for Central America under scenario (a) and 16 per cent under scenario (b). There would be regions, however, experiencing productivity increases under scenario (b), for example, Oceania and Central and South Sub-Saharan Africa. Under the mitigation scenario (b), Europe would barely experience any changes in productivity (in a range between –0.1 per cent and 0 per cent), while North America could experience productivity losses of up to 5 per cent.

The size of this last figure can somewhat explain the findings of Deryugina and Hsiang (2014). When considering several forms of adaptation, they estimate a negative impact of temperature on productivity for the United States. These findings emphasise that, although the country is an advanced economy, adaptation there is still sub-optimal and insufficient to cancel out the negative effects of high temperatures. In China, high-temperature subsidies are granted to employees who work under extreme heat conditions, which means that an increase in the frequency of high-heat events will lead to a rise in labour costs (Zhao et al., 2016).

Furthermore, there are research efforts dedicated to understanding the mechanisms through which climate change impacts different economic sectors, human health and natural systems (Auffhammer, 2018). Agriculture, forestry and fishery are highly dependent on climatic conditions and hence are among the sectors most affected by climate change. Thiault et al. (2019) analyse the effect of climate change on the agriculture and fishery sectors for countries around the globe in a comprehensive manner. They consider a country's dependency on each sector for food, economic output and employment and also the respective adaptive capacity. The results are striking: by 2100, under a high emissions scenario, around 90 per cent of the world population would be in countries estimated to have productivity losses in agriculture and fisheries. When considering a strong mitigation scenario, this figure could be reduced to 60 per cent of the population.[1]

Climate change is also changing energy consumption patterns (Auffhammer & Mansur, 2014) and could have negative impacts on the supply side (Ciscar & Dowling, 2014). For example, lower water availability due to reduced rainfall could force power plants to reduce production capacity given the essential role of water for power plant cooling. Financial institutions are also greatly affected by climate change and its consequences (Financial Stability Board, 2020). For instance, natural disasters can have a significant impact on the value of certain assets, such as real estate (Ouazad & Kahn, 2019). The transition to a low-carbon economy can lead to necessary, sometimes sudden, value adjustments of assets and liabilities, potentially creating stranded assets (Shimbar, 2021). Accounting for climate risk has become crucial to ensure the resilience and stability

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[1] Thiault et al. (2019) compare different Representative Concentration Pathway (RCP) scenarios, which are reference scenarios adopted by the Intergovernmental Panel on Climate Change. The RCPs – originally RCP 2.6, RCP 4.5, RCP 6 and RCP 8.5 – are labelled after a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6 and 8.5 W/m^2, respectively). Thiault et al. (2019) use RCP 8.5 as their high emissions scenario and RCP 2.6 as the strong mitigation scenario.

of the financial system (Brunetti et al., 2021; European Central Bank, 2021). The impacts of climate change are not limited to economic activity; there is also evidence of its negative impact on population health and mortality (Carleton et al., 2020; Romanello et al., 2021). The increased intensity of heat waves and the heightened risk of infectious disease transmission are just two examples of climate change consequences that can have serious health implications.

1.3 EMPIRICAL LESSONS FROM IAMS

Integrated Assessment Models are designed to simulate the steady state of an economy according to given emissions targets and to map its evolution to this steady state over the long run, for example up to 100 years ahead. This framework has been used to answer two types of questions. The first approach is to use this modelling infrastructure to determine what is the socially optimal quantity of emissions, given different characteristics of the model, such as the value of economic activity and people's impatience. The main concept that is associated with this approach is the social cost of carbon (SCC).

The second approach is the reverse: these simulations can tell us how specific paths of emissions lead to changes in economic activity. This is the approach used by policy institutions to estimate how many points of GDP will be lost or gained from achieving specific emissions targets. The relevant concept in this second approach is the 'shadow price of carbon', which tells us by how much could output increase if an additional tonne was added to the carbon budget.

This shift in the debate happened following the Paris Agreement in 2015 (Weder di Mauro, 2021). The expert debate moved away from a Pigouvian internalisation approach to carbon pricing, namely one that estimates the present value of the flow of marginal damages of one tonne of CO_2. Instead, the focus has increasingly shifted to a maximum quantity approach, which consists in estimating the optimal dynamic path for the shadow carbon price compatible with the carbon budget that would limit warming to 1.5 or 2°C (Gollier, 2021).

1.3.1 Social cost of carbon

Most of the academically oriented research using IAMs has focused on estimating the SCC. This is the net marginal economic loss coming from an additional tonne of atmospheric carbon. In other words, it measures the trade-off between an extra unit of GDP and the additional climate damage associated with emitting an additional tonne of carbon. This number is used to assess the urgency needed to reduce emissions: a higher SCC implies larger damages from emissions and hence suggests that faster mitigation action is economically desirable. It also corresponds to the optimal value of a carbon tax, which is the preferred policy tool to address GHG emissions.

