Chapter 11: Economics of climate mitigation

Abstract

Carbon emission reduction can be brought about by a wide range of technologies, developed and deployed through innovation and investment in both technologies and the skills needed to operate them. Such investment is still well short of where it needs to be for Real Zero by 2050. What is required to bring about more investment is greater zero-carbon ambition from businesses, more transparency in how they intend to achieve it, and government that is prepared to intervene strategically in markets to ensure that businesses can deliver large emissions reductions and remain profitable.

Investment in the transition to clean energy will lead to a net increase in jobs, and, contrary to degrowth literature, to economic growth. The reduction and then elimination of fossil fuel use, and improving the diets of affluent people, will result in a number of benefits apart from GHG emissions reduction, called ‘co-benefits’, the largest being health benefits from improvement in both outdoor and indoor air quality from greater active travel in cities and reducing excess meat and dairy consumption. Afforestation and better land management that stores carbon should also improve ecosystems and lead to increased biodiversity.

Summary

Earlier chapters have shown that carbon emission reduction can be brought about by a wide range of technologies. This chapter explores how the costs of these technologies have changed and may change in the future, and what the effects of their large-scale introduction will be on economic growth.

The most important economic characteristic of the clean energy transition is innovation, the process that creates new technologies and that leads to their cost reduction so that they can achieve large-scale deployment. This chapter first explores the nature of this process throughout the journey from the laboratory to the mainstream, and presents the extraordinary cost reductions in low-carbon technologies which have been brought about.
However, the large-scale global deployment pf these technologies, to reach zero emissions by mid-century, will require huge levels of investment in low-carbon technologies. Such investment has increased greatly in recent years, but is still well short of where it needs to be. The issue is not shortage of capital *per se*, but a shortage of projects with the right risk-return ratio for it to invest in. There are now many initiatives in the financial sector to try to direct more capital into zero-carbon projects and technologies, but what is required to bring this investment about is greater zero-carbon ambition from businesses, more transparency in how they intend to achieve it, and government that is prepared to intervene strategically in markets to ensure that businesses can deliver large emissions reductions and remain profitable.

Investment is required not just in technologies, but also in the skills that are needed to manufacture and operate them effectively. The evidence suggests that the transition to clean energy will lead to a net increase in jobs, but there are challenges to ensure that those who lose their jobs in declining sectors are retrained to be able to take jobs in the low-carbon economy. With innovation and technical progress, and investment in physical and human capital, it is likely that decarbonising economies will grow, and evidence to this effect is presented in this chapter. It is therefore surprising that a current of academic thought has arisen that posits that decarbonisation to zero emissions will require a reduction in economic output, in rich countries at least. This chapter argues that not only is this not necessary, but also that the suggestion itself is potentially very damaging politically in a world in which increased material living standards are still a major aspiration for most people.

Reducing and then eliminating fossil fuel use, and improving the diets of affluent people, will result in a number of benefits apart from GHG emissions reduction, called ‘co-benefits’. The largest of these is the health benefit from the improvement in outdoor air quality that would come from reducing fossil fuel use, and in indoor air quality from moving towards cooking and heating with cleaner fuels. Active travel in cities also has health benefits, as does reducing excess meat and dairy consumption. Afforestation and better land management that stores carbon should also improve ecosystems and lead to increased biodiversity. This chapter finishes by exploring explores the size and extent of these benefits.

Introduction

An obvious, and important, question that arises from the discussion in previous chapters of the many technologies that can reduce GHG emissions is: what will introducing them at the necessary scale to get to zero emissions actually cost? To answer that question it is necessary first to explore how technologies are created and the processes of innovation that take them to success and deployment at scale in markets.

Technology and innovation

The apparently simple question about the ‘cost’ of a technology can in fact mean a number of different things. The most obvious is: how much money needs to be spent to bring about mass deployment of these technologies? This is often referred to as the ‘investment’ needs of decarbonisation. However, because the costs of deploying technologies over time can change dramatically, as will be seen below, and because the deployment will need to take place over many years, it is not just the current costs of the technologies that need to be calculated. Their future costs over the relevant time period also need to be estimated, and, again, as will be seen, this is no simple task.

However, it is misleading simply to refer to these expenditures on technologies as ‘costs’. As investments they will produce a range of economic benefits. They will employ people, they will generate incomes and, perhaps, exports. They will thus contribute to the Gross Domestic Product (GDP) of the country in question, and, potentially, to GDP growth. At this macroeconomic level, the cost of decarbonisation is therefore computed as the difference in GDP at a certain date between a scenario with high carbon emissions and a scenario with low, or zero, carbon emissions. These are the issues which will be explored in this chapter, but it all starts with the costs of decarbonisation technologies now, and estimates of how they will develop in the future.

The IPCC (Intergovernmental Panel on Climate Change, 2022a, Figure SPM 7, p.SPM-50) estimated both the potential carbon saving and the estimated 2030 costs for the whole range of low- or zero-carbon technologies in energy, transport, buildings, buildings, agriculture, forestry and other land use (AFOLU), waste, wastewater and F-gases. Many of these technologies have been discussed in earlier chapters. Taken from around 175 underlying sources, the costs are expressed in terms of USD/tCO2e/year not emitted, compared to the cost of a reference high-carbon technology which would otherwise have been likely to be used. The costs and emission reduction potential for the main technologies are discussed here.

Energy
Wind and solar are the big hitters, able to save more than 2 GtCO2e/year each by 2030, at a *negative* cost (i.e. the cost than that of the fossil fuel technology). Another 1-2 GtCO2e/year can be saved at cost of less than USD 50/tCO2e/year. Bioelectricity, geothermal, nuclear and reducing upstream oil and gas emissions each save around 1 GtCO2e/year, with costs that go up to around USD

100/tCO2/year for each technology except bioelectricity, which is more expensive. Hydropower, reducing coal mine methane, CCS and BECCS save well under 1 GtCO2e/year, with hydropower and coal mine methane reduction being fairly cheap (< USD 50/tCO2e) but CCS and BECCS being expensive (USD 50-200/tCO2e)

Buildings

Demand reduction (e.g. turning down thermostats, wearing more clothes in winter) and more efficient lighting, appliances and equipment save money (i.e. have *negative* cost) and together can save more than 1 GtCO2e/year. So can very energy-efficient new buildings, but the costs there can go up to USD 200/tCO2e saved. Onsite renewables save around 0.5 tCO2e/year at a similar cost of high-performing buildings. Home retrofits (most relevant in colder climates) save around 0.25 tCO2e/year, again at a cost of up to around USD 200/tCO2e/year.

Transport

All the main technologies listed for this sector are estimated to actually *save* money by 2030. They include shifting to EVs, bikes or e-bikes, and adopting fuel-efficient heavy-duty vehicles, ships and aircraft. In total these negative-cost measures can save in excess of 1 GtCO2e/year. Biofuels come in at a cost of up to USD 100/tCO2e/year, and save up to 0.5 GtCO2e/year. The zero-carbon fuels for aviation and shipping (e.g. synfuels, bio-kerosene, hydrogen, ammonia) are not mentioned, but would be significantly more expensive.

Industry

Industry is shown as having no negative-cots mitigation opportunities, apart from small no-cost reductions in F-gases and methane from solid waste. Its cheapest opportunities, at less that USD 20/tCO2e/yr, lie in energy efficiency, which in 2030 can save over 1 GtCO2e/year at that cost. At under USD 50/tCO2e/year, material efficiency and enhanced recycling can save around 1.5 GtCO2/year. Fuel-switching (e.g. to hydrogen) has about the same opportunity at this cost, but can save 2 GtCO2e/year at under USD 100/tCO2e. Changing feedstocks and industrial processes (e.g. in cement and chemicals) can save another 0.5 GtCO2e/year at USD 50-100/tCO2e.

AFOLU

CO2 sequestration, and reducing emissions of methane and N2O, in agriculture can save around 2GtCO2e/year, at a cost below USD 50/tCO2e, making this the most cost-effective option after wind and solar. Ecosystem restoration, afforestation, reforestation and improved sustainable forest management can save nearly 1.5 GtCO2e/year, but at higher cost, up to USD 100/tCO2e. And as was discussed in Chapter 7, there is always a chance that the CO2 from such measures can be released if the forests are later degraded or destroyed (e.g. by wildfires during heat waves).

While the IPCC does not make this calculation, a quick summation down the bars of Figure SPM 7 in Intergovernmental Panel on Climate Change, (2022a, p.SPM-50), suggests that over half of current GHG emissions (59 GtCO2e) could be reduced by technologies that, by 2030, will cost less than USD100 per tonne CO2e.

The IPCC is at pains to stress the uncertainties involved in such estimates, which could turn out to be higher or lower. In addition, the estimated costs obviously depend on the assumptions made about the technologies which the low-carbon technologies will replace, and how the costs of both sets of technologies will develop between now and 2030. The costs will also vary between countries according to their technological capacities and economic and political contexts. The renewable electricity costs, for example, may not include the costs of incorporating them into electricity systems, which may become significant after 2030 as their proportion in electricity systems increases beyond about 20%.

However, the estimates above also do not contain the avoided costs from climate change, which is of course the main purpose of introducing them. Nor do they include the other benefits, called ‘co-benefits’ which substituting these technologies for fossil fuel technologies would bring about. The main co-benefit is the reduction of local air pollution associated with burning fossil fuels, but the co-benefits also include reduced traffic congestion, and more potential green space, in cities (from the shift away from cars), less pollution of rivers from reduced use of fertilisers, and reduced health problems from obesity (from the adoption of healthier diets). Estimates of these co-benefits are given later in this chapter.

One of the major uncertainties of the costs estimates of the various technologies above, as has already been noted, is how they will develop over time. This is well illustrated by how the costs of several of these technologies have in fact evolved over the past couple of decades.

The IPCC has shown the extent to which the cost of key renewables technologies has fallen over 20 years: by more than a factor 6 for solar PV, more than half for onshore wind and concentrating solar power (CSP), and more than half for offshore wind since 2015 (Intergovernmental Panel on Climate Change, 2022a, p. SPM-13). All four of these technologies now have costs in the range of fossil fuel generation costs, with PV costs falling from around USD 600/MWh in 2000 to around USD 50/MWh in 2020. It is especially encouraging that batteries for EVs have experienced an even faster cost reduction than PV, with their cost coming down from around USD 1400/kWh in 2005 to less than USD 100/kWh in 2020. However, enthusiasm over these cost reductions, and the very fast rates of increase of adoption of these technologies that they have stimulated, must be tempered by the very small proportions of the global electricity supply that these technologies still account for (see Figure 4.1). There is still a very long way to go before these technologies comprise even a significant share, let alone the majority, of their markets.

