Notes

Preface

1. See Howson (2011).

2. A number of independent enquiries, including one from the UK Parliament and one in which the Royal Society (the leading scientific society in the UK) was involved, have indicated that the work of the UEA scientists was sound. See the following UEA website for details: http://www.uea.ac.uk/mac/comm/media/press/CRUstatements/independentreviews.

3. This is the usual benchmark, representing a period before “hydrocarbon growth” took hold on a large scale.

4. See, for example, the World Bank 2012 report “Turn Down the Heat” (World Bank 2012b).

Introduction

1. Throughout the book, with regard to countries, I use the adjectives “developed,” “rich,” and “high-income” (and their opposites) interchangeably and in an intentionally rough sense, unless a more precise meaning is specified.

Chapter 1

1. This book focuses on the impact on the lives and livelihoods of humans. However, climate change has wide influence over the planet’s natural ecosystems, affecting biodiversity and endangering many species of animals.

2. For the most part, we do not distinguish in our discussions between risk and uncertainty; but when we do, we speak of “uncertainty” in the Knightian sense of unknown probabilities. See also Smith and Stern (2011) for an examination of the different types of risk and uncertainties and their potential influence in policy discussions.

3. CO_2e is "carbon dioxide equivalent." It is the expression of greenhouse gases in terms of the CO_2 that would generate the equivalent amount of warming potential as measured over a specific timescale (typically 100 years); ppm (parts per million) is the ratio of the number of GHG molecules to the total number of molecules of dry air.

4. Including halogenated hydrocarbons such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs).

5. Radiative forcing is the change in average net radiation that occurs because of a change in the concentration of a GHG or some other change in the climate system, such as in levels of solar radiation (Houghton 2004). It is typically measured at the top of the troposphere (the lower atmosphere up to around 10 km altitude, where temperature begins to fall with height).

6. See NASA Earth Observatory (2014); Met Office Hadley Centre (2013); Berkeley Earth (2011).

7. See, for example, IEA (2012e and 2013e); Stern (2013); Rogelj, Meinshausen, and Knutti (2012); and tables 1.1 and 1.2. To learn more about the science, consult the learned scientific societies, such as the US National Academy of Sciences and the UK Royal Society.

8. See also box 4.2 in chapter 4 on possible impacts on lives and livelihoods of 4°C warming.

9. Lüthi et al. (2008).

10. Pagani et al. (2009).

11. See, for example, Zachos, Dickens, and Zeebe (2008).

12. I am grateful to Liz Moyer and David Archer (of the Department of the Geophysical Sciences at the University of Chicago) for guidance on this evidence.

13. Stewart and Stringer (2012). See also http://www.worldmuseumofman.org/hum.php.

14. Stringer (2007); IPCC (2007); Törnqvist and Hijma (2012).

15. See Marcott et al. (2013) or Alley (2004). The Intergovernmental Panel on Climate Change *Fourth Assessment Report* (IPCC 2007), chapter 6, implies that estimates of Northern Hemisphere temperature fluctuations for the last 2,000 years are within ±1°C of mid-nineteenth-century temperatures. Looking further back, there is little evidence of global temperature outside this range for the last 7,000 years or so of the Holocene. We make such statements with caution as the proxy data have their limitations, but the point is clear: the temperature rise observed during the late twentieth century appears unprecedented in the history of modern human civilization.

16. The magnitude and potential duration of such impacts have led some to suggest that we should regard current times as the beginning of a new geological epoch, dubbed the Anthropocene (Crutzen 2002). We are not only contemplating temperature increases which are, in many ways, unknown territory, but also CO_2 is very hard to extract and may last for hundreds of years in the atmosphere.

And damage from some impacts of these changes, such as desertification or inundation, can be very long-lasting.

17. See Stern (2013) for a description of the possible impacts at 4°C or warmer.

18. World Bank (2012b), xiii; see also World Bank (2013a).

19. An era called the "Green Sahara" or the African Humid Period: see deMenocal and Tierney (2012) for more information and further reading.

20. See, for example, Hsiang and Meng (2014); Hsiang, Burke, and Miguel (2013); Hsiang, Meng, and Cane (2011); Gemenne (2011); Royal Society (2011); Steinbruner, Stern, and Husbands (2012), box 1.2 and the section on disruptive migration; Licker and Oppenheimer (2013); Gilmore et al. (2013); and the January 2012 "Special Issue on Climate Change and Conflict," *Journal of Peace Research*.

21. See also IEA (2012e and 2013e), where probabilities of exceeding 4°C are 37–83% based on scenarios of current and new policies; Stern (2013); Rogelj, Meinshausen, and Knutti (2012).

22. See Meinshausen (2006).

23. Including the need for more accurate reporting from media outlets and other public sources of information. See chapter 10 for a further discussion.

24. See Ward (2013).

25. A review of the 2°C target was launched at the UNFCCC meeting in Doha in late 2012.

26. Current global data on CO_2e emissions is limited to the year 2010, which is the most recent dataset at the time of writing this book, despite some national updates on CO_2 emissions. See chapter 7 for information.

27. That is the approximate emissions target used by the Global Commission on the Economy and Climate, drawing on the IPCC report (2014b), but it does make strong assumptions about zero or negative emissions toward the end of the century (GCEC 2014).

28. See also the work of Myles Allen on cumulative emissions, e.g., Allen et al. (2009).

29. See chapter 12 in Working Group 1 of IPCC (2013). Note that there is a subtle interplay between probabilities of reaching certain trajectories (e.g., a chance of at least 50% or 66%) and accurate measurements of CO_2 emissions levels, its equivalents, or non-CO_2 forcings.

30. Bearing in mind that data limitations restrict us to calculating "CO_2 budgets" as opposed "CO_2 equivalent budgets." CO_2 is the most important driver of radiative forcing, the gas that is easiest to measure, and is long-lasting in the atmosphere.

31. See Vivid Economics (2011).

32. Unless otherwise specified, dollar references in this book are to US dollars ($).

33. See IEA (2011f).

34. In the language of statistics, the former case, the false alarm, is termed a Type I error and the second, a false negative, a Type II error.

35. Many of these methods of denial—and how they are financed—are discussed in two excellent books: Oreskes and Conway (2010) and Michaels (2008).

36. See the books cited by Oreskes and Conway (2010) and Michaels (2008).

37. See http://www.skepticalscience.com/argument.php, which provides scientific evidence and information refuting around 230 of the most commonly stated climate change queries and questions.

38. A forcing mechanism is a process that alters the energy balance of the climate system, i.e., changes the relative balance between incoming solar radiation and outgoing infrared radiation from Earth. See http://www.epa.gov/climatechange/glossary.html#F.

39. Flattening has occurred before, from the 1940s to the 1970s, when it is attributed to a rough balance of cooling caused by aerosols and GHG warming.

40. See Hansen, Sato, and Ruedy (2012a); Buckle and MacTavish (2013). Hansen et al. note that although the five-year mean global temperature has been flat over the last decade, global average temperature is likely to resume its rapid rise over the coming years as we move into an El Niño phase.

41. See IPCC (2013), 5, "Summary for Policymakers."

42. See http://www.skepticalscience.com/coming-out-of-little-ice-age.htm.

43. See Mann (2002).

44. See Marcott et al. (2013) or Alley (2004) for anomalies in last 8,000 or more years ago, NOAA (2014a) for anomalies in last 100 years.

45. See http://www.skepticalscience.com/December-2009-record-cold-spells.htm.

46. The period from January to August in 2014 has been the second warmest on record for this period (NOAA 2014b), while August and September have surpassed monthly temperature records.

47. These observations are based on temperature anomalies relative to the twentieth-century average. See NOAA (2010).

48. See http://www.skepticalscience.com/water-vapor-greenhouse-gas.htm.

49. See Gerlach (2010).

50. Commitments, targets, plans, and intentions of developed and developing countries that are embodied in the Copenhagen Accord and Cancún Agreements can be found at http://unfccc.int/meetings/copenhagen_dec_2009/items/5262.php and at http://cancun.unfccc.int/. The longer-term 2011 Durban Platform set out a negotiating path to agree a legally binding treaty to address climate change defined in 2015 and effective from 2020. See https://unfccc.int/meetings/durban_nov_2011/meeting/6245.php.