There is little consensus over the actual value of the SCC, and there are rising concerns about its usefulness as a concept, precisely because of its sensitivity to particular assumptions and to modelling shortcomings. Golosov et al. (2014) find that the SCC depends on only three quantities: the discount rate, the damage function and the rate at which carbon depreciates in the atmosphere. Researchers such as Pindyck (2013) and Heal (2017) argue that this simplification weakens the framework, because the assumptions that economists make on the first two dimensions are particularly arbitrary.

Choosing the right discount rate has sparked a vivid debate. On the one hand, researchers such as Nordhaus argue for using a discount rate close to the market interest rate, around 1.5 per cent (Nordhaus & Boyer, 2003). On the other hand, researchers such as Nicholas Stern (2007) argue for using a much more conservative interest rate, as low as 0.1 per cent. Golosov et al. (2014) estimate the SCC using these two discount rates to illustrate this sensitivity. In their baseline model, the SCC is equal to $57/ton of coal when using a discount rate of 1.5 per cent and $500/ton of coal when using the more conservative discount rate of 0.1 per cent. They also provide estimates calculated over a range of possible damages. For a discount rate of 1.5 per cent, the SCC ranges from $25/ton for moderate damages to $489/ton in the case of catastrophic damages. For a discount rate of 0.1 per cent, these estimates

Table 1.1 *Estimates of the SCC from Golosov et al. (2014), in $/ton of coal*

Discount rate	Low damages	Baseline	Catastrophic damages
1.5%	25	57	489
0.1%	221	500	4,263

range from $221/ton to $4,263/ton. The range of estimates is summarised in Table 1.1. The work of Gerlagh and Liski (2018a) shows that the value of the SCC is also sensitive to the shape of the discount rate and to the ability of decision-makers to commit to a given path of emissions. Comparing various approaches, Gerlagh and Liski estimate values of the SCC that differ from each other by an order of 20.[1]

The strongest criticism addressed to the IAM framework concerns its inability to take into account the possibility of catastrophic climate events (Wagner & Weitzman, 2016). This is not a specificity of climate models. In fact, all economic models are notoriously ill-suited to include non-linearities and threshold effects, therefore ruling out the possibility of extreme scenarios. However, in the field of climate economics this is a major shortcoming, given that not only the damages but also the response of the economy are very likely to have these characteristics.

Cai and Lontzek (2019) address this concern by allowing for both threshold effects in the damage function, that is, climate tipping points, and uncertainty around the response of the economy to productivity shocks. They circumvent the theoretical limitations by exploiting the opportunity offered by massive computational power and estimate these effects numerically. They argue that including both economic and climate risks in an IAM leads to higher estimates of the SCC than are common in the literature. Gerlagh and Liski (2018b) additionally test how sensitive the estimate of the SCC is to society's ability to learn

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[1] Gerlagh and Liski (2018a) assume hyperbolic, as opposed to exponential, discounting. This assumption introduces a discontinuity between the discount rate used for the near future and that used for the distant future.

about future damages. They find that if past events are poor predictors of future damages then the optimal SCC should rise faster than GDP.

The SCC remains a controversial concept and has been superseded in the policy debate, at least in European policy circles. Climate policy is increasingly being seen as an insurance mechanism against catastrophic damage (Wagner & Weitzman, 2016). Along with companies, cities and financial institutions, more than 130 countries have now set or are considering a target of reducing emissions to net zero by mid-century (United Nations, 2022). In the rest of this book, we take these commitments as given and credible and focus on understanding how reaching these commitments will affect economic structures.

1.3.2 Long-Term Impacts of Decarbonisation

Policy institutions such as the European Commission, the International Monetary Fund (IMF) and the European Bank of Reconstruction and Development (EBRD) also make use of IAMs to answer a different question. These institutions seek to evaluate the economic impact of reaching specific emissions targets or adopting specific climate policy packages. In this section, we discuss how IAMs are used to quantify the net effect on the economy of reaching net zero emissions within the next three decades. In practical terms, this involves simulating the evolution of the economy in a reference scenario and in an emissions reduction scenario and comparing the level of GDP and associated employment between these two scenarios in 2050.

Comparing the different estimates produced by the literature is difficult, because different exercises use different assumptions, focus on different geographic areas and assume different reference scenarios. Most point estimates are often reported with margins of error that increase with the time horizon of the exercise, to warn the reader of the amount of uncertainty.

The choice of reference scenario is particularly important. It can range from a business-as-usual scenario – which would imply global warming beyond 3°C – to relatively ambitious targets, such as the Nationally Determined Contributions (NDCs) submitted under the Paris Agreement – which would imply global warming of around 2°C (Climate Action Tracker, 2021). Studies that use an ambitious reference scenario, such as the NDCs, lead to smaller estimates of the costs associated with an additional tightening of emissions targets.