The technology cost reductions cited in the previous paragraph have not come about by accident. They are the result of government policies that supported research into and development of these technologies, and then created early markets for them, following which private sector companies deployed them at scale. In this way, public policy, aided in the later stages by markets, has driven these technologies through what are called Technology Readiness Levels (TRLs), which are described in Table 11.1.

Technology Readiness Levels (TRLs)	
Research	TRL 1—Basic principles observed and reported.
	TRL 2—Technology concept and/or application formulated.
	TRL 3—Analytical and experimental proof of concept.
Development	TRL 4—Component or technology validated in laboratory.
	TRL 5—Component or technology validated in an industrially relevant environment.
	TRL 6—System or sub-system model or technology prototype demonstrated in relevant environment.
Deployment	TRL 7—System prototype demonstration in operational environment.
	TRL 8—Actual system completed through test and demonstration.

	TRL 9—Actual system proven through successful operation.

Table 1.1: Technology Readiness Levels (TRLs)
Source: Adapted from NASA, 20112, https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level. Accessed April 24, 2023.

The idea of TRLs was introduced by NASA (the US National Aeronautical and Space Administration), originally in the context of space technology, to describe the various stages which a technology must pass through from a basic conception in research, through to operational deployment. TRLs are now used to describe this journey for technologies in general. Universities and corporate research laboratories tend to concentrate on TRLs 1-4. At that point the technology tends to face what is sometimes called 'the Valley of Death', often requiring substantial sums of money to be developed and demonstrated in a real-life industrial environment. Those technologies that are successful at that stage, passing through TRLs 5 and 6, are then ready for deployment, first in niche markets and then, if successful there, at scale.

This very much describes the journeys of the technologies shown in Intergovernmental Panel on Climate Change, 2022a, Figure SPM 7, p.SPM-50, and described at the beginning of this chapter. At each stage of this innovation journey, the technology may experience cost reduction through learning: 'learning by research' in TRLs 1-4, and 'learning by doing' thereafter. 'Learning by doing' becomes particularly important as the technology is deployed at scale. The relationship between the unit cost and the cumulative deployment of a technology is called a 'learning (or experience) curve', which gives the percentage reduction in the cost of a technology with a doubling of its cumulative deployment.

But it would be a mistake to imagine that this journey of technologies through the TRLs is brought about by technological innovation and development alone. On the contrary, large-scale technological deployment requires innovation in a wide range of social and economic systems as well, including business organisation, business models and supply chains, consumer preferences and behaviours, financing, regulation and standard-setting in markets, institutions of research and governance (e.g. patenting) and infrastructure (e.g. smart grids, charging points for EVs) (Grubb et al., 2017). Public policy has an absolutely critical role to play to stimulating and setting the direction of innovation in all these areas such that it results in low- and zero-carbon emission outcomes, rather than a continuing dependency on fossil fuels.

The Fraunhofer Institut 2023 Photovoltaics Report shows the cost development for a large PV system between 2010 and 2021 (Fraunhofer Institut, 2023, p.44[1]). In 2010 the cost was EUR 0.315/kWh. By 2021 the cost had fallen to EUR 0.041/kWh – a fall of 87%, with a year-on-year decrease in the cost of electricity of 17% (Fraunhofer Institut, 2023, p.44). Over the same period global cumulative installed capacity increased more than 20-fold, from about 40 GW to 940 GW[2].

	Mean cost (2021 USD/kWh)

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[1] https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf, Accessed April 24, 2023

[2] https://www.statista.com/statistics/280220/global-cumulative-installed-solar-pv-capacity/#:~:text=Global%20cumulative%20installed%20solar%20PV%20capacity%202000%2D2021&text=Global%20cumulative%20solar%20photovoltaic%20capacity,installed%20in%20that%20same%20year. Accessed April 24, 2023

	2010	*2021*
Bioenergy	0.078	0.067
Geothermal	0.050	0.068
Hydropower	0.039	0.048
Solar photovoltaic	0.417	0.048
Onshore wind	0.102	0.033
Offshore wind	0.188	0.075
Concentrating solar power	0.358	0.114
Fossil fuel electricity	0.075	0.067
Fossil fuel cost range	Approx. USD 0.03-0.18/kWh	

Table 11.2: Unit cost developments in a range of power generation technologies, 2010-2021
Source: Adapted from International Renewable Energy Agency, 2022, Figure 1.2, p.32

The International Renewable Energy Agency (2022, Figure 1.2, p.32) gives the costs of a range of power generation technologies over 2010-2021, derived from the large database of actually installed electricity projects, held by the International Renewable Energy Agency (IRENA). These costs are shown in Table 11.2 and have a number of points of interest. First, Table 11.2 shows that not all power generation technologies have experienced a reduction in costs since 2010. The unit costs of both geothermal and hydropower have increased since 2010. Second, it shows that fossil fuel generation has also come down in costs, though this may not be the case in 2022, with the great increase in oil and gas prices. Third, it shows that the cost reductions in PV have been exceptional. The costs of wind and Concentrating Solar Power (CSP) have come down less quickly. Fourth, it shows that the variability in the costs of projects (especially PV), has been very great, though it is much less in 2021, when the technologies had matured. Fifth, it shows that all the renewable generation technologies are either below the lowest cost of fossil fuel technologies (solar PV, onshore wind, hydropower), or well within that band (offshore wind, geothermal, CSP).

The cost reductions cited above have both driven, and been driven by, the very fast rates of deployment of these technologies. The innovation that has brought about these cost reductions has been critical in giving the world any chance at all of reducing carbon emissions to the extent necessary to avoid devastating climate change. The hope must be that similar rates of deployment of a wide range of the technologies shown in Intergovernmental Panel on Climate Change (2022a, Figure SPM 7, p.SPM-50), and described above, will bring about similar cost reductions in the future, through 2030 and beyond.

However, there is no certainty that cost reductions for technologies will occur along with their cumulative deployment, as Table 11.2 makes clear – the costs of both geothermal and hydro-power shown there actually increased over 2010-2021. However, to estimate the costs of getting to net zero by 2050, some estimate of future cost development must be made. Way et al. (2022, p. 4) note that "Successful technologies tend to follow an ''S-curve'' for deployment, starting with a long phase of exponential growth in production that eventually tapers off due to market saturation." They find that, for a their four chosen technologies (PV, batteries, wind, electrolysers), experience curves derived from past data (e.g. 1976-1990) actually predict future prices (e.g. to 2020) remarkably well, and they use these curves to project the prices of these key low-carbon technologies into the future.

Way et al. (2022, Figure 5C, p.9) shows their results for batteries, the future price development of which will be critically important for the success or otherwise of electric vehicles (EVs). The main figure shows the cost development of two kinds of battery – Li-ion consumer cell batteries and Li-EV battery packs. In 1995 the cost of the former was around USD 5,000/kWh and in 2010 the cost of the latter was around USD 1,000/kWh. By 2020 the cost of these had broadly converged at around USD 150/kWh. Way et al. (2022, Figure 5C, p.9) also show various cost projections for EV batteries from Integrated Assessment Models (IAMs) or the IEA, which have consistently underestimated the cost reductions that have in fact taken place.

Way et al. (2022) further estimated for three different scenarios the probabilities of further cost reductions in their four technologies on the basis of the cost reductions that had occurred in the past. The three scenarios envisaged No Transition, with deployment of these technologies on the basis of past rates of deployment, a Slow Transition with increased rates of deployment, and a Fast Transition with much increased rates of deployment. The key message from this exercise was that the cost of these technologies depends on how fast they are deployed, with most cost reduction occurring in the scenario with the highest deployment (Fast Transition).

A note of caution around these results may be introduced related to the discussion of those minerals that are critical for the energy technologies, discussed in Chapter 8. If there is a failure to produce enough of these minerals over the requisite timescale, or to develop technologies that are less dependent on them, then their increase in cost might negate the cost reductions that might otherwise occur through a Fast Transition scenario. There were signs in 2022 that this might already be happening. The IEA reported in 2022 that key material costs for solar PV (silicon metal), wind turbines (steel) and lithium batteries (lithium) had all risen substantially, increasing the overall costs of solar PV and wind turbines in 2021 and slowing the cost reduction in batteries ((International Energy Agency, 2022, p. 20).

Of course, achieving large-scale deployment of any technology requires significant investment and it is the scale of the investment required, and where it is likely to come from, that is the subject of the next section.

Investment, finance and business

This chapter quotes extensively from the IEA's *World Energy Investment* reports from both 2021 and 2022, because the latter saw some departures from trend due to the Russia/Ukraine war, and because some of the breakdowns in the earlier version of the report are more appropriate in this book.

In the normal course of events the world invests a large amount in energy, just short of USD2 trillion in 2017-2019, with a dip because of Covid in 2020, and an estimated rebound in 2021 (<Figure 11.1 here>
Figure).

<Figure 11.1 here>
Figure 11.1: Global energy investment, 2017-2021 (2021 estimated)
Note: Energy infrastructure includes midstream and downstream oil and gas infrastructure, electricity networks and batteries
Source: International Energy Agency, 2021, p. 6

This investment is broken down by sector in <Figure 11.2 here>

Figure 11.2. While it is encouraging that 70% of 2021 investment in power generation was estimated to go to renewables (and this share increased to an estimated 80% in 2022), less positive is that fossil fuel (coal and gas) power generation was still estimated to attract USD 100 billion, and USD 350 billion a year is still being spent upstream (i.e. exploration and production) in oil and gas, when the IEA makes clear that any new oil and gas wells or coal mines are inconsistent with its Net Zero Emissions (NZE) trajectory. The war between Russia and Ukraine in 2022 increased investment in fossil fuels – coal as well as oil and fossil methane gas (International Energy Agency, 2022, p. 16), but 2021 had also seen the approval of 30 GW of new coal-fired power plants (International Energy Agency, 2022, p. 43), which hardly reflects a 'phase-down' of coal – something to which countries committed themselves at the COP26 climate conference at the end of that year.

<Figure 11.2 here>
Figure 11.2: Global energy investment by sector, 2017-2021E
Source: International Energy Agency, 2021, p. 7

Total investment in clean energy technologies was expected to be over USD1,400 billion in 2022 (International Energy Agency, 2022, p. 11), with investment growing in both renewable power and energy efficiency, where an energy efficiency investment is defined as the incremental spending on new energy-efficient equipment or the full cost of refurbishments that reduce energy use. However, the IEA estimates that this will need to double even to meet all the NDCs and pledges made at COP26 (broadly consistent with the 2ºC Paris target), and triple to meet the 1.5ºC target (International Energy Agency, 2022, p. 24). The good news, as will be seen, is that such investment levels are perfectly feasible if the investment incentives (i.e. the ratios of risk to return) are right. The bad news is that there is currently a chronic shortage of projects that satisfy this requirement.