51. UNEP (2012).

52. The *Globe Climate Legislation Study 2012* (Townshend et al. 2013) provides a comprehensive examination of climate legislation in 33 major developed and developing countries. It is designed to assist legislators in advancing climate

legislation and to support successful negotiation of an international climate agreement in 2015.

53. UNEP (2012), appendix. This analysis used 2010 as a base; information since then is roughly consistent with the story it tells.

54. IEA (2012e).

55. IEA (2012e).

56. These per capita emissions figures are rough and for illustration only. They depend heavily on the definition of developed and developing countries as discussed in chapter 9. The overall message on *global* efforts to reduce emissions, however, remains the same.

57. See, for example, Royal Society (2009). It concludes that no geoengineering method evaluated offers an immediate solution to climate change or reduces the need for strong emissions reductions.

58. World Economic Forum (2013).

59. GCEC (2014).

60. See chapter 6 ("Assessing Transformative Pathways") of the IPCC's Working Group III for details and references (IPCC 2014b).

61. IEA (2012e).

62. IEA (2013e).

63. See further discussion in chapter 3, and the work of the IEA, Carbon Tracker Initiative (2013), HSBC (2013), and Leggett (2013).

64. We discuss gas (with a focus on unconventional gas) in chapter 3, due to its potential scale and its potential to replace coal.

Chapter 2

1. See also chapter 7 of this book, and GCEC (2014).

2. See, for example, Perez (2002 and 2010).

3. In fact, theory (Acemoglu et al. 2012; Aghion et al. 2012), modeling (Fischer 2008; Fischer and Newell 2008), and empirical evidence (Popp 2006) show that an effective and efficient low-carbon innovation strategy would combine two complementary sets of policy instruments: one set to price emissions, and one set to target each link in the innovation chain, from R&D through to deployment. Aghion et al. (2014) note that the reduction of greenhouse gas emissions is highly dependent upon both technological innovation and practices. This leads to a path-dependent process in which history and expectations matter greatly in determining eventual outcomes.

4. See, for example, the special issue of *Energy Policy* (2012), which provides a detailed and thorough review of knowledge on past and prospective energy transitions. Many people are trying to put together the evidence on innovation and industrial revolutions. Pearson and Foxon (2012) review different perspectives on the drivers of the first industrial revolution in Britain, including those

of Allen (2009), Mokyr (2009), and Crafts (2010), and explain the importance of new transformative technologies, often referred to as "general-purpose technologies." Such technologies may have been responsible for five long periods, or waves, of innovation, productivity gains, and growth. See figure 2.1 and Freeman and Perez (1988)—which draws on a lifetime of work by Chris Freeman, an outstanding economic historian of such periods, on how technological change takes place—and Broadberry (2007). A separate strand of work focuses on policy insights that can be gained from the study of innovation across multiple nonenergy sectors—see, for example, Henderson and Newell (2011). There are many lines of enquiry, and it is rightly an active area of research.

5. Yet the public has an important role in incentivizing and supporting the mobilization of private investment, because there are important market failures in the "publicness" of such innovation and R&D, and in capital markets associated with information, credibility, reputation, collateral, and so on.

6. As the Global Commission on the Economy and Climate argues; see GCEC (2014), and section 2.10 below.

7. See Hamilton (2014), who found that health damage from air pollution averaged above 4% of GDP in the 15 largest CO_2 emitters in 2010.

8. See section 8.2 for more discussion.

9. See IPCC (2014b).

10. Low-carbon electricity currently looks the most promising for road transport, but that will be part of the story of discovery, as it will be for air and sea.

11. See GCEC (2014).

12. The Deep Decarbonization Pathways Project is a collaboration between the UN's Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations. See IDDRI/SDSN (2014).

13. The countries are Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Japan, Mexico, Russia, South Africa, South Korea, the UK, and the US. See IDDRI/SDSN (2014) for more information.

14. Bowen and Rydge (2011). For innovation, see, for example, the work of Henderson and Newell (2011), who identify common factors across transitions in multiple nonenergy sectors, providing further evidence that rapid change is possible. Indeed, the rapid uptake of modern telephonic technology on the African continent is a remarkable example.

15. See chapter 7 for a discussion on climate action developments around the world.

16. See IEA (2013b).

17. China is also promoting innovation in seven strategic lower-carbon industries (see chapter 7).

18. DuPont (2011).

19. Co-operative Group (2012).

20. Virgin Group (2014).

21. Google (2014).

22. McKinsey (2012a).

23. IEA (2010b).

24. US Clean Heat and Power Association (2012).

25. Oak Ridge National Laboratory (2008).

26. Smart technologies employ two-way communication of (typically) live system data and information to improve operating efficiencies and foster energy efficiency and cost savings. They have a wide range of applications such as in buildings, motor systems, and logistics. One of the biggest areas of interest is smart meter and electricity grids, defined by the IEA as a “network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, resilience and stability.” IEA (2011d).

27. See www.nest.com for more information.

28. See www.smartthings.com for more information.

29. Climate Group (2008).

30. See Zysman and Huberty (2011).

31. Coriolis Energy (2013).

32. See Hamilton (2014) and GCEC (2014).

33. AC: alternating current. Russian and Chinese electricity grids operate at 1,000 kilovolts (kV). Smaller countries, for instance the UK, operate electricity grids at 275 kV and 400 kV.

34. DC: direct current. In China, HVDC cables are used to transmit electricity over very long distances (1,000 kilometers) from the Three Gorges Dam in the center of the country to demand sources on the coast.

35. See Parsons Brinckerhoff (2012).

36. IEA (2011b).

37. The learning rate is defined as the percentage decrease in unit cost for each doubling of installed capacity or doubling of output production.

38. Kersten et al. (2011).

39. Grau (2012).

40. See Candelise, Winskel, and Gross (2013).

41. Personal communication with the author.

42. Grid parity means that the delivered cost of solar is competitive with electricity delivered by the grid. It is important to highlight that in any given system, the price for energy can change from one day to the next because of shifting demand and supply conditions. For this reason, testing whether a renewable energy technology has reached grid parity requires a perspective that looks across

different periods. It also requires an assessment of how the “variability” of some renewable energy sources can be accommodated in the energy system.

43. See the 2014 update to the IEA’s solar PV Technology Roadmap (IEA 2014c), and Gore (2014).

44. See World Energy Council (2013).

45. Average weekly usage per household is 25 kWh in China, 66 kWh in Germany, and 226 kWh in the US. The average retail price in China in 2012 was $0.1/kWh (range $0.075–0.11/kWh) (Shenzhen Municipal Government 2012); the average household electricity price in Germany in 2013 was €0.30 ($0.37)/kWh (Eurostat 2014); the US average price was $0.13/kWh (EIA 2014b).

46. European Photovoltaic Industry Association (2011). See also Eclareon (2014).

47. New Mexico Public Regulation Commission (2012). See also http://www.bloomberg.com/news/2013-02-01/first-solar-may-sell-cheapest-solar-power-less-than-coal.html.

48. Depending on the local currency exchange rate (South Africa Department of Energy 2013).

49. IRENA (2013b), cited in Boyd, Rosenberg, and Hobbs (2014).

50. This largely depends on the electricity billing structure, which differs from region to region. For instance in California, “net metering” allows the household to offset domestic energy use with what they generate and so pay only for what they use, while in Germany the household sells all the energy they generate domestically at an incentivized rate, then buys back energy to cover their total demand.

51. IEA (2014c).

52. IEA (2014c).

53. Three types of commercial CSP technology are available: parabolic trough, linear Fresnel, and power tower/central receiver (a fourth variety, dish Stirling CSP, remains in an early stage of development). Each concentrates solar radiation using mirrors to superheat a fluid or heat transfer medium. This medium, in some cases molten salt, turns water to steam to drive a turbine and generate electricity.

54. See IEA (2012a).

55. Stadelmann et al. (2014).

56. Stadelmann et al. (2014); IEA (2014d).

57. See Stadelmann et al. (2014) for more information.

58. Global Wind Energy Council (2014).

59. In 2010 USD, based on Danish wind farms (in IEA 2012c). €1 is approximately $1.25 at current exchange rates.

60. See IEA (2012c) for more details.

61. Range based on China-US costs. EU average costs in 2011 were approximately $1.2 million/MW (in IRENA 2013a).

62. IEA (2012c).

63. IEA (2012c). Prices in 2010 US$. An annual market study by Wiser and Bolinger (2012) estimates onshore wind learning rates of 7.5% in the period 1982 to 2011, or 14.4% in the period 1982 to 2004 (before increases in system costs as highlighted earlier).