It is also worth noting that many reference scenarios do not fully account for the benefits of avoiding climate change, as these are difficult to estimate. This is a reasonable assumption given the time lag involved between emissions and realised climate damage. The climate consequences felt within the next decades will depend on the accumulation of past emissions more than on current emissions. Although unrealistic, this omission does not alter the nature of the conclusions: including these averted damages in the analysis only strengthens the case for climate action, by lowering the total burden of mitigation especially over long time horizons.

Köberle et al. (2021) argue that reports estimating mitigation costs tend to misrepresent their results, to the detriment of the policy dialogue. A key assumption of the reference scenario that is rarely emphasised is that there is a constant rate of technological progress that drives GDP growth in the background. Hence, reporting a 1 percentage point drop in GDP compared to a growing baseline means that the economy in 2050 will nevertheless be larger than it is today, although not quite as large as it would be without climate policies. It is often mistaken to mean that the economy in 2050 will be 1 percentage point smaller than it is today. The correct interpretation puts the mitigation costs in the appropriate perspective and suggests that mitigation costs can be manageable.

Finally, Köberle et al. (2021) make a methodological proposal to use the IAM framework in a more policy-relevant manner. They suggest using this modelling infrastructure to compare various policy scenarios that achieve the same path of emissions or of temperature.[2] This would reduce the sensitivity of the results to the choice of reference scenario and circumvent the need to estimate averted climate damages.

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[2] The former exercise allows for temperature overshooting, while the latter is the stricter target.

Despite the difficulty in comparing these different results, a consensus seems to emerge. Decarbonisation appears achievable and affordable given the present state of technology, projections for technological improvement and realistic strengthening of existing policy instruments. This conclusion crucially depends on assuming that full decarbonisation is indeed technically possible given existing technologies and some form of exogeneous technological progress that improves energy efficiency. In particular, the models allow for a wide array of substitution options,[3] which ensures a lot of flexibility in the economy and means that estimated costs will be on the lower end of those proposed by the literature.

For example, estimates for the European Union suggest that achieving net zero emissions by 2050 will come at moderate costs in terms of GDP. Vrontisi et al. (2020) compare the effect on the EU-28 of achieving the NDCs submitted to the Paris Agreement (namely reducing emissions by 40 per cent by 2030 compared with 1990 levels) with a pre-Paris Agreement scenario. They find that GDP will be 0.2 percentage points lower than the baseline scenario in 2030 and between –0.6 and +0.4 percentage points different by 2050. This difference between a positive and a negative effect depends on whether there is international coordination on emissions reductions. Additionally, when, in 2020, the European Commission proposed to tighten the European Union's emissions reduction target for 2030 from at least 40 per cent to at least 55 per cent, it published a thorough impact assessment based on the conclusions of three IAMs. The results suggest that there would be an additional loss of 0.3 percentage points of GDP compared to the targets set in the Paris Agreement (European Commission, 2020; Varga et al., 2021).

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[3] For example, in the more fine-grained models, firms can substitute between fossil fuel and carbon-free energy, and they can substitute energy for other factors of production, such as labour and capital. Another dimension that allows for flexibility is the sectoral breakdown available in the model. In general, the more margins of response are present in the model, the quicker the transition and the lower the estimated impact on the economy.

At the global level, an IMF report paints a similar picture (IMF, 2020). Using a combination of a green investment push, carbon pricing and redistributive transfers delivers a net positive effect on global growth in the initial years. But in the medium run, after fifteen years, GDP is lower by up to 1 per cent compared to the reference scenario and does not fully recover to the baseline level by 2050. The report argues that this is in line with other estimates, which range between 1 and 6 percentage points of GDP lost by 2050. In a sensitivity analysis that allows for faster technological progress, world GDP goes back to baseline by 2050, suggesting no loss of output in the long run.

These recent results stand in contrast to those reported in the 2010s, when renewable energy, especially wind and solar photovoltaic, was still very inefficient and expensive compared to existing sources of energy. For example, the EBRD reported in 2011 average global GDP losses of around 1.5 per cent compared to a business-as-usual scenario and losses of up to 5 percentage points of GDP for the EBRD's region of interest (Bowen & Albertin, 2011). In these scenarios, nuclear energy makes a much larger contribution to the final energy mix and the switch to decarbonised electricity creates more significant productivity losses than would be predicted in 2020. Indeed, during the 2010s, the levelised cost of energy of onshore wind declined by 70 per cent while that of utility-scale solar photovoltaic costs declined by 90 per cent (Lazard, 2021), as shown in Figure 1.1.

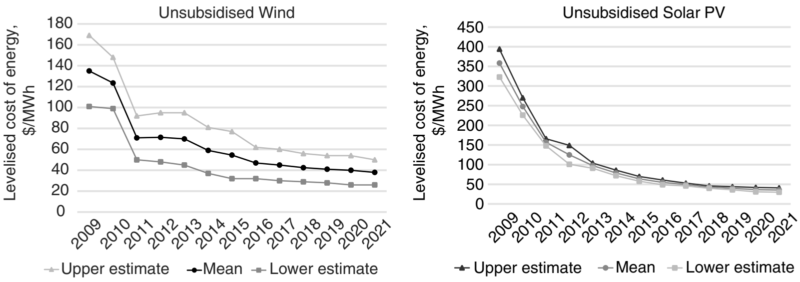

FIGURE 1.1 Evolution of the levelised cost of energy from onshore wind and solar photovoltaic
Source: Authors' calculations, from Lazard (2021).