The IEA's 2021 conclusion was "Today's investment spending on fuels appears caught between two worlds: neither strong enough to satisfy current fossil fuel consumption trends nor diversified enough to meet tomorrow's clean energy goals." (International Energy Agency, 2021, pp. 11–12). Oil and gas prices started to rise in response to this situation in the latter part of 2021, a trend that was reinforced with a vengeance in 2022, especially in Europe, by the war in Ukraine. At the time of writing, it is still not clear what this will do to energy investment flows. In his 'A Call to Clean Energy' published in December 2022[3], the IEA Executive Director, noted that the high oil and gas prices could stimulate increased investment in renewables, or fossil fuels, but at the time was doing neither, running the risk of "the worst of both worlds" – ongoing high fossil fuel prices and excessive carbon emissions.

The scale of the investment challenge is most stark in the electricity sector, in which investments over 2011-2020, at around USD 1.5 trillion for the ten years, are not at the required level even to meet the 2026-2030 requirements of the IEA's Stated Policies Scenario (STEPS), let alone its Sustainable Development Scenario (SDS, broadly compatible with the Paris 2ºC) or its Net Zero Emissions (NZE) scenario (broadly compatible with the Paris 1.5ºC) (International Energy Agency, 2021, p. 22).

The increase in energy efficiency (as measured by the decline in the energy intensity of the world economy[4]) was only 0.8% in 2020, and needs to increase to 4% per year according to the NZE scenario. This too will require a significant increase in investment levels, in both energy efficiency and more efficient end use. The IEA estimates that the USD 300 billion total for 2016-2020 will need to increase in 2026-2030 to USD 700 billion for STEPS, to USD 1.1 trillion for SDS, and to over USD 1.4 trillion for NZE (International Energy Agency, 2021, p. 49). Of course, the greater the increase in energy efficiency, the lower the investment needs in new energy (electricity) supply. If the

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[3] Article in Finance and *Development*, published by the International Monetary Fund (IMF), December 22, 2022, https://www.imf.org/en/Publications/fandd/issues/2022/12/a-call-to-clean-energy-fatih-birol . Accessed April 24, 2023.

[4] Energy intensity is energy use divided by economic output.

investments in energy efficiency projections in these three scenarios do not materialise, then the scale of the investments in new supply in **Error! Reference source not found.** will have to be correspondingly greater.

The UNEP 2022 *Emission Gap Report* (United Nations Environment Programme, 2022) confirmed this substantial shortfall in the required investment to 2030 required to achieve net-zero emissions in 2050. The total investment required is USD 4-6 trillion per year, a factor increase of 3-6 across the global economy (United Nations Environment Programme, 2022, p. XXVI). Table 11.3 shows that the shortfall is across all economic sectors and regions, with AFOLU among the sectors, and developing countries, particularly falling short. The investment challenge is especially great for the Middle East, with its current heavy reliance on fossil fuels.

Sector	**Approx. current annual investment 2017-2020 (USD billion)**	**Factor increase in required annual mitigation investment to 2030**	
		Low	High
Energy efficiency	250	x2	x7
Transport	150	x7	x7
Electricity	300	x2	x5
Agriculture, forestry and other land use (AFOLU)	50	x10	x31
Type of economy			
Developing countries	400	x4 (4% GDP)	x7 (9%GDP)
Developed countries	350	x3 (2% GDP)	x5 (4% GDP)
Region			
East Asia	250	x2	x4
North America	150	x3	x6
Europe	200	x2	x4
South Asia	50	x7	x14
Latin America and Caribbean	50	x4	x8
Japan, Australia and New Zealand	50	x3	x7
Eastern Europe and West Central Asia	<50	x7	x15
Africa	<50	x5	x12
South East Asia and developing Pacific	<50	x6	x12
Middle East	<50	x14	x28

Table 11.3: Mitigation investment needs by sector, type of economy and region to 2030 for Net Zero by 2050
Source: Compiled from data in (United Nations Environment Programme, 2022, Figure 7.1, p.66), itself adapted from (Intergovernmental Panel on Climate Change, 2022b, Figure TS.25, p.134)

However, a brighter spot on the investment landscape was the investment in batteries for energy storage, which, as discussed in Chapter 5 will be critical for the stability of power systems when they have a high share of renewables. estimated battery storage investment doubled in 2022, with increases both at grid scale and 'behind the meter' (e.g. roof-top PV) (International Energy Agency, 2022, p. 54).

The low-carbon energy transition will not take place unless the very large required investments that have been identified in this section are mobilised and committed to the low-carbon technologies that require them – what is sometimes called ‘shifting the trillions’. (Polzin & Sanders, 2020) show that in principle the necessary investment is available in aggregate in the required quantity, but that there is often a mismatch between the types of funding that are available and the kinds of projects, or stage of the TRL journey, that they are able to fund. In addition to this, (Hafner et al., 2019, p. 6) identify numerous barriers to investment in activities to reduce emissions, including: immaturity or lack of climate change policy frameworks and stable policies; policies in favour of ‘brown’ energy infrastructure (e.g., fossil fuel subsidies); constraints on decision making within investor companies; returns on renewable infrastructure investments being too low to justify high initial capital investments, leading to limited projects with acceptable risk-return profiles; projects lacking an adequate credit rating; risk associated with uncertain and unproved technologies; lack of transparency of climate-related disclosure and data; lack of suitable financial vehicles/financial instruments; high transaction costs or fees; lack of knowledge/technical advice on green infrastructure investment. A particular problem in emerging and developing countries is the cost of capital. Financing costs can account for up to 60% of the total cost of renewables, and the cost of capital (CoC) in emerging and developing countries can be seven times that in developed countries, which reflects the level of risk perceived by private investors. (International Energy Agency, 2022, p. 39).

Country	**Cost of capital for solar PV projects (%)**	**Cost of electricity generated by solar PV (EUR/MWh)**
Sudan	25.2	32
Democratic Republic of Congo (DRC)	12.1	21
Italy	6.1	15
Peru	4.7	10
South Korea	3.8	12
Switzerland	3.1	13

Table 11.4: Cost of capital (CoC) for solar PV projects in selected countries (the source gives 152 countries), and the effect on the Levelised Cost of Energy (LCOE) in those countries.
Note: LCOE is a standard way of calculating the cost of an energy technology
Source: Egli et al., 2019, Figure 1, p.2

Table 11.4 shows the difference that this makes to the cost of solar PV projects Sudan and DRC, with much more sun than Switzerland, nevertheless generate more costly solar electricity because their cost of capital is eight and four times higher respectively. This explains why many developing countries, despite having much better solar resources, get far less investment in solar PV.

This, and barriers identified by (Hafner et al., 2019), comprise a formidable list of problems that will need to be solved if investments at the necessary scale are to flow into low-carbon technologies and infrastructure, especially in emerging and developing economies. Through the setting up of such financial sector initiatives as the Paris Aligned Asset Owners, the 53 members of which are said to have around USD 3.3 trillion under management[5], or the Glasgow Financial Alliance for Net Zero (GFANZ)[6], with its more than 500 members and reputed USD133 trillion under management or advice[7], it would appear that the financial sector has the appetite for low-carbon investment.

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[5] Paris Aligned Asset Owners – Investing for a net zero future. Accessed April 25, 2023.

[6] https://www.gfanzero.com/about/. Accessed April 25, 2023.

[7] https://www.argusmedia.com/en/news/2359675-gfanz-issues-draft-framework-for-net-zero-portfolios#:~:text=GFANZ%20is%20made%20up%20of,assets%20under%20management%20or%20advice. Accessed April 25, 2023.

Climate change represents substantial risk to investors in two distinct ways. The first risk derives from potential impacts from climate change. Any business that depends on resources that may be affected by climate change (energy, food, travel and tourism) is clearly subject to such risks. The second risk derives from businesses' own effect on the climate (e.g. fossil fuel companies). These are clearly at risk both from the sentiments of investors who care about climate change, and may avoid or engage critically with such companies, affecting their reputations, or from policy makers who seek to mitigate climate change in ways that affect their businesses (e.g. through carbon taxes, emissions trading systems, or, in the limit, banning certain uses of fossil fuels leading to stranded assets). These two sources of risk comprise the 'double materiality' of companies' exposure to climate change[8].

It was to enable investors to understand these risks that the Financial Stability Board in 2015 set up the Task Force on Climate-related Financial Disclosure (TCFD), which released its first guidance report in 2017[9], and recommendations as to the implementation of that guidance, by both the financial and other climate-exposed sectors (energy, transportation, materials and buildings, agriculture, food and forest products) in 2021[10]. While the 2022 TCFD status report concluded that more companies each year were reporting in line with at least some of the TCFD guidance and recommendations, it was also clear that "*more urgent progress* is needed in improving transparency on the actual and potential impact of climate change on companies" (The Task Force on Climate-related Financial Disclosures, 2022, p. 3).

Undoubtedly one of the barriers to businesses taking action on climate (and other environmental) issues is the plethora of reporting standards and methodologies with which they are confronted, and the complexities of calculating and reporting businesses' environmental impacts – measuring Scope 3 emissions (see Chapter 5) from global value chains can be particularly challenging. In order to standardise corporate reporting on climate and broader sustainability issues, the International Sustainability Standards Board (ISSB) released in 2022 for consultation its Exposure Draft of recommendations for climate-related disclosure[11]. It is to be hoped that such standards to simplify the sustainability reporting landscape will be readily agreed across both the financial and business communities, so that the information disclosed is material, comprehensive and comparable between companies.

The risk from climate change to the financial system is also being taken seriously by central banks and supervisors, who in 2017 set up the Network for Greening the Financial System (NFGS)[12], which in March 2023 had 123 members of central banks and supervisors. Governments are also legislating for disclosure of climate risks to become mandatory, for example, the EU's 2019 Regulation on Sustainability Related Financial Disclosure[13]. Furthermore, in order both to facilitate investments into zero-carbon and other environmentally beneficial areas, and also to prevent misleading environmental claims ('greenwashing') being made by the plethora of new supposedly responsible funds, many countries have now set up a Taxonomy to define the criteria according to which such claims can be made. One of the most advanced of these taxonomies is the one recently agreed by the EU, which describes it as an "EU-wide classification system for sustainable activities"[14]. The Taxonomy, embodied in a Regulation in 2020, grew out of the EU's 2018 Sustainable Finance Action Plan,

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[8] For a longer discussion of this, see https://www.lse.ac.uk/granthaminstitute/news/double-materiality-what-is-it-and-why-does-it-matter/. Accessed April 10, 2023.