64. Bloomberg New Energy Finance (2011). BNEF also estimates onshore wind levelized cost of energy at around €200 ($250) /MWh in 1984 and €52 ($65) /MWh in 2011, with a corresponding learning rate over the period of 14%. BNEF suggests that on shore wind might now deliver energy only €6 ($7.50)/MWh more expensive than the average cost of energy from a combined-cycle gas power plant based in the EU/US in 2011.

65. If we assume that gas power plants produce approximately 0.4 metric tonnes of CO_2 for each MWh generated. Thus, $7.50/MWh with 0.4t$CO_2$/MWh = $18.75/t$CO_2$.

66. FS-UNEP (2014).

67. See figure 2.6.

68. Compared with around $1.2–2/W onshore (Stadelmann et al. 2014).

69. http://www.carbontrust.com/media/105314/foundation_innovators_29may2012.pdf.

70. http://www.theguardian.com/environment/2013/jan/22/suction-bucket-offshore-wind.

71. The Crown Estate (2012).

72. IEA (2013c).

73. See Europe's Strategic Initiative for Ocean Energy (SI-Ocean) for more information: http://www.si-ocean.eu/en/.

74. Corresponding to wave and tidal stream energy potential of 30–50 GW and tidal barrage energy potential of 25–30 GW or even 60 GW. See DECC (2013b) or House of Commons Energy and Climate Change Committee (2013b).

75. In pumped storage, the generation turbines can be used in reverse to pump water back up to the reservoir. In many locations, these variants can sell energy during the day when prices are high, and use energy to pump water at night when prices are low.

76. IEA (2012d).

77. More than 25 countries currently depend on hydropower for over 90% of their electricity supply, and 12 countries for 100%. See IEA (2012d); IRENA (2012).

78. Notable examples being Norway with over 95%, Brazil (80%), and Canada (62%) (IEA 2012d).

79. IRENA (2012).

80. IEA (2012d).

81. IRENA (2012).

82. Such as, but not limited to, the European electricity network (IRENA 2012).

83. The World Commission on Dams has estimated that 40–80 million people have been displaced by dams, with India and China accounting for between 26 and 58 million people displaced between 1950 and 1990 (World Commission on Dams 2000). The World Bank has estimated that dams account for 63% of worldwide displacement (cited in World Commission on Dams 2000).

84. IEA (2014b).

85. Under the 2°C scenario in the IEA's "Energy Technology Perspectives" (IEA 2014b).

86. As part of a modern energy system that is secure and increasingly integrated, electrical batteries are useful to energy systems with or without high levels of variable renewable energy generation and can provide valuable energy services in both developing and developed countries (IEA 2014b).

87. The Berlin-based grid and storage company Younicos recently installed Europe's first and largest battery power plant. The 5 MW lithium-ion unit benefits from a 20-year performance guarantee from the technology provider that addresses the perception that the technology is risky. See http://www.younicos.com/en/media_library/news/022_2014_09_16_Wemag_Open.html.

88. As we will see in section 3.5, even gas leakage as little as 3% of total production could greatly affect the emissions benefits of a coal-to-gas shift.

89. IPCC (2014b).

90. See also the work by Carbon Tracker Initiative (2013).

91. Confirmation of reserves is also called "reserves growth," where the volume of reserves grows due to changes in technology and prices. This is typically in addition to "proven reserves" (a probabilistic calculation dependent on current technology and prices) and "new discoveries."

92. See GCCSI (2012 and 2013). I am a member of the International Advisory Panel of the GCCSI. Large-scale integrated CCS projects are defined by the GCCSI as capturing at least 800,000 tonnes of CO_2 annually for a coal-based power plant, or at least 400,000 tonnes of CO_2 annually for other emission-intensive industrial facilities (including natural gas-based power generation) (GCCSI 2014).

93. The Massachusetts Institute of Technology also tracks CCS projects. They list 52 projects in some stage of development (split evenly between industry and power plant arrangements): 2 closed after operating, 12 operational, 3 under construction (including the two power plants mentioned above), and 35 in planning (24 of which are power plants). See http://sequestration.mit.edu/tools/projects/index_capture.html for more information.

94. IEA (2014a).

95. Given changes in planned projects in recent years, there is a gap between what is planned now and what was planned before. GCCSI data (2014) show that the total number of projects in 2013 was approximately the same as in 2009. In the four years since 2010, the number of planning-stage projects has decreased by 20 while the number of projects moving into construction phase increased only by 4.

96. Current costs would be substantially higher. At present most of the cost lies in the capturing process, and there is scope for technical progress on that front.

97. Interagency Working Group on Social Cost of Carbon (2013). And see chapter 4 for more details on climate models.

98. See chapter 4, and Stern (2013).

99. See Stern (2007).

100. Nuclear Energy Institute (2013).

101. European Nuclear Society (2013). Pressurized water reactors use water as both coolant and moderator. A moderator is used to slow down neutrons and increase the likelihood that they will be captured by uranium-235 and cause fission.

102. One terawatt-hour is equal to 1,000 gigawatt-hours.

103. IEA (2010c).

104. United Nations Development Programme (2013).

105. See Bassi, Bowen, and Fankhauser (2012); for more detail, see Barrs (2011).

106. See Bassi, Bowen, and Fankhauser (2012); for more detail, see Barrs (2011).

107. United Nations Development Programme (2013).

108. IEA (2011c).

109. Clean Energy Ministerial (CEM), Electric Vehicle Initiative (EVI), http://www.cleanenergyministerial.org/Our-Work/Initiatives/Electric-Vehicles.

110. McKinsey (2012b).

111. Musk (2014).

112. See the Tesla Motors Gigafactory, http://www.teslamotors.com/blog/gigafactory.

113. However, options to overcome "range anxiety" exist: with every new electric vehicle sold, German car manufacturer Volkswagen offers one month free rental per year of the equivalent petrol/diesel-fueled model if the buyer needs to make longer journeys.

114. International Civil Aviation Organisation (2010).

115. DG Clima (2013).

116. See US-Brazil Partnership for the Development of Aviation Biofuels, http://brazil.usembassy.gov/biofuel-partnership.html.

117. International Maritime Organisation (2009).

118. International Maritime Organisation (2013).

119. See Food and Agriculture Organization of the United Nations (2010).

120. Also referred to as the System of Crop Intensification when applied to other crops such as potatoes. See http://sri.ciifad.cornell.edu/aboutsri/othercrops/otherSCI/.

121. And in some countries, less labor is needed as a result (Africare, Oxfam, and World Wildlife Fund 2010).

122. Africare, Oxfam, and World Wildlife Fund (2010).

123. World Economic Forum (2012b).

124. The CGIAR is an informal association of 57 public- and private-sector members, established in 1971, which supports a network of 16 international agricultural research centers.

125. Lal (2009). Equivalent to 4.4 billion tonnes of CO_2 (converting carbon × 44/12 to carbon dioxide).

126. World Bank (2010).

127. Consultative Group on International Agricultural Research (2012).

128. There is much uncertainty around these estimates, as it is impossible to count the trees (thus emissions generated by their destruction) in a given area "manually." Instead, scientists derive estimates of trees from several points—including estimates on what kind of and how many trees there are, soil type, and satellite data. Advances in data-gathering processes and increasing resolution of satellite imagery are improving data reliability.

129. Murdiyarso et al. (2011).

130. Both of which are potentially involved in or infiltrated by illegal operations.

131. Romani, Stern, and Zenghelis (2011).

132. See, however, a number of papers by Aghion and colleagues in which path dependency is central (e.g., Aghion et al. 2012). Aghion et al. (2014) note that the reduction of greenhouse gas emissions is highly dependent upon both technological innovation and practices. This leads to a path-dependent process in which history and expectations matter greatly in determining eventual outcomes.

133. Other consistent estimates include den Elzen, Meinshausen, and van Vuuren (2007); Knopf et al. (2009); and Edenhofer, Carraro, and Hourcade (2009).