1.4 POLICY LESSONS FROM IAMs

Beyond the general conclusion that a transition to a decarbonised economy by 2050 is achievable with manageable shifts in the economy, the main value of the exercises reported in the previous section is in identifying the conditions under which the economic costs of the transition can be minimised, and even turned into net gains. Using economic models, even with limitations, helps us to understand the transmission channels and reallocations that are predicted to take place. Three policy lessons emerge from simulations run using IAMs:

1. Carbon pricing is a necessary policy tool to spur the transition.
2. The ways in which carbon revenues are redistributed make the most difference in the total economic impact.
3. Global coordination is necessary to achieve ambitious emissions reduction at the lowest possible cost.

1.4.1 Carbon Pricing Is Necessary

The reduction in global GHG emissions necessary to limit global warming to 1.5°C, which we take as our starting point, will not be achieved without making all actors in the economy take into account the societal damage caused by their GHG emissions. Policies need to be introduced for this externality to be internalised.

Charging a price for carbon emissions is widely recognised as the single most important policy tool to align incentives with this objective. By directly addressing the externality to be tackled, it creates a clear signal concerning which harmful behaviour needs to be corrected. But it also leaves enough flexibility for the market to determine which margin of adjustment is most efficient (e.g. demand switching, energy efficiency, investment in abatement technology). In practice, the design of the carbon pricing mechanism matters for how effective emissions reduction will be. See Box 1.2 for an overview of the main carbon pricing schemes.

BOX 1.2 **Implementation of carbon pricing**

Carbon pricing is the preferred instrument of economists to tackle climate change because it directly addresses the main externality at the heart of this problem. Setting a price on carbon requires emitters to pay for the GHG emissions they release into our collective atmosphere, which affect our collective climate system. This forces them to take into account the consequences of their action on everyone else. However, it does not prescribe how this is to be done. This flexibility ensures that firms and consumers who can lower their emissions at the lowest cost will do so first. In practice there are two mechanisms to introduce a price on carbon: through the creation of a market or through taxation.

Creating a market for carbon requires assigning emissions certificates to companies and allowing them to exchange these among each other. The reduction in emissions is obtained by reducing the number of certificates through time. The efficiency of reductions is achieved by letting firms decide whether they would rather reduce emissions, for example through changing practices or investing in abatement technology, or rather purchase certificates at the going market price. The clear advantage of this mechanism is that it ensures certainty regarding emissions, as these are fixed, but it leaves firms to bear the risk in terms of price volatility.

The other mechanism is the imposition of a carbon tax, whereby governments require firms to pay a fixed monetary amount per quantity of emissions. This is often referred to in economic theory as a Pigouvian tax. For this tax to achieve the promised result efficiently, its level needs to be calculated precisely. It needs to reflect the trade-off between the societal benefits of reducing emissions and the additional abatement costs borne by firms. In other words, the level of the tax should equal the SCC. In contrast to market-based mechanisms, carbon taxes provide firms with certainty regarding the price they have to pay for emissions and leave society to bear the risk in terms of the quantity of GHG being emitted.

As the discussion on the SCC suggests, the optimal carbon price is difficult to estimate. The High-Level Commission on Carbon

Prices (2017) provides a useful focal point. It suggests that a carbon price level consistent with achieving the Paris Agreement is \$40–\$80/tonne of CO_2 by 2020, rising to \$50–\$100/tonne of CO_2 by 2030. The number of countries implementing carbon pricing instruments has been steadily increasing, from seven in 2000 to nineteen in 2010, fifty-eight in 2020 and sixty-four in 2021 (World Bank, 2021). The share of global emissions covered by these instruments reached 5 per cent in 2005 with the introduction of the European Union's Emissions Trading System (EU ETS), rose to 10 per cent in 2014, rising steadily to 15 per cent by 2020. In 2021, the launch of an ETS in China, which covers the energy sector, meant that an additional 7.5 per cent of world GHG emissions were covered by a carbon pricing instrument. However, the level of the carbon price in these schemes remains much below the \$40–\$80/ tCO_2 recommended by the High-Level Commission on Carbon Pricing. Figure B1.2.1 shows the share of emissions from the energy sector covered by various effective levels of carbon price. Figure 4.2 shows the cumulative amount of emissions covered by a carbon price (tax and certificates) in 2022.

Market-based and taxation-based systems also differ in terms of administration costs and political feasibility. Whereas both systems require monitoring the emissions of the firms subject to the carbon price, the cap-and-trade system additionally requires setting up a well-functioning market for emission permits. However, these schemes tend to be more politically feasible, as they are perceived as better reflecting the 'polluter-payer' principle. On the other hand, carbon taxes tend to be more acutely felt by final consumers and may meet more resistance.