[9] https://assets.bbhub.io/company/sites/60/2021/10/FINAL-2017-TCFD-Report.pdf. Accessed April 10, 2023.

[10] https://assets.bbhub.io/company/sites/60/2021/07/2021-TCFD-Implementing_Guidance.pdf. Accessed April 10, 2023.

[11] https://www.ifrs.org/content/dam/ifrs/project/climate-related-disclosures/issb-exposure-draft-2022-2-climate-related-disclosures.pdf. Accessed April 10, 2023

[12] https://www.ngfs.net/en/about-us/governance/origin-and-purpose. Accessed April 10, 2023.

[13] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32019R2088. Accessed April 10, 2023.

[14] https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en. Accessed April 25, 2023.

which, in addition to the Taxonomy, envisaged an EU Regulation on investors' duties and disclosures, and benchmarks for different economic activities to identify those which were most sustainable.

The Taxonomy itself sets out six environmental objectives (climate change mitigation, climate change adaptation, the sustainable use and protection of water and marine resources, the transition to a circular economy, pollution prevention and control, and the protection and restoration of biodiversity and ecosystems). To be 'sustainable' under the Taxonomy, an investment must make a positive contribution to at least one of these objectives, while doing no significant harm to any of the others.

However, both GFANZ and the EU Taxonomy are at the centre of controversy. A 2023 report from a climate research and campaigning group, Reclaim Finance[15], found that GFANZ members were still investing heavily in fossil fuels, accusing GFANZ of 'greenwashing' and its members of being 'climate arsonists'[16]. However, a number of investors dropped out of GFANZ in late 2022, and GFANZ itself watered down its objectives by leaving the UN's 'Race to Zero' campaign[17].

With respect to the EU Taxonomy, a row erupted in 2022 when the European Commission proposed to include in the list of 'sustainable activities' both nuclear power and certain fossil methane gas investments, which opponents again characterised as blatant examples of 'greenwashing'. However, the European Parliament passed the Commission's proposal in July 2022, whereupon the governments of Austria and Luxembourg, as well as Greenpeace, said that they would challenge this decision in the courts[18].

The purpose of these Taxonomies and 'responsible funds' is to facilitate investment in the businesses that are actually going to have to deliver Real Zero. There are now numerous organisations of businesses that claim that their members have credible commitments to decarbonisation in line with the temperature targets of the Paris Agreement. For example, the Climate Group claims a membership of over 500 multinational businesses in 175 markets[19]. The Science Based Targets initiative (SBTi) describes itself as "a global body enabling businesses to set ambitious emissions reduction targets in line with the latest climate science" (Science-Based Targets Initiative, 2022, p. 3).

According to the Carbon Trust, "a carbon emissions target is defined as science-based if it is in line with the scale of reductions required to keep [the] global temperature increase below 2°C above pre-industrial temperatures"[20]. The targets derive from a complicated methodology that seeks to allocate the carbon budgets for 2°C (or 1.5°C) to individual sectors, and thence to individual companies within those sectors. For 1.5°C this should involve a commitment to net-zero emissions by 2050. Founded in 2015, the SBTi's 2021 Progress Report claims that it is now working with 2,253 companies, of which 1,082 have science-based targets approved by SBTi, and the rest of which have commitments to adopt such targets. These companies have a market capitalisation of USD38 trillion, one third of the total.

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[15] https://reclaimfinance.org/site/en/2023/01/17/throwing-fuel-on-the-fire-gfanz-members-provide-billions-in-finance-for-fossil-fuel-expansion/. Accessed April 25, 2023.

[16] https://www.theguardian.com/environment/2023/jan/17/banks-still-investing-heavily-in-fossil-fuels-despite-net-zero-pledges-study?utm_source=UKERC+Communications+Preferences&utm_campaign=fa359f08b8-EMAIL_CAMPAIGN_2020_05_22_09_37_COPY_01&utm_medium=email&utm_term=0_fbad6d46e4-fa359f08b8-155429161. Accessed April 25, 2023.

[17] *Financial Times*, December 7, 2022, https://www.ft.com/content/48c1793c-3e31-4ab4-ab02-fd5e94b64f6b. Accessed 25 April, 2023.

[18] https://www.euronews.com/my-europe/2022/07/06/meps-back-controversial-eu-plan-to-label-nuclear-and-gas-investments-as-green. Accessed April 25, 2023.

[19] https://www.theclimategroup.org/about-us. Accessed April 10, 2023.

[20] https://www.carbontrust.com/news-and-insights/insights/what-exactly-is-a-science-based-target#:~:text=To%20put%20it%20simply%2C%20a,C%20above%20pre%2Dindustrial%20temperatures. Accessed April 10, 2023

(Science-Based Target Initiative, 2022, p. 6). As of April 2023, SBTi's website claimed it was working with 4799 companies, of which 1,748 had net-zero commitments[21].

Despite all the initiatives in the financial sector, such as GFANZ, NFGS and a sustainability Taxonomy in different countries, so far the barriers to low-carbon investment, and the continuing financial attraction of fossil fuel investments, seem to be preventing investors from committing their resources to the clean energy transition at anything like the required scale. For investors, it is clear that they do not yet take the risk of 'stranded assets' referred to in Chapter 5 at all seriously. Both the financial sector itself, and the policy makers that set the economic context in which they invest, have a huge task to dismantle these barriers to investment.

In respect of businesses, it is clear that initiatives such as the Climate Group and SBTi are not yet having a material effect on global emissions, which are still rising. Whatever businesses are doing to reduce their emissions, it is clear that they still need to do a lot more.

Labour markets, employment and skills

It is not only technologies that require huge investments. There is also the labour force that is required to design, build and maintain them. The International Renewable Energy Agency (IRENA) estimates that in 2020 the renewable energy sector employed around 12 million people globally (International Renewable Energy Agency, 2021), with the breakdown across renewables technologies as in Table 11.5

	Jobs (thousands)
Solar photovoltaic	3975
Liquid biofuels	2411
Hydropower	2182
Wind energy	1254
Solar heating/cooling	819
Solid biomass	765
Biogas	339
Geothermal energy	96
Municipal and industrial waste	39
CSP	32
Others	105

Table 11.5: Global renewable energy employment by technology in 2020
Source: (International Renewable Energy Agency, 2021, Figure 4, p.20)
Note: CSP is concentrated solar power; Others include tide, wave and ocean energy, and jobs not broken down by particular technology

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[21] https://sciencebasedtargets.org/. Accessed April 10, 2023.

At present China has over a third of these jobs, as shown in Table 11.6. All countries face the challenge, as the world decarbonises, of growing their renewable energy sector and capturing some of the enormous job opportunities that will be provided by these renewable technologies – IRENA estimates that, in a scenario compliant with the Paris 1.5ºC target, employment in this sector could grow to 38 million jobs by 2030 and 43 million by 2050. Some jobs (IRENA estimates 7 million) will be lost too, as some sectors, principally those supplying fossil fuels, downsize through the low-carbon transition. The transition employment challenge will be to ensure that there will be suitably qualified people to fill these new jobs. The majority of these jobs will not require high-level certification, although a fifth to a third of them will need STEM (science, technology, engineering, mathematics) professionals, depending on the technology (International Renewable Energy Agency, 2021, Figure 15, p.66.

	Jobs (thousands)
China	4732
EU	1300
Brazil	1202
United States of America	838
India	726
Germany	297
North Africa	23
Southern Africa	73
Rest of Africa	228

Table 11.6: Location of renewable energy jobs in selected countries in 2020
Source: (International Renewable Energy Agency, 2021, Figure 9, p.34)

Apart from the quantitative challenge of training this number of people to do these jobs, IRENA identifies four main ‘misalignments’ of the new, renewable sector, jobs, with those that will be lost: temporal misalignments, where jobs are lost before the new jobs are available; spatial misalignments, where the jobs lost are in different places to those gained; educational misalignments, where old skills are not required, and new skills need to be learned; and sectoral misalignments, where jobs lost in one sector need to be shifted to a completely different sector. Labour market policies will be crucial in seeking to smooth these misalignments as far as possible, so that people with the right skills are available in the right places at the right time in the right sectors as decarbonisation gathers pace. This will require an appropriate mix for the country concerned of on-the-job training, apprenticeships, formal vocational training and higher education.

The ‘energy transition scenario’ to 2030 of the International Labour Office gives further insights into the possible sectoral implications of the jobs gained and lost through decarbonisation (<Figure 11.3 here>
Figure), but also shows a substantial net gain in jobs in a wide range of sectors, with construction, mining, manufacturing, transport showing more than 3 million new jobs each.

<Figure 11.3 here>
Figure 11.3: Jobs gained and lost in different sectors in the ILO's energy transition scenario to 2030
Source: (International Labour Office, 2019, Figure 6.3, p.132)

Clearly the employment implications of decarbonisation will differ for different countries, depending on the availability of renewable energy sources, their level of development and their current economic and industrial structure. For the UK a modelling study carried out for the Climate Change Committee by Cambridge Econometrics indicated what might be expected in terms of employment in the meeting of the UK's target of net-zero emissions by 2050.

Cambridge Econometrics found that meeting the 2050 net-zero target would lead to a net increase of 300,000 jobs in the UK, job losses in some sectors being outweighed by job gains in others, as shown in Table 11.7. The biggest shift in employment, not surprisingly, is the loss of jobs in mining fossil fuels and refining them and the gain in renewables jobs in the utilities sector.

	Output		**Employment**	
(% difference from baseline)	*2030*	*2050*	*2030*	*2050*
Agriculture, etc.	4.5	4.3	4.2	2.9
Mining & Refinery	(19.0)	(42.9)	(7.8)	(11.0)
Utilities	20.5	34.6	4.5	35.5
Manufacturing & Construction	7.7	5.5	1.1	0.5
Distribution, Retail, Hotel & Catering	1.3	1.0	1.8	0.9
Transport & Communications	2.4	0.3	2.0	0.1
Services	1.8	1.7	0.2	0.0

Table 11.7: Change in sectoral employment between a scenario that meets the UK's target of net-zero emissions by 2050 and one based on current policies
Source: Cambridge Econometrics, 2020, Table 3.1, p.17

A sectoral breakdown such as that in Table 11.7 can hide job needs in particular industries that could, if not met, prove serious bottle-necks in decarbonisation. In the UK two such industries are the retrofit of buildings for energy efficiency and the installation of heat pumps. In respect of building retrofits, the Royal Institute of Chartered Surveyors (RICS) calculated in 2020 that achieving a high level of building energy efficiency would create 5.3-6.7 million jobs, of which 4.7-5.9 million were for retrofitting homes, and the rest retrofitting non-residential buildings[22]. In respect of heat pumps, a 2022 report from Nesta suggested that meeting the UK Government's target of installing 600,000 heat

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[22] https://ww3.rics.org/uk/en/journals/property-journal/retrofit--saving-energy-and-creating-jobs.html. Accessed April 25, 2023. This is calculated on the basis that investment of £1 million in retrofit creates 10-13 jobs, and the total retrofit investment requirement for retrofit is £444 billion. No timescale is given over which the investment would be made, and therefore how many jobs would be created each year.

pumps per year by 2028[23] would require 27,000 heat pump installers, a nine-fold increase from the current level of around 3,000[24]. This rate of required jobs and skills increase puts the achievement of targets in these areas in serious doubt, because there is as yet nothing like the training programmes required for heat pump installers, or the required commitment to home energy retrofits for decarbonisation by the middle of the century.