134. Shah et al. (2013).

135. IEA (2012e).

136. IPCC (2014b).

137. See the work on efficiency by McKinsey (2011) and the World Economic Forum (2012a).

138. See Hamilton (2014), who found that health damage from air pollution averaged above 4% of GDP in the 15 largest CO_2 emitters in 2010.

139. UNFCCC (2007).

140. Frisari et al. (2013); Multilateral Investment Guarantee Agency (2014).

141. World Bank (2005).

142. FS-UNEP (2014).

143. FS-UNEP (2014).

144. Nidumolu, Prahalad, and Rangaswami (2009).

145. Kopernik (2012).

146. IEA (2013e).

147. The Lighting a Billion Lives initiative set up by TERI (The Energy and Resources Institute) in India has brought electricity to more than one million people in 2,400 villages since 2008. See http://labl.teriin.org for details.

148. IEA (2012e).

149. See http://www.selco-india.com/finance.html.

150. See http://www.grampower.com/.

151. See http://pollinateenergy.org.

152. See World Bank (2012a).

153. Zenghelis (2011).

154. See GCEC (2014).

155. See www.newclimateeconomy.report/global-action-plan/ (in GCEC 2014).

156. See, for example, IEA (2010d).

Chapter 3

1. See Freeman (1974).

2. See, for example, Allen (2009 and 2012); Mokyr (2009).

3. See, for example, Fouquet and Pearson (2012).

4. See, for example, Pearson and Foxon (2012).

5. See, for example, Bliss and Stern (1982); Lanjouw and Stern (1998).

6. Henderson and Newell (2011).

7. Pearson and Foxon (2012).

8. Public economics includes theories of policy for optimum growth (a subject of my doctoral thesis). They were popular in the 1960s and 1970s and helpful in studying criteria for saving and investment, but they usually involve fairly fixed structures of technological change and economic institutions.

9. Externalities can be either "positive" or "negative." An example of a positive externality is the inability to appropriate the full benefits of research and development; benefits of R&D often accrue to others. This reduces the incentive to invest in R&D and represents a market failure.

10. Stern (2007), 1.

11. Feed-in tariffs are a form of financial arrangement that pays generators a fixed, usually above-market, price for energy from renewable sources. The amount typically depends on the type of technology (with higher prices for the less mature varieties) and is fixed for up to 20 years in some cases (to provide long-term investment security); the eligible amount usually diminishes over time (to encourage earlier deployment). Ultimately, the feed-in tariff encourages

exploitation of ideas by offering a premium and provides stability for revenue streams, bringing down the cost of capital.

12. GCEC (2014).

13. Feed-in tariffs became a political issue in Germany, Spain, and Italy. As PV system costs fell faster than expected, Germany eventually redesigned the feed-in tariff to reduce in line with system costs. Spain retroactively reduced payments to existing generators, and Italy capped the total volume of PV allowed under the support. See REN21 (2013) for more information.

14. See Hobbs et al. (2013) for a discussion of solar PV leasing in California, where it has grown significantly in popularity in recent years.

15. I had extensive direct observation of this effect in my years as chief economist of the European Bank for Reconstruction and Development (1994–1999).

16. See John Stuart Mill on "deliberative democracy"; for references and a brief discussion, see Stern, Dethier, and Rogers (2005), 260–261.

17. See Climate Works (2011a).

18. See Green and Stern (2014).

19. See, for example, King (2008).

20. For instance, in 2013, Australia's Clean Energy Finance Corporation leveraged close to $3 for every $1 of their investment (see www.cleanenergyfinancecorp.com.au). The German national development bank KfW in 2010 generated revenues of four to five euros for each one "promotional" euro that went into energy-efficient construction and refurbishment (see www.kfw.de).

21. See European Bank for Reconstruction and Development (2014).

22. Designing suites of policy instruments so that they are complementary to one another is critical here. A poorly designed and uncoordinated policy mix can be counterproductive: see, e.g., Fankhauser, Hepburn, and Park (2010).

23. See, for example, Otto and Reilly (2008); Fischer (2008); Fischer and Newell (2008); Acemoglu, Akcigit, and Kerr (2012); Acemoglu et al. (2012).

24. Including funding energy efficiency measures. See Brixton Energy for more information: brixtonenergy.co.uk.

25. See LSE Growth Commission (2013) for further discussion of these ideas.

26. Hepburn (2010).

27. Helm, Hepburn, and Mash (2003).

28. Deutsche Bank, in Wall Street Journal (2009).

29. See for example the Transition Report of the EBRD (European Bank for Reconstruction and Development 1999) and Stern, Dethier, and Rogers (2005).

30. See note 13 above on feed-in tariffs.

31. HM Revenue and Customs (2014).

32. Another option may be *constitutional*. National constitutions are typically countries' most authoritative, certain, and long-term legal instruments, requiring

more onerous legislative and/or popular processes to amend. Some countries may consider enshrining long-term climate change objectives into their constitutions. Ecuador became the first such country to include “Rights of Nature” in the national constitution in 2008, followed by the Dominican Republic and Tunisia.

33. Some of these ideas were elaborated in the LSE Growth Commission of 2013, of which I was a member.

34. Research by McKinsey (2009) has produced estimates of MACs across a number of industries, economies, and at a global level. But there is controversy over how robust the estimates are to changes in assumptions about the economy-wide feedbacks from climate policies, and over the reliability of engineering estimates of the real-world potential for energy efficiency improvements. To be fair, the long time horizons of possible technologies, and the centrality of innovation inherent to the issue, militate against precision here.

35. If the business-as-usual MSC curve is steep in the long run, as the evidence suggests it is, setting an incorrect tax rate and maintaining it through time risks excess emissions and large damage costs (see Weitzman 1974). Therefore, given the nature of the uncertainty, a quantity target is preferable in the long run. But setting a quota in the short run risks imposing very high costs on firms if governments misjudge its size, because the short-run MAC curve is likely to be much steeper than in the long run (when firms can alter their capital stock and technologies).

36. This can be compared with the range of MSC estimates to check that prices are within a “reasonable” range, assuming we have some confidence in such a range—not an easy assumption.

37. See Gruell and Taschini (2011), who discuss hybrid approaches to pricing carbon.

38. For more discussion on the choice of policy, see Vogt-Schilb and Hallegatte (2011). They show that while policy choice depends on whether targets are ultimate objectives (e.g., 2050) or merely an interim target on the way (e.g., 2020), an expensive option now is potentially most efficient in both cases.

39. Taschini, Kollenberg, and Duffy (2013).

40. Introducing responsiveness in the supply of allowances will have an impact on the EU Emissions Trading System. Its effectiveness, however, depends on the design of the mechanism (automated activation, its target dimension, and its activation triggers, for instance). Moreover, the mechanism should work within the existing architecture and use data which are readily available.

41. O’Gorman and Jotzo (2014).

42. See also IPCC (2013).

43. For a discussion of US regulatory measures through the end of 2013, see Bassi and Bowen (2014). Details of EPA proposed regulation of power plant CO_2 emissions can be found on the EPA’s website at http://www2.epa.gov/carbon-pollution-standards.

44. See also Stern (2007), chapter 11; Bassi and Zenghelis (2014).

45. See, for example, Aldy and Pizer (2009).

46. UNEP (2009).

47. US steam coal exports increased from approximately 0.5 million tonnes per month in January 2010 to almost 3 million tonnes by July 2012. In parallel, US wholesale natural gas prices (Henry Hub) decreased from $6/million Btu to around $3 in the same period. Data cited in Chazan and Wiesmann (2013).

48. Hughes (2013).

49. See Cleveland and O'Connor (2011) for a discussion, including of Brandt (2009) who suggests that GHGs from producing liquid fuels from unconventional oil are possibly 50–75% higher than from conventional oil. Brandt, Boak, and Burnham (2010) also have a more detailed investigation into emissions from oil shale.

50. In some cases, industry may be attempting to reduce this: Shell announced in September 2012 that it will capture and store in deep saline formations more than 1 million tonnes a year of CO_2 produced at its Athabasca Oil Sands Project in Canada.

51. Which we touched on in chapter 1 with regard to leaving hydrocarbon reserves in the ground to meet the carbon budget.