Finally, fossil fuel subsidies act as a negative price on carbon, incentivising consumers to emit more. The rapid elimination of fossil fuel subsidies is therefore an important climate policy. The distributional and poverty alleviation goals of these subsidies can be achieved with other tools less detrimental to the climate.

Figure B1.2.1 should be read as follows. In Finland, 6 per cent of emissions are priced at a rate between €0 and €5/tonne of CO_2, 39 per cent of emissions between €5 and €30, 5 per cent of emissions

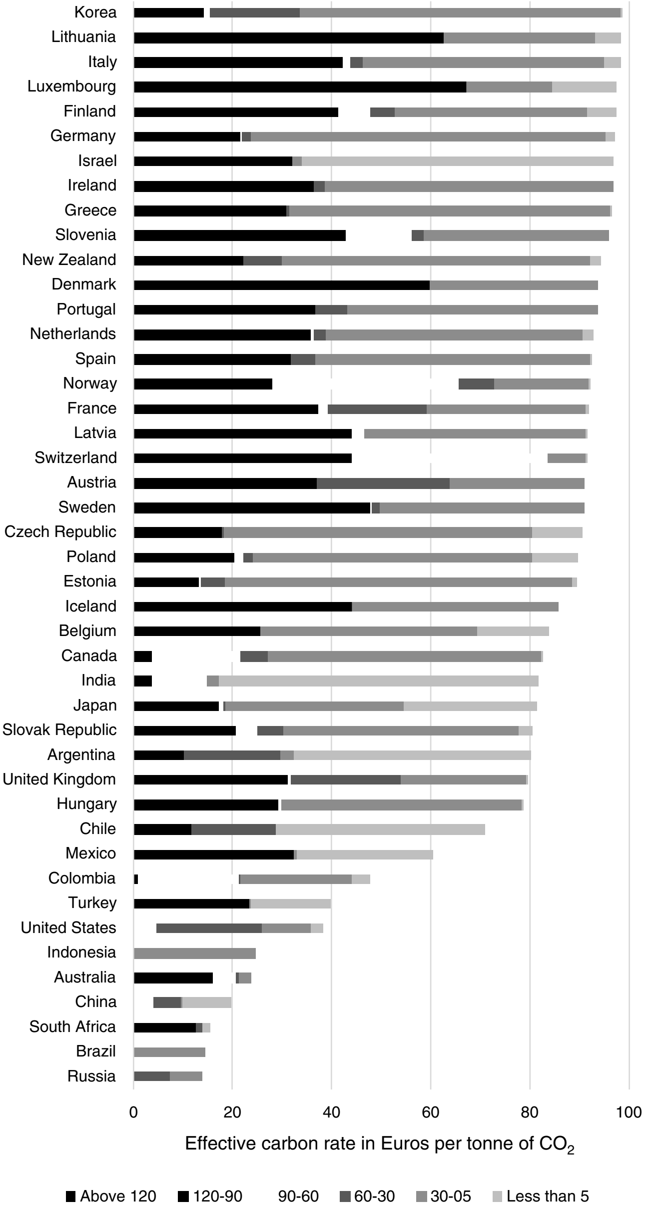

FIGURE B1.2.1 Share of emissions from the energy sector priced at an effective carbon rate, in €/tonne of CO_2, 2018
Source: Authors' calculations based on the OECD effective carbon rates (OECD, 2021).

between €30 and €60, 6 per cent of emissions between €60 and €90, 17 per cent of emissions between €90 and €120, and finally 24 per cent of emissions are taxed above €120/tonne of CO_2. This sums to 97 per cent of emissions from the energy sector being subject to a carbon pricing scheme.

In the context of IAMs, the optimal level of emissions and the optimal price of carbon are two sides of the same coin and are often used interchangeably. When modelling the evolution of the economy along a fixed path of emissions (e.g. reaching net zero by 2050), IAMs assume the existence of a carbon price even if it operates mostly in the background (Bowen & Albertin, 2011; European Commission, 2020; IMF, 2020). Understanding the economic effects of decarbonisation cannot be separated from an analysis of the transmission channels of the climate policies used to change behaviour.[4]

1.4.2 Redistributing Carbon Revenue

The introduction of a price on carbon can yield substantial revenues and how this revenue is redistributed can make large differences for the overall macroeconomic effects of the transition.

In an empirical analysis, the European Commission's impact assessment of the revised emissions reduction target predicts that energy taxes and carbon prices combined would raise, by 2030, between €55 billion and €75 billion annually, representing between 1.8 per cent and 2.25 per cent of GDP (European Commission, 2020). The impact assessment presents different options for recycling these revenues and finds contrasting results between lump-sum redistribution and redistribution aimed at reducing other distortionary taxes. Using a hybrid model that mixes IAM elements with a more standard model of the macroeconomy, Estrada García and Santabárbara García

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[4] As will be discussed in Chapter 2, Dynamic Stochastic General Equilibrium models, which look at the short-term effects of decarbonisation, tend to focus on the carbon price itself and discuss its effect on the demand side of the economy and on variables such as inflation and consumption.