Economic growth

Some people call the very significant investments in energy efficiency and low-carbon electricity supply required for the NZE and related scenarios 'costs', and indeed they are very large expenditures. But they are more correctly termed investments, because they would provide the foundation for delivering energy services to 2050 and beyond. And investment is fundamental to delivering economic growth and prosperity in the future.

Economic growth has been one of the defining characteristics of the industrial age. Before the industrial revolution economic output person increased slowly if at all. Indeed, human societies did not think in these terms, and had no tools or metrics to measure aggregate economic output. Gross Domestic Product (GDP), and the related metrics of Gross National Product (GNP) and Net National Product (NNP), also called National Income (NI)[25], only became global standards in widespread use in the 1950s.

It is now well established in theories of economic growth that it is the product of the three factors that have been discussed in the previous three sections of this chapter: innovation, leading to technical change; investment leading to renewal, increase and improvement of the capital stock; and both the quantity and skills of the workforce. It is therefore to be expected that decarbonisation which, as has been seen, requires great innovation (in technology, business organisation and institutions), huge investment, and more jobs with enhanced skills, will generate economic growth, and such intuitions are borne out by the available evidence, only a small portion of which will be cited here.

A study which was particularly designed to illustrate the impact of decarbonisation on economic growth is Drummond et al. (2021), some results of which were also published in Ekins et al. (2022), from which the figures below are taken. The decarbonisation pathway of this study has already been shown in Chapter 2. Of more interest here is its impact on economic growth. For this scenario Figure 11.4 shows the relative contribution to global economic growth of population growth, and investment in technology and skills, leading to increases in the capital stock, greater productivity and technical progress. The growth of population peters out later in the century, but the economic change deriving from investment and technical progress persists, albeit at a lower rate.

<Figure 11.4 here>
Figure 11.4: Relative contribution to global economic growth to 2100 of investment, population growth and technical progress
Source: Ekins et al., 2022, Figure 12, p.11

The result of the global economy growing over the 21st century as in Figure 11.4 is that by 2100 it is five times its size in 2015 by 2100 (Ekins et al., 2022, Figure 13, p.12), with the share of investment

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[23] This was one the targets in the then Prime Minister's 2020 '10-Point Plan for a green industrial revolution', https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf. Accessed April 25, 2023.

[24] https://media.nesta.org.uk/documents/How_to_scale_a_highly_skilled_heat_pump_industry_v4.pdf. Accessed April 25, 2023.

[25] GNP = GDP plus net income from abroad; NNP = NI = GNP minus capital depreciation; Gross World Product (GWP) is the summation of the world's national GDPs

and public consumption in Gross World Product (GWP) gradually growing through the century. Given that GDP globally is the sum of investment and consumption, this must mean that private consumption must take a smaller share of world product. This is hardly surprising given the enormous investment that is required by the clean energy transition. It can hardly be imagined that poorer countries will reduce their consumption over this century. Therefore it will be the richer countries that will have to channel a greater proportion of their output into investment for the clean energy transition to come about. From thinking of themselves as 'consumer societies', they should begin to regard themselves as 'investor societies', holding back somewhat on their consumption so that they can make possible a clean energy future.

In this context, it needs to be remembered that the relation between investment and economic growth is a two-way street. It is certainly true that investment is a prime driver of economic growth, but it is also true that, in the currently existing economy of Western countries, it is the prospect of economic growth that drives further investment, especially from the private sector, which is where most of the investment for the clean energy transition is going to have to come from.

Outcomes from deep decarbonisation that show continuing economic growth are very much the norm in the scientific literature. <Figure 11.5 here>
Figure 5 shows the economic trajectories of five of the scenarios from the IPPC 1.5ºC scenarios database. The scenarios come from different economic models (REMIND, AIM, MESSAGE, WITCH), with different assumptions about the global socio-economic contexts in which they unfold (shown as S1, S2, S4, S5), and include the Low Energy Demand (LED) scenario that was also encountered in Chapters 2 and 3. For each scenario, except the LED, two lines are shown: the solid line is the baseline, a model run with no decarbonisation beyond current policies; the dashed line is the scenario with carbon emission reduction policies such that the 1.5ºC Paris temperature target is met.

Two broad messages are conveyed by <Figure 11.5 here>
Figure 5. The first is that GWP increases in all the 1.5ºC scenarios. The second is that GWP grows slightly slower with decarbonisation than in the baseline without it, i.e. there is a small net GWP cost associated with decarbonisation. However, this second conclusion is somewhat misleading, because the baselines do not take account of the damages associated with global warming, which the decarbonisation measures in the 1.5ºC scenarios are explicitly intended to reduce. Remembering the projected loss of GDP from global warming in Burke et al. (2018) (see Chapter 1), where even 2ºC or warming could result in a loss of 5% of GWP by mid-century, and perhaps 20% by 2100, it begins to seem that the cost of meeting the Paris targets is at worst good insurance, given the uncertainties of damages from climate change, and at best a strategy for economic growth, given the conservatism in the projection of cost reductions from low-carbon technologies that was revealed in Way et al. (2022, , Figure 5C, p.9), discussed earlier in this chapter.

<Figure 11.5 here>
Figure 11.5: Gross World Product (GWP) projections from the IPCC scenarios database
Source: Ekins et al., 2022, Figure 7, p.6. Data from Rogelj et al., 2018 and Huppmann et al., 2018

Such aggregate results for the world as a whole mask a wide range of different outcomes for different countries. For the UK there are good reasons to think that decarbonisation will lead to net economic benefits, even before counting the benefits of avoided climate damages, and 'co-benefits' (discussed below). This because, not only would the UK benefit from the economic boost of technical change and greater investment, but it would also reduce its imports of fossil fuels, substituting these with its own wind and solar resources. In its modelling for the Climate Change Committee's assessment of the Sixth Carbon Budget, Cambridge Econometrics found that achieving the UK's 2050 net-zero target would lead to an increase in UK GDP of 2% by 2030 and 3% by 2050 (Cambridge Econometrics, 2020).

It may seem surprising that the huge investments for decarbonisation, that manifest themselves as ‘costs’ for some businesses and households, should actually increase the prosperity of the economy as a whole. Cambridge Econometrics (2020, p. 14) explains that this is because the direct costs to industry/households are business opportunities and income to companies in other sectors. The overall impact of these costs/investments on the economy as a whole can only therefore be ascertained through the use of economic models that take all these interactions in the economy into account.

In the light of such evidence it is remarkable that the myth persists that decarbonisation in general, and UK decarbonisation in particular, will be unaffordably costly. For example, it is said that the Net Zero Scrutiny Group of UK Conservative Members of Parliament (MPs) believe that attempting to achieve the UK Government’s net-zero target for 2050 would be “economically and politically disastrous”[26]. Leaving the politics aside (though the YouGov poll in July 2022 showed 67% of those polled were either very or fairly worried about climate change, against 28% who were not[27]), these fears of unaffordability seem to derive either from a lack of understanding of macroeconomics, or from climate scepticism more generally, which it is no longer acceptable to admit to. The findings of the Net Zero Review of Chris Skidmore, also a Conservative MP, was designed to confront this economic scepticism head on. Part I of the Review was entitled ‘Net zero is the growth opportunity of the 21st century’. (Skidmore, 2023) His 129 recommendations showed in considerable detail how the UK Government, with industry, local government and civil society, could realise the economic benefits of this opportunity.

More surprising than the politically and ideologically charged views of the Net Zero Scrutiny Group are those of some academics and environmentalists who believe that decarbonisation at the required rate cannot be achieved without *reductions* in GDP, called ‘degrowth’, in rich countries at least. One review of the literature characterised degrowth “as a radical call for a voluntary and equitable downscaling of the economy” (Weiss et al., 2017, p.220). Kallis et al. 2018 (pp.292, 309) consider that degrowth “signifies radical political and economic reorganization leading to drastically reduced resource and energy throughput” which, because this was not “physically likely” with continuing economic growth, would require such growth to stop or go into reverse.

The core arguments of this literature are that economic growth has historically been associated with increased energy use and GHG emissions, that there is no evidence that this relationship can be sufficiently changed so that emissions fall at the required rate (i.e. that emissions can be adequately decoupled from economic growth), that some of the technologies shown to be necessary for achieving the 1.5°C target (e.g. CCS, BECCS, NETs, DACC) are either too risky or infeasible, and that therefore the size the global economy will need to shrink if environmental targets are to be met. If in this context the economies of developing countries are to continue to grow (as is generally considered desirable in this literature), the economies of rich countries will need to shrink proportionately more.

Ekins et al. (2022), where more references to the degrowth literature may be found, contested this view and the arguments that follow largely draw on that paper.

Global greenhouse gas (GHG) emissions, which are responsible for anthropogenic global warming, have increased along with growth in the economy since records began, as was seen earlier in this book with historically the emissions of the old industrial countries increasing most and first (see Figure 2.3), and global emissions increasing more or less steadily since 1960 (Figure 1.5).

This trajectory is not surprising, as the major part of GHGs are CO2 emissions, which come from burning fossil fuels. Fossil fuels have been the predominant source of energy since the Industrial

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[26] https://conservativehome.com/2022/03/31/tory-wars-over-climate-change-the-conservative-environment-network-v-the-net-zero-scrutiny-group/. Accessed April 25, 2023.

[27] https://docs.cdn.yougov.com/hdemoi825d/Internal_ClimateChangeTracker_220720_GB_W.pdf. Accessed April 25, 2023.

Revolution, and energy use is at the heart of most economic activity. The question now is, if emissions are reduced at the rate required to achieve the Paris target to limit global warming well below 2ºC, while aiming for 1.5ºC, can the economy keep on growing? In other words, can emissions be "decoupled" from economic growth to the required extent? As noted above, those advocating degrowth suggest that this is "physically unlikely".