52. See Sinn (2008) and Pearson and Foxon (2012).

53. Knopf et al. (2009).

54. Carbon Tracker Initiative (2013).

55. HSBC (2013).

56. See Carbon Tracker Initiative (2013) and www.carbontracker.org for more information. Oil and gas major BP suggests in its 2013 Sustainability Report (BP 2014) that while it agrees that "burning all known fossil fuel reserves would raise global temperature by more than 2°C," the "unburnable carbon approach … oversimplifies the complexity of the issue and overstates the potential financial impact."

57. Carbon Tracker Initiative (2013).

58. In a March 2014 message to shareholders (ExxonMobil 2014), ExxonMobil reports that "we are confident that none of our hydrocarbon reserves are now or will become 'stranded.'" Further, it considers a scenario to reduce emissions 80% by 2050 as "highly unlikely."

59. CCS is a key technology in many emissions scenarios, e.g., the IEA's scenarios (see figure 2.3 in chapter 2). If its deployment falls behind, greater action will be required from other areas.

60. IEA (2009).

61. IMF (2013).

62. Political pressure can be very effective in ensuring that the financial benefits of the fossil fuel subsidies are captured by higher-income groups. The subsidies are an inefficient use of public money that could be spent on a more focused and effective development agenda, such as education or health.

63. OECD (2013).

64. Limitations of this method are discussed in IMF (2013).

65. The IEA (2012e) sample size is 37 countries. The IEA states that its sample represents 95% of global subsidized fossil fuel consumption. All but 2 of the 37 countries are non-OECD.

66. IMF (2013).

67. See, e.g., Stern (2013).

68. In 2012 euros. See European Commission (2014b) for more information.

69. See European Commission (2014b).

70. IEA (2012e).

71. IEA (2012e).

72. EIA (2014c).

73. EIA (2014a).

74. The effect on global emissions is less clear, as the US is now exporting displaced coal to Europe, where this is displacing higher-priced and cleaner gas. It is also less clear whether a rise in US gas prices, as forecast, would lead to a switch back to coal in the US. This will depend, in part, on the impact of EPA regulations on the scrapping of aging coal-generating capacity.

75. According to the EIA, US energy-related CO_2 emissions were six billion tonnes in 2005, and had declined by over 600 million tonnes by 2013. Broderick and Anderson (2012) investigate what level of the reduction can be accounted for by a gas fuel switch. While they find that precision is difficult, they note that other studies suggest 30–50% of the emission reductions could be from fuel switching to gas. This topic continues to be actively debated, with data analysts Greenpeace Energydesk and Carbon Brief both attempting to determine what caused emissions to fall: see http://www.greenpeace.org.uk/newsdesk/energy/data/data-what-accounts-huge-cut-us-coal-use-2007 and http://www.carbonbrief.org/blog/2014/10/what-is-the-impact-on-the-us-emissions-of-switching-from-coal-to-gas/.

76. See Bassi et al. (2013), 23–24.

77. See Bassi et al. (2013).

78. See IEA (2011a), 57, 68.

79. In May 2014, China reached a deal with Russia for a 30-year supply of gas to the country, reportedly worth over US$400 billion, at US$10 per mmBtu.

80. IEA (2013e).

81. IEA (2013e).

82. Illustrative calculation only; it does not consider additional relevant factors such as changes in electricity demand over time. World demand for energy is increasing, but particularly in large emerging economies such as China and India.

83. Methane (CH_4) is a strong GHG with 25 times the warming potential of CO_2 over a 100-year period.

84. See Bassi et al. (2013) and Hirst, Khor, and Buckle (2013) for further discussion of the use of shale gas and its climate change implications, and Clark et al. (2011) for a life cycle analysis of shale gas.

85. Howarth, Santoro, and Ingraffea (2011).

86. See Jenner and Lamadrid (2012).

87. See Clark et al. (2011).

88. Howarth, Ingraffea, and Engelder (2011).

89. Joint Research Centre (2012).

90. IEA (2012b).

91. Italian Home Office (2011).

92. See, for example, Ipsos Social Research Institute (2012).

93. Germany's greenhouse gas emissions increased by 1.6% in the year 2011–2012 (preliminary estimates) (German Federal Environment Agency 2013). But they are 25% below 1990 levels.

94. OECD (2010). The report defines an accident as an event with more than five prompt deaths.

95. See Hamilton (2014), who calculates that health damage and mortalities from air pollution averaged above 4% of GDP in the 15 largest CO_2 emitters in 2010.

96. Delayed fatalities associated with indirect or ongoing impacts from an accident are important but are much more difficult to measure. OECD (2010) suggests estimates of delayed fatalities should be compared to impacts from fossil fuel use as best we can. They conclude, acknowledging the great uncertainty in the statistics, that the indirect death toll from fossil fuel use, e.g., air pollution, far outweighs fatalities from exposure to radiation from nuclear accidents.

97. DECC (2013a).

98. See Bassi, Bowen, and Fankhauser (2012); Parkhill et al. (2013).

99. See DECC (2013a).

100. See IEA (2013a and 2013b).

101. In 2020–2030 energy and climate policy proposals by the European Commission, setting energy efficiency targets was delayed until a thorough review of the existing Energy Efficiency Directive has been completed. See European Commission (2014a).

102. Sorrell et al. (2000).

103. See, for instance, the 2006 book *Green to Gold* which argues that pollution control and natural resource management have been used to foster a business advantage (Esty and Winston 2006).

104. IEA (2013a).

105. IEA (2011e).

106. World Resources Institute (2013).

Chapter 4

This chapter is based on Stern (2013), which was published in the *Journal of Economic Literature* in September 2013.

1. For more on this see, e.g., Pindyck (2013).

2. I owe this quote to Sir Brian Hoskins FRS, Professor at Imperial College London, Chair of the Grantham Institute for Climate Change at Imperial College London, and Professor of Meteorology at the University of Reading.

3. See, for example, Lenton et al. (2008).

4. Valdes (2011). As in most modeling, one can try to make ad hoc assumptions to accommodate problems such as a "natural disturbance," but these would have to be very large.

5. I am grateful to Jason Lowe of the UK Met Office Hadley Centre for guidance on this.

6. Based on the mainstream scientific literature, at 4°C or warmer relative to preindustrial period.

7. The major rivers include the Yellow (Huang He), Salween, Yangtze, Mekong, Brahmaputra, Yamuna, Ganges, and Indus.

8. Wet bulb temperatures rarely exceed 30°C in any part of the world today.

9. See, for example, World Bank (2012b); Rosenzweig et al. (2013).

10. Nordhaus (1991a and 1991b).

11. In chapter 6 of *The Stern Review* we made use of the PAGE model developed by Chris Hope, for example.

12. Examples of recent literature examining IAMs include: Kopp, Hsiang, and Oppenheimer (2013); Marten et al. (2013); Anthoff and Tol (2013); Ackerman and Munitz (2012); Ackerman and Stanton (2012); Tol (2012); Nordhaus (2011); Van Vuuren et al. (2011); Warren et al. (2010); Ackerman et al. (2009); Mastrandrea (2009); Parry et al. (2009); Weitzman (2009); Hof, den Elzen, and van Vuuren (2008); Mastrandrea and Schneider (2001); Schneider (1997). See also Moyer et al. (2013).

Tol (2012) surveys estimates of the total economic impacts of climate change and calculates the expected value of the social cost of carbon (SCC) at \$29/tC (\$8/tCO_2) in 2015, rising at around 2% per annum. Anthoff and Tol (2013) undertake a decomposition analysis of SCC using the FUND model. They identify key parameters that contribute most to variation in SCC estimates, including climate sensitivity, agriculture, energy demand, and migration, and note that the latter two have received insufficient research attention. They recognize the uncertainty in modeling impacts, with many results based on extrapolation and incomplete research and with some potentially important factors omitted, such as conflict and ocean acidification. I am grateful to Richard Tol for these references. For reasons set out in this chapter, I think that these numbers embody gross downward biases as estimates of SCC.

13. Pindyck (2013).

14. Lenton and Ciscar (2013).

15. Ackerman and Stanton (2012).

16. See Greenstone, Kopits, and Wolverton (2011); Interagency Working Group on Social Cost of Carbon (2010).

17. See Interagency Working Group on Social Cost of Carbon (2013). The reasons for the revisions were changes in the underlying models, largely to incorporate greater damages, rather than change in method of computation (see Moyer et al. 2013). The models still yield results like those shown in figure 4.1 with damages of only a few percent, even at 5°C.