(2021) analyse the effect of introducing a carbon tax in Spain and find that the total costs on the economy depend on how carbon revenues are recycled.

There are four main avenues through which carbon revenues can be recycled. First, carbon revenues can be distributed back to households in a lump-sum manner, with varying degrees of universality. The purpose of this alternative is to focus on redistributive justice and alleviate the burden of a higher carbon price for low-income households. The second option is to reduce public deficits and debt levels. These first two alternatives do not change the relative prices in the economy and hence have a limited impact on economic activity and emissions but pursue other policy objectives. The third option is to use the carbon revenues to improve the carbon efficiency of energy and production, by investing in research and development (R&D). Finally, the revenues can be used to reduce other distorting taxes in the economy, such as capital taxes, consumption taxes and social security contributions. Research shows that these last two alternatives have a strong potential to lower the overall cost of the transition. R&D subsidies hasten technological progress and the availability of low-carbon alternatives (Acemoglu et al., 2012; Aghion et al., 2009). Decreasing social contributions lowers the cost of hiring labour and has positive effects on employment, especially of low-wage workers most likely to bear the burden of increased energy prices. These considerations will be discussed in more detail in Chapter 4, which focuses on carbon pricing in the context of fiscal policy.

1.4.3 International Coordination

The final policy lesson is that international coordination lowers the cost of reducing GHG emissions for every individual country. IAM-based analyses point to the importance of international coordination of emissions reductions. GHG emissions create a global externality, and a consistent result across all models, including approaches other than IAM, is that the emissions reductions are more pronounced and the economic losses are dampened under scenarios with effective international coordination compared to unilateral efforts, for example by the European Union (Vrontisi et al., 2020). This is because in a world with trade openness, carbon-intensive industries that are subject to a domestic carbon price are vulnerable to international competition. Carbon leakage refers to the situation where domestic demand for goods subject to carbon pricing is substituted by imports coming either from foreign producers or relocated domestic producers. This will imply important losses of economic activity domestically, as activity decreases, but results in limited reductions in global GHG emissions, which happen in regions where carbon is not priced. In particular, Estrada García and Santabárbara García (2021) and Ferrari and Pagliari (2021) find that double dividends, that is net GDP gains, are feasible only in a scenario with international coordination.

1.5 MAIN SHORTCOMINGS OF IAMS

In practice, the carbon price is not a sufficient tool to achieve decarbonisation. For the carbon price to create the right incentives, the rest of the economy needs to operate perfectly. However, on the issue of climate change, additional market failures compound with the externality of GHG emissions, which necessitate additional policy responses (Köberle et al., 2021; Krogstrup & Oman, 2019). However, these market failures are assumed away in IAMs. This means that we need to look to other fields of economic analysis for evidence in these areas. IAMs abstract away from the following considerations:

1. Nominal variables, agents' expectations and business cycle dynamics
2. Distributional effects
3. Knowledge spillovers in the innovation system
4. Policy uncertainty and instability
5. Imperfect information and market frictions

1.5.1 Looking at the Short Run

Integrated Assessment Models were developed to analyse the conditions under which an optimal transition to a low-carbon economy could take place. In this framework, the time horizon of the transition is not of concern because it is assumed that long-run adjustment processes can take place without inherent frictions. However, climate science shows that there is an increasingly pressing need for reducing GHG emissions to mitigate climate change. IAMs are ill-adapted to provide guidance at this much shorter time horizon, because they do not include nominal variables (namely prices and wages), rigidities and inflation in these nominal variables, a central bank with a monetary policy rule, financial instruments for lending and borrowing (i.e. bonds), imperfect information, agent's preferences and the formation of expectations. All of these elements are necessary to explain how economies respond to shocks and the presence of risk. Some IAMs do have dynamic (e.g. capital accumulation, intertemporal consumption) and stochastic (productivity shocks) elements, but they are at heart designed to look at the evolution of the steady state of the economy, rather than its deviations from trend.

Chapter 2 will describe in detail how Dynamic Stochastic General Equilibrium models can provide insights on the short-run disruptions created by an accelerated transition. These models are designed precisely to look at the transmission of shocks and the resulting business cycle dynamics. This allows for an understanding of how the introduction of climate policies themselves can affect the economy, for example how the carbon price can have inflationary consequences that effect aggregate demand. These models can also tell us how this will affect the volatility of variables of interest and the transmission mechanisms of other policies, such as monetary policy.

1.5.2 Technological Progress, Innovation and Knowledge Spillovers

At the heart of the decarbonisation challenge is the issue of the technological feasibility of decoupling economic activity from emissions. When faced with a carbon price, the availability and cost of various alternatives determine the scope that firms and households have to reduce emissions and the resulting macroeconomic impact.