Emissions (Em) from economic activity may be expressed as the product of four terms:

$$Em = P \cdot \frac{A}{P} \cdot \frac{En}{A} \cdot \frac{Em}{En}$$

where P is population, A is affluence, measured by GDP, En is energy use. A/P is therefore GDP per person, En/A reflects the energy per unit of GDP (the energy intensity of the economy), and Em/En is the emission intensity of energy.

Reducing emissions with ongoing growth in population (P) and GDP per person therefore requires more than proportional reductions in the energy intensity of the economy (En/A) and the emission intensity of energy (Em/En). As has been seen in earlier chapters of the book, this can come about in two main ways:

- increasing efficiency in the use of energy and structural changes in the economy whereby consumption of low-energy goods and services replaces consumption of high-energy goods and services (thereby reducing En/A);
- replacing fossil fuels with low- or zero-carbon energy sources (thereby reducing Em/En).

These developments occur in different countries in different ways and to different extents, but in those countries taking emission reduction most seriously, they have been driven by public policy stimulating and reinforcing some market forces and constraining others, as is discussed in some detail in the next chapter.

And these policies have worked. Between 1990 and 2016 the EU economy, for example, grew by more than 50%, while CO2 emissions from fuel combustion fell by 25% (Figure 11.6)

<Figure 11.6 here>
Figure 11.5: Gross domestic product (left axis) and CO2 emissions (right axis) from fuel combustion in the EU (EU-28, including the UK), 1990–2016
Source: Ekins et al., 2022, Figure 2, p.3

Moreover, European countries are not the only ones to have reduced CO2 emissions. 32 countries with populations greater than one million, including Jamaica, Japan, Singapore and USA outside Europe, reduced their territorial (production) carbon emissions over 2005-2019, while their economies kept growing. Moreover, this emission reduction applied to consumption emissions (production emission plus emissions from producing imports, minus emissions from producing exports) over the same period too (Hausfather 2021).

Given that the decarbonisation policies introduced by these countries have not achieved the rates of CO2 emission reduction to reach the Paris Agreement targets, it is very likely that such achievement will require a considerable intensification of the policies that have generated or reinforced these developments.

As input to the IPCC's Special Report on Global Warming of 1.5 °C (Rogelj et al., 2018), 90 decarbonisation scenarios in the modelling literature that were consistent with the 1.5 °C target were identified, using different modelling frameworks. As has been extensively discussed in earlier chapters, the modellers chose the values for the parameters in their scenarios in the following areas: developments

in economic structure and output; energy demand and efficiency; material demand and efficiency; use of low-carbon energy carriers and technology; availability and use of Carbon Capture and Storage (CCS) and Negative Emission Technologies (NETs); land use and the availability of biomass for energy; choice and implementation of policy measures; and costs of carbon reduction technologies. Many of the scenarios generated were in line with the Paris target of limiting warming to 1.5 °C by 2100. *All* the scenarios, a small sample of which are shown in <Figure 11.5 here>
Figure 5, showed continuing growth in the economy, as well as meeting the 1.5ºC climate target. None of the scenarios came anywhere near declines in economic output from the 2020 level (i.e. they all experienced economic growth). The scenarios therefore all exhibited the necessary "decoupling" of emissions from economic growth to reach the 1.5°C target.

To understand the economic results of these scenarios, it may be noted that economic growth for the world as a whole could be negatively affected by decarbonisation if reducing carbon emissions were to raise the cost of energy or reduce rates of technical progress. With renewable electricity now competitive with that produced from fossil fuels in many countries (International Renewable Energy Agency, 2022), as shown above in some detail, the cost impact on economic growth from the switch to zero-carbon energy sources seems likely to be limited and may even be positive. With regard to technical progress, this is likely to be stimulated by decarbonisation, rather than the reverse, with fossil-fuel industries being relatively mature and low-carbon energy generating whole new industries. It is therefore unsurprising that in these scenarios the global economy experienced continuing economic growth as it decarbonised in line with the Paris Agreement 1.5ºC target.

One critique in the degrowth literature of the evidence cited above (that deep decarbonisation is consistent with continuing economic growth throughout this century) is that the modelling approach that is adopted in these studies 'assumes' economic growth in the future. In fact, *all* projections of the future make assumptions about future technological and social developments. For example, projections of population growth assume some continuation or departure from the human relations and social norms that produce children and affect health and life expectancy. Economic growth, as was seen earlier in this chapter, arises from capital accumulation (investment), population growth, and technical progress. Such processes have been widely observed in many different countries over the past two hundred years. 'Assumptions' of economic growth are therefore based on a perception that, for the rest of this century at least, these processes will continue to produce economic growth. Given historical and current levels of investment and rates of technical change, and the investment and technical change that is required for decarbonisation, such a perception seems not unreasonable.

There are claims by those advocating degrowth that, notwithstanding the reduction in GDP, and therefore their average incomes, people in rich countries could still expect 'a good life' (O'Neill et al., 2018), although it is clear that persuading them of this would be politically challenging. Nor have the policies to bring about such a societal transformation, which might include "making social services growth-independent, reducing working hours, introducing basic incomes and a maximum wage, decelerating life and democratising (economic) decision-making" (Kuhnhenn et al., 2020, p. 9) been worked through in detail, with their economic and social, as well as their environmental implications, made apparent. (Keyßer & Lenzen, 2021, p. 9) acknowledge: "it is clear that a degrowth transition faces tremendous political barriers".

There is also the issue that, given the twin feedback between economic growth and investment (higher growth is driven by higher investment, but also prospects for growth drive higher investment), if degrowth were to occur, it is most unlikely that the huge investments required for decarbonisation would be forthcoming.

Even more than that, arguments that degrowth is necessary to achieve climate targets are a gift to those who, like the Net Zero Scrutiny Group referred to above, want to derail the decarbonisation agenda altogether. Given current life aspirations of the great majority of people in all countries, if degrowth were necessary to achieve deep decarbonisation, then it is vanishingly unlikely politically that such decarbonisation would be implemented by governments. Luckily, as has been argued here, there is no evidence that this is the case.

The degrowth debate includes consideration of necessary reductions of resource use and environmental impacts apart from GHG emissions, which are not discussed in this book. That said, many of the arguments rehearsed above, about the potential compatibility of environmental improvement with economic growth, seem to apply more widely (Ekins & Zenghelis, 2021).

Co-benefits of climate mitigation

The purpose of climate change mitigation policies is to reduce GHG emissions, and hence to reduce the extent of global warming and climate change. This reduction in emissions and climate change will have many effects on the natural environment, as well as on human societies, including reducing biodiversity and forest loss, ecosystem change, ice melt, ocean warming, and the intensity of extreme weather events, compared to a situation in which climate change proceeds as a result of current emission trajectories. These effects may be called the ‘ancillary environmental benefits’ of reducing climate change.

However, there may be other benefits to humans and the environment from reducing GHG emissions, that have nothing to do with the reduction in global warming that is the principal aim of emission reduction. Such benefits are here called the ‘co-benefits’ of climate mitigation, and they are the subject of this section.

Air pollution and health co-benefits

The most important co-benefit of climate mitigation derives from the reduction in local air pollution from the combustion of fossil fuels, as they are increasingly replaced by other energy sources. Premature and avoidable deaths from outdoor air pollution due to the burning of fossil fuels in 2015 was estimated at 3.61 million (Lelieveld et al., 2019, p. 7193), or 65% of all deaths from anthropogenic air pollution. For comparison, the World Health Organisation is currently estimating that global deaths from Covid 19 were 3.3 million[28]. Covid 19, of course, was a single pandemic event. The deaths from pollution from fossil fuels happen every year, year-in, year-out.

A more recent estimate of premature mortality from the smallest particles ($PM_{2.5}$) from burning fossil fuels (Vohra et al., 2021) put the figure for 2012 much higher, with a global estimate of 10.2 million premature deaths, with the highest burdens in China (3.91 million per year) and India (2.46 million per year). However, deaths in Europe (1.4 million per year) and the USA (355,000 per year) are also substantial. Of course, many of these deaths could be avoided by pollution control measures, as witnessed by the death rate from all sources of outdoor pollution in China falling by 30-50% over 2013-2018 (Zhai et al., 2019). But these premature deaths could be removed forever by stopping the burning of fossil fuels completely, through attaining Real Zero.

The Centre for Research on Energy and Clean Air (CREA) estimated the monetary costs of this level of air pollution from fossil fuels (Myllyvirta, 2020). The 20 countries with the highest absolute costs, and when those are expressed as a share of GDP, are shown in Table 11.8. The total cost of the pollution in 2018, taking account of premature death, the costs of healthcare and of loss of labour participation and productivity was USD1.2 trillion, or 3.3% of GDP. The highest costs per person are in more affluent countries, which tend to have a higher valuation per year of life lost and more expensive healthcare systems. The highest cost in terms of GDP was in less wealthy countries with

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[28] https://www.who.int/data/stories/the-true-death-toll-of-covid-19-estimating-global-excess-mortality. Accessed April 10, 2023.

high levels of pollution and a relatively high level of chronic diseases (China, and the Central and Eastern European countries in the % GDP part of the table).

Highest cost per capita by country/region (USD)		**Highest cost as % of GDP by country/region**	
Luxembourg	2600	China Mainland	6.6%
United States	1900	Bulgaria	6.0%
Switzerland	1900	Hungary	6.0%
Austria	1700	Ukraine	5.8%
Germany	1700	Serbia	5.8%
Netherlands	1200	Belarus	5.4%
Denmark	1200	India	5.4%
Norway	1100	Romania	5.3%
Belgium	1100	Bangladesh	5.1%
South Korea	1100	Moldova	5.0%
Canada	1100	Poland	4.9%
Czech Republic	1000	Slovak Republic	4.8%
Italy	1000	Bosnia and Herzegovina	4.6%
United Kingdom	1000	Czech Republic	4.5%
Japan	1000	Croatia	4.4%
Hungary	1000	Lithuania	4.2%
Slovak Republic	900	Russian Federation	4.1%
Slovenia	900	North Macedonia	4.1%
France	800	Georgia	4.0%
Lithuania	800	Montenegro	3.8%
Ireland	800	Latvia	3.6%
		Germany	3.5%
		Kosovo	3.4%

		Slovenia	3.4%
		South Korea	3.4%

Table 11.8: Countries with the highest costs of air pollution from fossil fuels in USD, per capita and as a percentage of GDP
Source: Myllyvirta, 2020, p. 6, https://energyandcleanair.org/wp/wp-content/uploads/2020/02/Cost-of-fossil-fuels-briefing.pdf. Accessed May 6, 2023,

The Organisation for Economic Cooperation and Development (OECD) (Roy & Braathen, 2017) estimated the monetary costs of mortality in 41 countries due to outdoor air pollution (from all sources, not just fossil fuels) in 2015 to be USD 5.1 trillion, or 6.7% of world GDP at that date. Their breakdown of these costs across different countries, as a percentage of the countries' GDP, showed that air pollution in the Russian Federation, India and Latvia cost those countries the equivalent of more than 10% of their GDP (Roy & Braathen, 2017, Figure 4, p.23).