18. See Stern (2013) and continued discussion in Dietz and Stern (forthcoming).

19. See Fankhauser and Tol (2005).

20. Some other forms of technical progress could be accommodated by keeping *t* as an argument of *F*( ).

21. In the FUND model, damages can also depend on output.

22. Some models, e.g., WITCH, have a form of endogenous technical progress. See Bosetti et al. (2006) and http://www.witchmodel.org/index.html for more information.

23. Dietz and Asheim (2012) use a linear, quadratic, and power function of 7, consistent with Weitzman (2012). In *The Stern Review* (Stern 2007, 660), damages are represented by $(T/2.5)^{\gamma}$. The damage exponent is treated as a Monte Carlo parameter using a triangular probability distribution with a minimum of 1 (results in a linear function) and a maximum of 3 (stronger convexity) (see also Stern 2008, table 2, $\gamma = 2$, 2.5, and 3). Some are trying to improve specifications of damage functions, e.g., Ackerman, Stanton, and Bueno (2010) and Kopp, Hsiang, and Oppenheimer (2013). DICE models, pioneered by Nordhaus, generally have a $D(T)$ which is one minus the inverse of a quadratic of T.

24. Nordhaus (2008); Stern (2007), chapter 6. See also Dietz and Stern (forthcoming), which investigates the development of the DICE model, and the role that in-built assumptions have in the underassessment of the overall scale of risks from unmanaged climate change. Dietz and Stern use DICE itself to provide an initial illustration that, if the analysis is extended to take into account three essential elements of the climate problem—the endogeneity of growth, the convexity of damages, and climate risk—the efficient policy will comprise strong controls.

25. In much of Tol's work (see Stern 2007; Dietz et al. 2007) on the FUND model, damages at 5°C are still lower, around 1–2% of GDP (figure 4.1). For a recent critique of the FUND model see Ackerman and Munitz (2012)—with responses, including from Bill Nordhaus, which highlight several additional concerns with the economic models, published at http://frankackerman.com/tol-controversy/. See Tol (2012) for a discussion on impacts at higher temperatures.

26. In a private communication (reproduced with permission), Bill Nordhaus remarks, "I think we do not have sufficient evidence to extrapolate reliably above

3 degrees C. … While damage estimates at high temperatures are necessary for modeling purposes (like many other variables such as GDP or energy technologies), they are placeholders subject to further research and should be used with sensitivity analyses to indicate their importance for the key result, such as estimates of current policy or the current social cost of carbon.” I am very grateful for his sharing of these thoughts.

27. Ackerman, Stanton, and Bueno (2010).

28. Such as Nordhaus (2008).

29. See Weitzman (2012).

30. See also Nordhaus (2008).

31. The sensitivity of welfare/policy analysis to the damage function assumptions was noted in Stern (2008), table 2: for example, increasing the damage function exponent from 2 to 3 raises the overall cost of climate change in the models there by a factor of 3 to 10. One side effect of increasing the exponent can be to make damages lower at lower temperatures where the curve is calibrated to fit through zero temperature change and one other point. Moyer et al. (2013) show the great sensitivity of the social cost of carbon to the assumption that damages affect only current output rather than all future output through lasting impacts on overall factor productivity.

32. See also figure 1 of Moyer et al. (2013), which illustrates that the core assumptions of these models imply that future generations will be much better off than our own.

33. I am particularly indebted to Peter Diamond for discussion of these issues.

34. See Pindyck (2013) and Moyer et al. (2013).

35. The PAGE model was used for chapter 6 in *The Stern Review*; see Stern (2007). More recent versions of PAGE move in the direction of including possible catastrophic events. There have been other attempts too, but they have all been rather limited. See Kopits, Marten, and Wolverton (2013).

36. See Weitzman (2011) and his valuable contributions emphasizing “fat tails.”

37. See, for example, IEA (2012e and 2013b); Rogelj, Meinshausen, and Knutti (2012).

38. See Nordhaus (2008).

39. Bolt and van Zanden (2013); Dikötter (2010); Zhu (2012).

40. See, for example, Broome (2004) and Stern (2014b), and chapter 6 below.

41. Nordhaus (1991b).

42. See Dietz and Stern (forthcoming).

43. See, for example, Nordhaus (2011) and Weitzman (2011).

Chapter 5

This chapter is based on Stern (2014b), which was published in *Economics and Philosophy* in November 2014.

1. See, for example, Drèze and Stern (1987 and 1990) for a detailed formal discussion.

2. In other words, where functions are differentiable, the Lagrange multiplier on the resource balance constraint for the good.

3. Well-behaved in the sense of appropriate continuities and convexities that allow marginal conditions to fully characterize an optimum.

4. Many discontinuities and nonconvexities are likely to arise in this context. It is difficult even to know what functions and spaces may be at issue. See Drèze and Stern (1987 and 1990) for the relationship between shadow prices and the theory of reform: this follows a tradition of Meade (1951, 1955), Guesnerie (2004), and others (see references in those papers).

5. See Weitzman (1974) for a thoughtful and influential discussion of circumstances where policies should focus on quantities or prices in problems where risk is central.

6. See, for example, Nordhaus (2008); Weitzman (2007a); IMF (2012), chapter 4.

7. See, for example, Nordhaus (2011) and Weitzman (2011).

8. For example, Weitzman (2007a) argued for 6% as consistent with a "trio of twos": growth rate at 2%, pure-time discount rate at 2%, and $\eta = 2$—see equation (5.8) in the technical appendix.

9. That is, the numeraire.

10. See, for example, data and analysis in Barclays (2011).

11. Weitzman (2007b).

12. See Giglio, Maggiori, and Stroebel (2014).

13. See, for example, Little and Mirrlees (1974). For a recent discussion in this context, see Gollier (2012) or Posner and Weisbach (2010).

14. Arrow et al. (2013).

15. See, e.g., Weitzman (1998); Gollier, Koundouri, and Pantelidis (2008); and a recent paper by Farmer et al. (2014). The result comes from examining the expectation of a product of exponential factors associated with the sequence of period-by-period interest rates.

16. Farmer et al. (2014) and Giglio, Maggiori, and Stroebel (2014) both deal with long-run market rates that presumably embody some level of risk, so presumably a notional "riskless" rate would be still lower.

17. This is essentially the first event in a Poisson process in this model.

18. I am very grateful to Cameron Hepburn for drawing this to my attention.

19. Hume (1888), Book 3, part 2, section 7.

20. It would be interesting to speculate, as Christopher Bliss has remarked in a private communication, how far Hume would have seen other parts of the world as having important "weight." Some in the Enlightenment era might have optimistically supposed that nations, as they "learn," would become more similar—"one of us"—and that until they did so they would have less importance.

Not an argument that would attract all of us now, from the perspective of common humanity, even if it might have been seen as relevant some two or three centuries ago.

21. Sen (2006 and 2009).

22. In the long run, N grows at rate n, utility of consumption per head at $(1 - \eta)\alpha$, and the sum of these two rates must be less than δ for convergence of the infinite integral. And see Stern (2007), chapter 2A.

23. Asymptotically, λ falls at rate $\eta\alpha + \delta$ (see equation (5.8)) since α is the long-run rate of growth of consumption per head and K grows at rate $\alpha + n$. For convergence of λK the former must exceed the latter.

24. See, for example, Stern (1972b) for a discussion of necessary and sufficient conditions for optimality in such models.

25. With a production function $F(K, Ne^{\alpha t})$, writing $\hat{c} = C / Ne^{\alpha t}$ and $\hat{k} = KNe^{\alpha t}$, we have in steady state, when $\hat{c}$ and $\hat{k}$ are constant, $\hat{c} = f\left(\hat{k}\right) - (\alpha + n)\hat{k}$. Maximization of $\hat{c}$ with respect to $\hat{k}$ gives $f'\left(\hat{k}\right) = (\alpha + n)$, where $f(x) \equiv F(x, 1)$.

26. See Stern (2013), and chapter 4 of this book. For some further discussion, see also Stern (2007), appendix to chapter 2.