As IAMs tend to adopt a static view of innovation and technological progress, the number and productivity improvements of various technologies is fixed in the premises of the model. On the one hand, by including enough alternatives in the assumptions, the models can predict a realistic and flexible response of the economy. On the other hand, this oversimplification can lead to overestimating the cost of the transition, because both the rate of technological progress and the number of alternatives are economic choices that can be influenced by policy.

First, the amount of innovation and hence the rate of technological progress can be incentivised. Because of the knowledge spillovers inherent in the innovation process, the private sector will not invest sufficiently in innovation. The rate of progress will be too slow, which means that for a given level of technology, reducing emissions will have to come from reducing output. This type of market failure justifies public support for innovation to increase the speed of improvements in emissions efficiency (Aghion et al., 2009).

Second, the relative efficiency of green versus brown technologies itself can be influenced. The models of Acemoglu et al. (2012, 2016) and Aghion et al. (2009) have a more sophisticated view of innovation, disaggregating innovation into different fields and allowing firms to switch between technologies. This view of technical change as a process with a direction implies that support to innovation can and should be targeted towards 'green' technologies. This line of research shows that targeted R&D subsidies can significantly lower the transition costs. In the extreme case where green technologies are very inefficient, this sector attracts little innovation because of its reduced market potential. If a carbon price is introduced to disincentivise carbon emissions, this will be achieved mostly through reductions in output and will require a very high carbon price. Generous research subsidies for green technologies can help this sector catch up to carbon-intensive technologies. Once this catch-up has taken place and green technologies become competitive unaided, a lower carbon price can be sufficient.

However, a number of questions remain regarding the role of technological progress in achieving decarbonisation at the smallest possible cost. Within the field of green technologies, policymakers can decide whether to incentivise technological paths or seek to remain technologically neutral. Furthermore, the economic tools at our disposal do not provide much guidance in terms of allowing for and supporting the emergence of radical innovations. On the one hand, these tools represent risky gambles with low probability of very high payoffs. On the other hand, these might lead to the sudden depreciation of investment efforts in previous vintages of technologies. Finally, the path of productivity growth in an economy on the transition path to decarbonisation is unclear. While switching to less efficient green technologies might lead to a drop of productivity in the short run, this could be compensated by higher productivity growth once green technologies have caught up. These questions will be discussed in further detail in Chapter 5.

1.5.3 Policy Uncertainty and Instability

Economic models assume that policies are credibly adopted and perfectly implemented. However, the policy process itself is subject to capture, renegotiation and error. In particular, the time inconsistency inherent in setting a carbon tax is likely to create uncertainty for economic actors. It may thus be rational to undertake less mitigation measures than in a world without uncertainty given that the policy measures that will be implemented may be smaller because of the credibility issue. Most models do not explicitly consider this policy uncertainty.

Moreover, the carbon price is not introduced in a vacuum but in the presence of other distortionary policies, which are likely to interact and possibly counteract the effectiveness of the carbon price. The models that look at the carbon price in isolation will tend to underestimate the total disruption caused by this transition. In Chapter 4, we will discuss how carbon taxation fits into a broader fiscal framework, where other taxes, such as capital or labour taxes, might dampen its effectiveness. In Chapter 8, we will discuss the role of monetary policy in a world with climate change and climate policies, in particular how it should respond to energy-driven inflation.

1.5.4 Imperfect Information and Market Frictions

Even with an efficient innovation system that provides the optimal amount of low-carbon alternatives, the cost of the transition will also depend on the ability of firms and households to adopt and deploy these alternatives. In other words, markets need to function smoothly for resources – goods, capital, workers – to relocate to these new uses. IAMs typically assume that markets function perfectly and allocate resources to their most efficient use. This assumption can be relaxed in two directions, with differing implications for the macroeconomy.

On the one hand, if there are unused resources in the economy, for example excess savings looking for returns or high unemployment, then these will tend to decrease the cost of the transition, because resources will not have to be taken out of otherwise productive uses. On the other hand, if there are frictions on other markets, then the reallocation will be more protracted, leading to a longer transition. This can happen for example if capital markets lack information to identify green projects and to price their risks correctly or if new green activities require a different set of skills that take time for workers to acquire. Finally, other issues concerning market design might also affect the efficient allocation of resources. For example, the potential of digital technologies to increase market concentration and the scope of competition policy in ensuring the emergence and deployment of green technologies are likely to matter.

The issue of information failures in financial markets is a particularly important market friction for achieving decarbonisation. Installing green technologies requires capital investments, but at present there is a lack of credible information as to which projects are green. This information failure hampers the ability of financial markets to direct funding correctly and highlights the importance of developing reporting tools such as disclosure standards and investment taxonomies to avoid greenwashing. Additionally, renewable energies have a different cost structure compared to fossil fuel-based electricity production. The former implies high capital expenditures in the installation phase but require much lower operating expenses once in operation. This is likely to have an impact on financial markets. Chapter 6 will discuss how decarbonisation is likely to affect financial markets and macroeconomic stability, highlighting the importance of macro- and micro-prudential policies to ensure an efficient transition.