A move to clean fuels would also much reduce the deaths from exposure to household air pollution indoors, which the World Health Organisation (WHO) estimates was responsible for an estimated 3.2 million deaths per year in 2020, and in 2019 the loss of 86 million healthy life years[29].

Of course, outdoor and indoor air pollution also cause significant illness, short of death. Barwick et al, 2018 calculated that in China in 2015 annual expenditure on illness from air pollution in excess of WHO's standard for $PM_{2.5}$ was USD 42 billion, or 7% of China's expenditure on health care in that year[30].

Combustion of fossil fuels is not the only cause of air pollution in urban areas. The wear and tear of roads, brakes and tyres from road traffic are also a major cause of the small particles ('particulate matter', PM_{10} and $PM_{2.5}$, with the numerical subscripts referring to their size) that are particularly damaging to health. In the low-carbon scenario for the UK of (Lott et al., 2017, Figure 6, p.48), the large-scale replacement of internal combustion engines by electric vehicles by 2050 reduced PM_{10} emissions only by around 10% compared to 2010, and $PM_{2.5}$ emissions only by around 30%, due to the growth of traffic over this period. Really deep reductions in the "around 40 000 deaths related to air pollution per year in the UK" (Jennings et al., 2020, p. e426) will require road traffic levels to be reduced as well, through investment in public transport and an increase in active travel (walking and cycling) over short distances. Of course, the latter would bring further health benefits (Avila-Palencia et al., 2018), and less traffic would reduce the economic costs of congestion in urban areas, the cost of which in London in 2019 was estimated at GBP 6.9 billion, with drivers each spending an average of 149 hours 'stuck in traffic'[31].

The International Monetary Fund (IMF) classifies air pollution from fossil fuel use as a subsidy to that use, in addition to explicit monetary subsidies to the production or use of fossil fuels, and foregone consumption taxes. The IMF's world total of such subsidies in 2020 comes to a mind-boggling USD 5.9 trillion, or 6.8% of world GDP (International Monetary Fund, 2021). Its detailed calculations show that the costs of air pollution and climate change are both considerably larger than the explicit subsidies to fossil fuel producers and consumers and foregone consumption taxes (International Monetary Fund, 2021, Figure ES3, p.4). On this reading, the co-benefits from reduced air pollution

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[29] https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health. Accessed April 25, 2023.

[30] 'The Morbidity Cost of Air Pollution: Evidence from Consumer Spending in China', mimeo, https://barwick.economics.cornell.edu/Morbidity%20Cost.pdf. Accessed April 25, 2023.

[31] https://www.autoexpress.co.uk/car-news/consumer-news/94871/traffic-jams-costs-in-the-uk. Accessed April 25, 2023.

would considerably outweigh the primary benefit of reduced global warming. The IMF further estimates that removing these subsidies in 2025 "would reduce global carbon dioxide emissions by 36% below baseline levels, which is consistent with the 1.5ºC target, would raise revenues worth 3.8% of global GDP and prevent 0.9 million deaths from local air pollution each year". (International Monetary Fund, 2021, p. 2)

Energy efficiency and health co-benefits

Chapter 3 laid out the importance of energy efficiency in reducing carbon emissions, with residential buildings offering major opportunities for improvement. In countries with cold winters and an energy-inefficient housing stock, like the UK, increasing the energy efficiency of housing would offer considerable health benefits in addition to emission reduction. The five-year moving average of excess winter deaths in the UK to 2018-2019 (pre-Covid) was 36,162[32]. Jennings et al. (2020, p. e426) report that in 2016 about a third of these deaths were attributable to living in a cold home, and that energy efficiency measures that result in warmer homes could save the UK National Health Service GBP 2.5 billion per year from avoided use of health services. The 2009 report of the UK Chief Medical Officer estimated that £1 invested in energy efficiency would save the NHS GBP 0.42[33]. It is important also to note that, to avoid negative health outcomes from retrofitting homes for energy efficiency, proper ventilation must be ensured.

The cost of heating in cold climates has led, in countries with cold winters and energy-inefficient housing, to the phenomenon of fuel poverty, which leads to a pernicious cycle of impacts, not just on health, but on education, work, and the economy. Figure 11.7 shows how this can be turned into a virtuous cycle by an improvement in the energy efficiency of the housing of the fuel-poor. The vicious cycle shows that poor communities are more likely to live in efficient homes, which they cannot afford to heat adequately, so that they get ill, with children missing school and adults missing work, imposing costs on the National Health Service (NHS), and reducing household income still further. Improving the energy efficiency of their home initiates a virtuous cycle. It saves them money, so that they can afford more heating, which is good for their health, reducing their use of the NHS, so that children get more education and adults miss fewer days at work. Their productivity and incomes increase. Taxes rise and NHS expenditure is reduced.

<Figure 11.7 here>
Figure 11.7: Multiple impacts of improvements in the energy efficiency of the housing of fuel-poor households
Note: the crosses indicate how the energy efficiency intervention breaks links in the cycle of poverty and achieves multiple benefits in respect of personal and financial circumstances, health, education, work, and the economy
Source: Jennings et al., 2020, Figure 2B, p.e428

Low-meat diets and health co-benefits

Chapter 10 showed that GHG emissions from the food system were about a quarter of the global total, and that 80% of these emissions came from livestock. It showed the importance of low-meat diets to emission reduction. Springmann et al. (2016) estimated both the health benefits and emission reductions of a healthy global diet (HGD), a healthy vegetarian diet (VGT) and a healthy vegan (VGN) diet, "which maintained the regional character of food consumption", against a reference diet,

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[32] https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/bulletins/excesswintermortalityinenglandandwales/2020to2021provisionaland2019to2020final. Accessed April 25, 2023.

[33] http://www.sthc.co.uk/Documents/CMO_Report_2009.pdf. Accessed April 25, 2023.

projected to 2050 by the Food and Agriculture Organisation (FAO). HGD comprised, per day, a "minimum of five portions of fruits and vegetables, fewer than 50 g of sugar, a maximum of 43 g of red meat, and an energy content of 2,200–2,300 kcal, depending on the age and sex composition of the population" (Springmann et al., 2016, p. 4147).

Their calculations suggest that HGD could avoid 5 million deaths annually, with VGT and VGN increasing that to more than 7 million and 8 million respectively (Springmann et al., 2016, Figure 1, p.4148). The largest number of avoided deaths comes from reduced red meat consumption. The change in diets also reduced the cost of illness: by USD 735 billion per year for HGD, and by 32% and 45% more than that for VGT and VGN respectively, these reduced costs amounting to 2.3-3.3% of world GDP.

Along with these health benefits comes emission reduction. HGD reduces emissions from the reference case by over 3 GtCO2e (although this is still 7% more than food-related emissions in 2005/07), with both VGT and VGN reducing them more than twice that. In each case the biggest reductions come from reduced red meat consumption. Although in absolute terms emission reductions in developing countries were larger than in developed countries, per person the reductions were twice as large in developed countries, because of their much larger consumption of red meat. However, even VGN results in food-related emissions of 3.5 GtCO2e in 2050, so that it is not consistent by itself with net zero targets, and would need to be supplemented by significant reductions in deforestation, afforestation or other carbon removals from the atmosphere for net zero to be achieved.

Environment and ecosystem co-benefits

Chapter 7 showed that a range of natural processes on land and in the oceans, termed natural climate solutions (NCS), could remove CO2 from the atmosphere. NCS are a subset of a broader category of beneficial environmental interventions 'nature-based solutions' (NbS), which (Seddon et al., 2020 Box 1, p.2), define as "a wide range of actions, such as the protection and management of natural and semi-natural ecosystems, the incorporation of green and blue infrastructure in urban areas, and the application of ecosystem-based principles to agricultural systems".

Like any environmental interventions NbS involve risks of damage if implemented inappropriately, but Seddon et al. (2020) give many examples of how "well-designed NbS that incorporate diverse native species, avoid damaging biodiverse ecosystems and respect social safeguards offer good opportunities for mitigation with key benefits for local people". (Seddon et al., 2020, p. 4). These include, in different countries: protection from erosion, inland flooding, coastal hazards and sea level rise; moderating urban heat waves and heat island effects; managing storm water and flooding in urban area; sustaining natural resources in drier and more variable climates; buffering communities from climate shocks by enhancing and diversifying ecosystem services; empowering communities; and improving governance and access to resources (Seddon et al., 2020, Table 1, pp.3-4). The money values of these benefits are not estimated, but they would be significant.

Conclusion

The first conclusion to note about the economic implications of the clean energy transition is that nowhere in the scientific literature is it suggested that it will result in negative economic growth. On the contrary, the least optimistic of the IPCC scenarios reviewed above (S2 in Figure 11.5) suggests that a 1.5^{o}C scenario will result in the economy growing over 2010-2100 from around USD 62 trillion to around USD 300 trillion. It should also be noted that the 'baseline' projections of global output (without large-scale emissions reductions) in these scenarios take no account of climate change, because of uncertainties in modelling this. Yet it is clear from the earlier discussion in this chapter of climate risks to the global financial system, and the likely impacts of climate change noted earlier in this book, that it is highly likely that investing to reduce emissions to meet the Paris temperature targets is, for the world as a whole, the most profitable strategy in which it could engage.

These investments in the decades to 2050 will need to come from the rich countries reducing the share of consumption in their GDPs. Coupled with the innovation in new technology this investment will support, the growth in investment is more likely to increase these countries' economic growth rates than reduce them, especially if low-carbon technologies continue to experience the dramatic rates of cost reduction that have been seen in recent years. In fact, such cost reductions, taking the cost of clean energy technologies below those of fossil fuels, could mean that a global clean energy transition has higher rates of economic growth than continuing on the current fossil-fuelled path even when climate damages are not taken into account.

Most of the new technologies and investments will be deployed by businesses. Those businesses that grasp the opportunities will be the global businesses of the future, but to attract the investment they need they will have to become more transparent in their reporting of climate (and other environmental) risks. The standardising of reporting to enable them to show their leadership over other companies is well under way. It will increasingly become mandatory.