27. Models that build in an infinite number of periods can open possibilities for a Pareto improvement by bringing consumption forward. In an overlapping-generations model, the first generation can be made better off by a gift from the second, which can be compensated by a gift from the third, and so on. In such models, existence of an optimum may well be a problem because any candidate for an optimum could, it seems, be improved by such a mechanism and therefore could not be an optimum—another example that tells us that we must be wary of a particular model constraint dominating the logic.

28. There is a useful recent review in Asheim (2010); see also the book by Blackorby, Bossert, and Donaldson (2005). This literature draws heavily on the early piece by Diamond (1965).

29. This builds on Koopmans (1960), and Diamond attributes the observation to Menahem Yaari.

30. These are essentially the results examined in a series of papers on social evaluation by Basu and Mitra (e.g., 2003, 2007), which is driven by the same logic as the Diamond result (with some strengthening of the theory).

31. A Pareto improvement is a change in which no one is worse off and at least one person is better off.

32. One can attempt to rank divergent integrals using an “overtaking criteria”; see, for example, Asheim (2010) for literature references. But this can deal with the problems only when the integrals are on the borderline of divergence: in the simple one-good growth framework when the convergence inequality holds with equality—see, for example, Mirrlees and Stern (1972), or Stern (1972b).

33. See Sen (1970a and 1970b), for example.

34. Sen (2009).

35. Peter Diamond, private communication, July 2013.

36. Asheim (2010).

37. Ramsey (1928); Harrod (1948).

38. See Harsanyi (1953 and 1955); Rawls (1971).

39. See also Quiggin (2012) for a formal proof in standard models with social welfare functions and overlapping generations that equal treatment of those currently alive at any point in time requires zero pure-time discounting.

40. See also Stern (2013), and chapter 4 of this book.

41. For recent innovative papers see, for example, Guesnerie (2004), who focuses on particular aspects of "more-than-one-good," and Sterner and Persson (2008), who incorporate changing relative prices. See also useful discussions by Dasgupta (2011), Cline (1992), Ackerman and Stanton (2012), Sagoff (2004), and Jamieson (1992). See also Neumayer (2007) for a discussion on the loss of nonsubstitutable natural capital as a justification for climate action. And there is an interesting literature on hyperbolic discounting (where later discount rates are assumed to be lower than near-term rates), although that has generally been focused on behavioral psychology, addiction, etc. rather than ethics. Arrow et al. (2013) discuss diminishing discount rates motivated by uncertainty over which discount rates to use.

42. Sen (1999).

43. For the sake of this argument, consider the issue of adults aged 25 versus adults aged 45.

44. See, for example, Bliss (1975).

45. A formal definition of the shadow price of good i at time t is the increment to social welfare arising from an extra unit of good i becoming available at time t. It will be relative shadow prices that matter to decisions. This definition of the notion needs some aggregate concept of social welfare or an objective function. See Drèze and Stern (1987 and 1990). A shadow price will depend both on the functioning of the model and the distributional and other values embodied in the concept of social welfare.

46. See, e.g., Malinvaud (1953) on heterogeneous capital goods.

47. See, for example, Little and Mirrlees (1974) or Stern (1972a).

48. See, for example, Gollier (2010).

49. See, e.g., Mirrlees (1971 and 1997).

50. A Bergson-Samuelson social welfare function is of the form $w(u^1, u^2, \dots, u^H)$, where social welfare is specified as a function of individual utility levels.

The concept of the social marginal valuation of income must in any case be used with care since, if market and shadow prices differ anywhere in the system, the marginal propensity to pay shadow taxes out of income (where shadow taxes are the difference between market prices and shadow prices) should influence the marginal conditions for optimum lump-sum taxes, or indeed for second-best optimum taxes. These issues are discussed formally at some length in Drèze and Stern (1987 and 1990).

51. E.g., Lomborg (2009).

52. Dasgupta (2008).

53. And it assumes an exogenously given structure and time profile of population.

54. For example, because climate sensitivity turned out bigger than expected.

55. It is possible to tell a story of a fixed income distribution, but we keep it simple.

56. In formal analysis of necessary conditions for optimal growth following Pontryagin or Lagrangean methods, the Ramsey rule plays the role of the differential equation for shadow prices. The capital accumulation condition (consumption plus investment is equal to output) gives the differential equation on quantities. The transversality condition on long-run value of capital is discussed below. For a discussion of sufficient conditions for optimum growth, see Stern (1972b).

57. See, e.g., Nordhaus (2008); Weitzman (2007a); IMF (2012), chapter 4.

58. The isoelastic form (and only this form) has the feature that these relative marginal valuations depend only on relative incomes. Some, such as Serge Kolm, have questioned this feature on the grounds that we might worry little about distribution of income among the rich, even if some of the rich were a good deal richer than the others. See, e.g., Kolm (1969).

59. See, e.g., Okun (1975), Stern (1977), and Atkinson and Brandolini (2010) in economics; Broome (2009) and Page (2007) in philosophy.

60. See Stern (1977); Atkinson and Brandolini (2010).

61. That, of course, abstracts from or ignores all the problems of asymmetric information (the taxpayer knows much that the government does not) which motivate the theory of income taxation à la Mirrlees.

62. See Atkinson and Brandolini (2010).

63. See Dasgupta (2008).

64. See, for example, Mirrlees and Stern (1972); Stern (2008); DeLong (2006); Dasgupta (2007).

65. Actually, the technical progress does not have to be exogenous. Similar results would follow from endogenous long-run technical progress.

66. This means, if the model involves the maximization of expected utility, that an individual would be willing to pay the same proportion of wealth, β, to insure against a given proportional loss, α, regardless of the level of income. In other words, β depends on α but not on income.

67. See, e.g., Ariely (2008); Slovic (2010); Kahneman and Tversky (2000). The many difficulties are compounded if we distinguish along Knightian lines, between uncertainty where probabilities cannot readily be specified and risk where they can be; see Stern (2007), 38–39.

68. See Barro (2013).

69. See Weitzman (2007a).

70. See Layard (2005).

71. See Stern (1977); Atkinson and Brandolini (2010).

72. See Weitzman (2009).

73. Stern (2007), technical appendix to postscript.

74. See also the discussion around table 2 in Stern (2008).

75. See https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-government.

76. Stern (2007), technical appendix to postscript.

77. See also Stanton (2011) for a discussion of using Negishi weights, which essentially stop the integrated assessment models from trying to redistribute income to poorer people at any one moment in time.

Chapter 6

This chapter is based on Stern (2014a), which was published in *Economics and Philosophy* in November 2014.

1. A Paretian improvement, or an improvement in the sense of Pareto, is a change such that no one is worse off and at least one person is better off. A Bergson-Samuelson social welfare function is of the form $w(u^1, u^2, \dots, u^H)$ where social welfare is specified as a function of individual utility levels.

2. See, for example, Sen (1997 and 1998) on Asian philosophical traditions; Wong (2011) on Chinese philosophy; and Taber (1998) on Indian philosophy.

3. This brief discussion of Kantian, contractarian, and Aristotelian ethics draws, inter alia, on Jamieson (2010). And I have benefited greatly from discussions with John Broome, the White's Professor of Moral Philosophy at Oxford University, Nancy Cartwright, Professor of Philosophy at Durham University, Amartya Sen, Lamont University Professor of Philosophy and Economics at Harvard University, and Cameron Hepburn and Dimitri Zenghelis, my colleagues at the Grantham Research Institute at the LSE. I have also benefited from the comments on these issues of Stephen Gardiner and Dale Jamieson and those from a meeting on "New Directions in Political Philosophy" at New York University on 13 October 2012, organized by Samuel Scheffler.

4. A rare example of economists basing their analysis on Kantian ethics is Greaker et al. (2013).

5. See Rawls (1971). For a thorough examination of the issues and challenges around approaches to intergenerational justice, with a focus on Rawls and the fundamental difficulties with contract theory, including its limitations when applied to climate change, see for example the volume edited by Gosseries and Meyer (2009). See also Gardiner (2011a and 2011b).

6. He also emphasized the avoidance of extremes, such as in the notion of courage which properly avoids either recklessness or timidity.

7. See, e.g., Cafaro and Sandler (2010).

8. Jamieson (2010).

9. While some think of utilitarianism with an individual focus, it is more common to think of it as a way of evaluating states of affairs, where the link to individual action is a distinct issue.