Chapter 7 will explore the effect of decarbonisation on labour markets, which creates a double challenge. On the one hand, workers currently employed in emitting activities will see their jobs transformed or altogether disappear. These workers will need to be accompanied as they find new opportunities in the labour market. On the other hand, the rise of green activities will create demand for 'green jobs' and much uncertainty remains regarding the ease with which firms will be able to find workers with the desired skill set.

1.5.5 *Fairness and Redistributive Justice*

Finally, in addition to efficiency concerns, the optimal design of climate policy needs to consider fairness and distributive justice. The costs of the transition will be concentrated sectorally, geographically, in low productivity firms and in low-income households (Zachmann et al., 2018). Designing compensatory policies is thus crucial to ensure the social acceptability and hence political viability of climate policies. Distributive considerations also matter across countries. This can be seen by the important weight given to funding for 'loss and damage' or 'climate reparations' in international climate negotiations, especially the yearly United Nations Conference of Parties. These issues will be discussed in further detail in Chapter 3.

1.6 CONCLUSION

The field of climate economics has developed a very sophisticated modelling framework capable of simulating the response of an economy to climate objectives over multiple decades. This framework has been used to determine the optimal rate at which GHG emissions should be reduced. However, these results remain inconclusive, while those coming from climate science have created a new sense of urgency. It has become clear that GHG emissions need to stop as fast as possible, with the middle of the twenty-first century being the ultimate deadline to avoid the most catastrophic impacts of climate change.

The models developed by climate economists tell us that in 2050, a decarbonised economy will differ from one that continues to use fossil fuels by only a few percentage points, in either direction. An important caveat to this statement is that both scenarios ignore the averted climate change damages. The key to achieving decarbonisation is to introduce a carbon price, which forces economic agents to integrate in their decision-making the externality they create by emitting. These models emphasise two policy choices that make the difference between having a smaller or a larger economy. First, a smart use of the revenues raised from pricing carbon, one which decreases other distortionary taxes, can lead to double dividends. Second, limiting economic losses requires concerted efforts from all emitters, in order to avoid displacing emissions and economic activity.

However, IAMs, like all models, need to ignore certain workings of the economy. In the case of climate change mitigation, some of these abstractions hide important aspects of the economic response to decarbonisation and thus the policy response. The purpose of this book is thus to bring together lessons from different fields of economics to obtain a broad-ranging view of this topic.

1.7 KEY TAKEAWAYS

1.7.1 How Economists Have Thought about Decarbonisation

- Integrated Assessment Models are the main economic tool through which environmental considerations have been included in economic thinking.
- They make three major additions to standard models of the economy: an emissions module, a climate module and a damage function.

1.7.2 *Empirical Lessons from IAMs*

- IAMs have been used to investigate two types of questions: What is the socially optimal quantity of emissions? How do specific emissions pathways lead to changes in economic activity?
- The SCC has been used to explore questions regarding the socially optimal quantity of carbon and is defined as the marginal economic loss coming from an additional tonne of atmospheric carbon.
- The SCC has been superseded in the climate policy debate due to its sensitivity to heavily debated modelling assumptions, such as the appropriate discount rate.
- Using IAMs to understand possible changes in economic activity along various emissions pathways has led to a consensus: decarbonisation appears to be achievable and affordable.
- But the achievability and affordability of decarbonisation is highly dependent on existing technologies meeting their expected potential and additional technological progress.

1.7.3 *Policy Lessons from IAMs*

- To achieve climate change mitigation, the global externality caused by carbon emissions should be directly addressed through carbon pricing.
- The approach taken to redistribute the revenues from carbon pricing has a significant impact on the total economic cost of the transition.
- Global coordination is necessary to achieve ambitious emissions reduction at the lowest possible cost. In a world with trade openness, the risk of carbon leakage needs to be acknowledged.

1.7.4 *Main Shortcomings of IAMs*

- In practice, the carbon price is not a sufficient tool to achieve decarbonisation, because the presence of market failures throughout the economy creates inefficiencies and obstructions to the transition.
- Moreover, IAMs do not account for many of the market failures present in real-world economies.
- They are silent on the impact of nominal variables and short-run rigidities, especially of prices and wages, and hence on the resulting short-term economic instability.

- They ignore the fact that the speed and direction of innovative effort can be steered towards the decarbonisation objective, which would reduce the overall welfare loss of the transition.
- They assume that policy decisions are perfectly calibrated and credible and are taken as given by all economic agents.
- They ignore the lack of information and market frictions that might slow down the reallocation of capital and labour out of emitting and into low-carbon activities.
- Finally, they ignore the distributional consequences of the transition, which is nevertheless vital for its social and political acceptability.

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