In addition to potentially higher rates of growth, the clean energy transition could lead to higher employment than sticking with fossil fuels. But many of the new jobs will need different skills to the old, and there is a huge training and re-training challenge that is currently hardly being addressed in many countries.

Finally, it has been seen that the 'co-benefits' of climate change mitigation go much wider than the reduction of climate damages, even if that is their main purpose. In particular, the replacement of fossil fuels with the far more energy-efficient use of clean fuels could bring about major improvements in public health, through the reduction of outdoor air pollution. In addition, there would be very significant health benefits, as well as emission reductions, from moving to healthier diets, in particular in respect of reduced red meat consumption in countries where it is excessive, and environmental co-benefits from using nature-based solutions to remove CO2 from the atmosphere. With their more extensive definition of 'co-benefits', the systematic literature review of (Deng et al., 2017) identifies further co-benefits relating to greater efficiency of material resource use, and greater energy and food security.

These co-benefits are not only important in respect of their addition to the quantity of the overall benefits of climate change mitigation. They are also significant because they improve the lives of people in the here and now, whereas the benefits from reducing global warming can often be seen to accrue mainly to future generations. An emphasis on the co-benefits of GHG emission reduction from the mitigation of climate change may serve to make the policies to bring about such emission reduction, reviewed in the next chapter, easier to implement.

References

Avila-Palencia, I., Int Panis, L., Dons, E., Gaupp-Berghausen, M., Raser, E., Götschi, T., Gerike, R., Brand, C., de Nazelle, A., Orjuela, J. P., Anaya-Boig, E., Stigell, E., Kahlmeier, S., Iacorossi, F., & Nieuwenhuijsen, M. J. (2018). The effects of transport mode use on self-perceived health, mental health, and social contact measures: A cross-sectional and longitudinal study. *Environment International*, *120*, 199–206. https://doi.org/10.1016/j.envint.2018.08.002

Burke, M., Davis, W. M., & Diffenbaugh, N. S. (2018). Large potential reduction in economic damages under UN mitigation targets. *Nature*, *557*(7706), 549–553. https://doi.org/10.1038/s41586-018-0071-9

Cambridge Econometrics. (2020). *Economic Impact of the Sixth Carbon Budget*. Cambridge Econometrics for the Climate Change Committee, Cambridge. https://www.theccc.org.uk/publication/economic-impact-of-the-sixth-carbon-budget-cambridge-econometrics/. Accessed May 6, 2023.

Deng, H.-M., Liang, Q.-M., Liu, L.-J., & Anadon, L. D. (2017). Co-benefits of greenhouse gas mitigation: a review and classification by type, mitigation sector, and geography. *Environmental Research Letters*, *12*(12), 123001. https://doi.org/10.1088/1748-9326/aa98d2

Drummond, P., Scamman, D., Ekins, P., Paroussos, L., & Keppo, I. (2021). *Growth-positive zero-emission pathways to 2050*. Sitra, Helsinki. https://www.sitra.fi/en/publications/growth-positive-zero-emission-pathways-to-2050/

Egli, F., Steffen, B., & Schmidt, T. S. (2019). Bias in energy system models with uniform cost of capital assumption. *Nature Communications*, *10*(1), 4588. https://doi.org/10.1038/s41467-019-12468-z

Ekins, P., Drummond, P., Scamman, D., Paroussos, L., & Keppo, I. (2022). The 1.5°C climate and energy scenarios: impacts on economic growth. *Oxford Open Energy*, *1*. https://doi.org/10.1093/OOENERGY/OIAC005

Ekins, P., & Zenghelis, D. (2021). The costs and benefits of environmental sustainability. *Sustainability Science*, *16*(3), 949–965. https://doi.org/10.1007/s11625-021-00910-5

Grubb, M., McDowall, W., & Drummond, P. (2017). On order and complexity in innovations systems: Conceptual frameworks for policy mixes in sustainability transitions. *Energy Research & Social Science*, *33*, 21–34. https://doi.org/10.1016/J.ERSS.2017.09.016

Hafner, S., James, O., & Jones, A. (2019). A Scoping Review of Barriers to Investment in Climate Change Solutions. *Sustainability*, *11*(11), 3201. https://doi.org/10.3390/su11113201

Hausfather 2021 *Absolute decoupling in 32 countries*, (data: territorial and consumption emissions from the Global Carbon Project; GDP data from the World Bank World Development Indicators database), Breakthrough Institute , California https://thebreakthrough.org/issues/energy/absolute-decoupling-of-economic-growth-and-emissions-in-32-countries. Accessed April 25, 2023.

Huppmann, D., Rogelj, J., Kriegler, E., Krey, V., & Riahi, K. (2018). A new scenario resource for integrated 1.5 °C research. *Nature Climate Change*, *8*(12), 1027–1030. https://doi.org/10.1038/s41558-018-0317-4

Intergovernmental Panel on Climate Change. (2022a). *Summary for Policymakers. In: Climate Change 2022: Mitigation of climate change, Working Group III contribution to the IPCC Sixth Assessment Report*. IPCC, Geneva.

Intergovernmental Panel on Climate Change. (2022b). *Technical Summary. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (P. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, Pathak. M., S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, & J. Malley, Eds.). Cambridge University Press, Cambridge/New York. https://doi.org/10.1017/9781009157926.002

International Energy Agency. (2021). *World Energy Investment*. IEA, Paris.

International Energy Agency. (2022). *World Energy Investment 2022*. IEA, Paris.

International Labour Office. (2019). *Skills for a Green Future: a Global View*. ILO, Geneva. https://www.ilo.org/wcmsp5/groups/public/---ed_emp/documents/publication/wcms_732214.pdf. Accessed May 6, 2023.

International Monetary Fund. (2021). *Still Not Getting Energy Prices Right: A Global and Country Update of Fossil Fuel Subsidies*. IMF, Washington DC

International Renewable Energy Agency. (2021). *Renewable Energy and Jobs: Annual Review 2021.* IRENA, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_RE_Jobs_2021.pdf?rev=98960349dbab4af78777bc49f155d094. Accessed May 6, 2023

International Renewable Energy Agency. (2022). *Renewable Power Generation Costs in 2021*. IRENA, Abu Dhabi. https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021. Accessed May 6, 2023.

Jennings, N., Fecht, D., & De Matteis, S. (2020). Mapping the co-benefits of climate change action to issues of public concern in the UK: a narrative review. *The Lancet Planetary Health*, *4*(9), e424–e433. https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(20)30167-4/fulltext. Accessed May 6, 2023.

Keyßer, L. T., & Lenzen, M. (2021). 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. *Nature Communications*, *12*(1), 2676. https://doi.org/10.1038/s41467-021-22884-9

Kuhnhenn, K., Costa, L., Mahnke, E., Schneider, L., & Lange, S. (2020). A Societal *Transformation Scenario for Staying Below 1.5°C*. Heinrich Boell Foundation, Berlin, Https://Www.Boell.de/En/2020/12/09/Societal-Transformation-Scenario-Staying-below-15degc.

Lelieveld, J., Klingmüller, K., Pozzer, A., Burnett, R. T., Haines, A., & Ramanathan, V. (2019). Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proceedings of the National Academy of Sciences*, *116*(15), 7192–7197. https://doi.org/10.1073/pnas.1819989116

Lott, M. C., Pye, S., & Dodds, P. E. (2017). Quantifying the co-impacts of energy sector decarbonisation on outdoor air pollution in the United Kingdom. *Energy Policy*, *101*, 42–51. https://doi.org/10.1016/j.enpol.2016.11.028

Myllyvirta, L. (2020). *Quantifying the economic costs of air pollution from fossil fuels*. Centre for Research on Energy and Clean Air (CREA), https://energyandcleanair.org/wp/wp-content/uploads/2020/02/Cost-of-fossil-fuels-briefing.pdf. Accessed May 6, 2023.

O'Neill, D. W., Fanning, A. L., Lamb, W. F., & Steinberger, J. K. (2018). A good life for all within planetary boundaries. *Nature Sustainability*, *1*(2), 88–95. https://doi.org/10.1038/s41893-018-0021-4

Polzin, F., & Sanders, M. (2020). How to finance the transition to low-carbon energy in Europe? *Energy Policy*, *147*, 111863. https://doi.org/10.1016/J.ENPOL.2020.111863

Rogelj, J., Popp, A., Calvin, K. v., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., … Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, *8*(4), 325–332. https://doi.org/10.1038/s41558-018-0091-3

Roy, R., & Braathen, N.-A. (2017). *The Rising Cost of Ambient Air Pollution thus far in the 21st Century: Results from the BRIICS and the OECD Countries*. OECD, Paris.

https://www.oecd-ilibrary.org/environment/the-rising-cost-of-ambient-air-pollution-thus-far-in-the-21st-century_d1b2b844-en. Accessed May 6, 2023.

Science-Based Target Initiative. (2022). *Science-Based Net Zero: Scaling urgent corporate climate action worldwide. Progress Report 2021*. https://sciencebasedtargets.org/reports/sbti-progress-report-2021

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

Skidmore, C. *Mission Zero: the Independent Review of Net Zero*, His Majesty's Government, London, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1128689/mission-zero-independent-review.pdf. Accessed April 25, 2023

Springmann, M., Godfray, H. C. J., Rayner, M., & Scarborough, P. (2016). Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences*, *113*(15), 4146–4151. https://doi.org/10.1073/pnas.1523119113

The Task Force on Climate-related Financial Disclosures. (2022). *Task Force on Climate-related Financial Disclosures: 2022 Status Report*. https://assets.bbhub.io/company/sites/60/2022/10/2022-TCFD-Status-Report.pdf

United Nations Environment Programme. (2022). *Emissions Gap Report 2022: The Closing Window - Climate crisis call for transformation of societies*. UNEP, Nairobi.

Vohra, K., Vodonos, A., Schwartz, J., Marais, E. A., Sulprizio, M. P., & Mickley, L. J. (2021). Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem. *Environmental Research*, *195*, 110754. https://doi.org/10.1016/j.envres.2021.110754

Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2022). Empirically grounded technology forecasts and the energy transition. *Joule*. https://doi.org/10.1016/j.joule.2022.08.009

Zhai, S., Jacob, D. J., Wang, X., Shen, L., Li, K., Zhang, Y., Gui, K., Zhao, T., & Liao, H. (2019). Fine particulate matter (PM&lt;sub&gt;2.5&lt;/sub&gt;) trends in China, 2013–2018: separating contributions from anthropogenic emissions and meteorology. *Atmospheric Chemistry and Physics*, *19*(16), 11031–11041. https://doi.org/10.5194/acp-19-11031-2019