10. Jamieson (2010).

11. We have noted that discussions of utilitarianism, for example, can and do treat rules and structures which, if they were in place, could lead to good outcomes in a utilitarian sense. They can be seen as "rules" that could guide individuals, but also as rules or structures that might be a good way of organizing society.

12. Berlin (1958).

13. Berlin (1990).

14. See, for example, Sen (1999) on capabilities, or Stern, Dethier, and Rogers (2005) on empowerment. The literature on international justice, for example Shue (1996) and Singer (2010a), includes discussion of the positive/negative distinction as applied to rights and duties.

15. For discussion of ways in which scientific evidence on climate change has been attacked and of who has carried out and financed the attacks, see Michaels (2008); McCright and Dunlap (2011b); Oreskes and Conway (2010); and Stern (2009, chapter 2).

16. Those who speak of climate justice are often drawing attention to current damage in the developing world as a result of previous rich-country action; see chapter 6.

17. As in Sen (e.g., 1999).

18. See Sen (2009).

19. This language was used by the environmental campaigner and Nobel Peace Prize laureate Wangari Maathai (who died in 2011). Similarly Mary Robinson, the distinguished former president of Ireland, has established the Mary Robinson Foundation for Climate Justice.

20. If our actions—here, emitting—deprive a future generation of its ability to exist, then different justice questions arise, including whether people have rights to exist. See Parfit (1984).

21. See Becker (1968); Carr-Hill and Stern (1977 and 1979).

22. Sandel (2012) provides a recent example of the expression of this position.

23. See, e.g., Titmuss (1970) and his focus on the example of blood donation.

24. Sometimes it is argued that income distribution should be tackled elsewhere. Often one can indeed argue that more should be done to redistribute income via tax and transfer methods, but that still leaves the issue that, on information grounds, tax/transfer policies would not equalize welfare weights.

25. See, for example, Arrow et al. (2012); Asheim (2007 and 2010); Pezzey and Toman (2002); Toman (1994).

26. See, for example, Asheim (2010) and Buchholz (1997).

27. Asheim (2010), for example, and see chapter 5 of this book.

28. For a discussion of rule and act utilitarianism see, for example, Sen and Williams (1982).

29. See Asheim (2010) for a discussion of formal results on sustainability and Paretianism as just mentioned.

30. Though, as philosophical discussion about the so-called "non-identity problem" (see Parfit 1984) has revealed, whatever path we take on climate change will ultimately lead to a different set of persons being born than would be born as a result of having taken a different path.

31. See, for example, Broome (2004, 2009, and 2012). As it happens, John Broome started his graduate work like myself as a student of James Mirrlees in Oxford in the late 1960s, working on the mathematical economics of public policy. He is now Professor of Moral Philosophy at Oxford. I am very grateful for his guidance.

32. See, for example, IPCC (2007).

33. World Health Organization (2002).

34. It is a position of longstanding interest in economics—see, for example, Meade (1951).

35. Parfit (1984), 388.

36. See Broome (2004). Also see Broome (2010 and 2012) for further discussion of some of the difficulties with "neutrality intuition."

37. For a useful summary discussion of the difficulties, see the online *Stanford Encyclopedia of Philosophy*: http://plato.stanford.edu/archives/fall2010/entries/repugnant-conclusion.

38. See, for example, Stern, Dethier, and Rogers (2005).

39. World Bank (2012c).

40. See, for example, Gwatkin (1979) for a description of the sterilization program and its subsequent effects.

41. Standard definition, for example in Meade (1955).

42. Broome (2010).

43. The possibility of making both current and future generations better off is emphasized and discussed explicitly in Stern (2009, 85) and Stern (2010). The remark from *The Stern Review* (Stern 2007) that climate change is the greatest market failure the world has seen has received very prominent coverage. Foley (2007) is the earliest written version of which I am aware that applies the Pareto-inefficiency idea explicitly to current and future generations; he gives the point strong emphasis. See also Sinn (2007), who argues that delaying fossil fuel extraction is Pareto-improving.

44. See, for example, Stern (2010) for a discussion.

45. See, for example, Stern, Dethier, and Rogers (2005), 261, for a discussion.

Chapter 7

1. The release of the four constituent Working Group reports of the *Fifth Assessment Report* was staggered: the first report, on the physical science basis, was released in September 2013; the second report on impacts, adaptation, and vulnerability in March 2014; the third, on mitigation actions, in April 2014; and the fourth, synthesis report was released in November 2014.

2. Such enforcement was destined to be weak, since it was essentially the obligation to do more in the next period if a country's reductions in this period were less than its obligations called for.

3. Technically, the aggregate Kyoto commitments were to reduce GHG emissions by 4.2% relative to 1990 levels (5.2% relative to the country-specific base years used for establishing national commitments) by the Protocol's first commitment period, 2008–2012 (measuring the average of those five years): see IPCC (2014b), chapter 13, p. 59.

4. Garnaut (2008); Wara and Victor (2008); IPCC (2014b), chapter 13.

5. See IPCC (2014b), section 13.13.1.

6. See IPCC (2014b), section 13.13.1.

7. See figure 1.3 in chapter 1.

8. Assuming the budget for a 50–50 chance of a 2°C path is less than 35 billion tonnes in 2030. Potentially, we can do less now and more later and still achieve a 2°C path. For example, with strong assumptions about the ability to go to zero or negative emissions in the second half of the century, the 35 billion tonnes in 2030 might be raised to 42.

9. Stern and Rydge (2012).

10. United Nations (2010). I was a member of this advisory group.

11. UNFCCC (2012).

12. See UNEP (2013), and the discussion in chapter 1.

13. UNFCCC (2013), clause 2(b).

14. UNEP (2013).

15. Ross Garnaut has used the term "concerted unilateral action" to describe the de facto system of global climate mitigation that has emerged from both international cooperation and domestic efforts in recent years (see, e.g., Garnaut 2011).

16. Nachmany et al. (2014).

17. Ibid. The GLOBE study defines laws as "Legislation, or regulations, policies and decrees with a comparable status, that refer specifically to climate change or that relate to reducing energy demand, promoting low-carbon energy supply, tackling deforestation, promoting sustainable land use, sustainable transportation, or adaptation to climate impacts." Only federal legislation has been taken into account. Of these nearly 500 laws, roughly 60 percent were legal acts passed by parliaments and 40 percent were executive orders or policies.

18. Ibid. Some flagship laws are aspirational rather than binding, and not all of them have the statutory force of an act of parliament; in some countries the main climate policy is an executive order or government white paper.

19. Ibid. Some carbon pricing mechanisms apply only to smaller areas within a jurisdiction, such as domestic carbon taxes in a number of EU member states or emission trading between some Canadian regions.

20. Bassi et al. (2014). The value of carbon prices, particularly for implicit prices, depends on the methodology used, which differs from study to study: see Bassi et al. (2014) for discussion. The prices from that study have been converted from pounds to US dollars at a rate of 1:1.6.

21. Nachmany et al. (2014).

22. See Green and Stern (2014).

23. At the time of writing, the latest available CO_2e data (World Resources Institute 2014a) record China's total emissions (excluding land use and forestry) at around 10.5 billion tonnes (Gt) in 2011, with CO_2 emissions (excluding land use and forestry) at 9 Gt and non-CO_2 GHG emissions at around 1.5 Gt (about 17% of CO_2 emissions). The most recent CO_2 data put China's CO_2 emissions from fossil fuels and cement at 10 Gt in 2013 (Global Carbon Project 2014). Assuming non-CO_2 GHG emissions are again about 17% of CO_2 emissions, we can infer that China's CO_2e emissions would have been roughly 11.7 Gt in 2013, meaning they are likely to have exceeded 12 Gt in 2014.

24. Hamilton (2014).

25. Umwelt Bundesamt (2014).

26. Central Committee of the Communist Party of China (2013).

27. Central Committee of the Communist Party of China (2013); National Development and Reform Commission (2013); Ministry of Environmental Protection of the People's Republic of China (2013).

28. The seven industries are energy-efficient and environmental technologies; new energy; new-energy vehicles; next generation information technology; biotechnology; advanced equipment manufacture; and new materials.

29. FS-UNEP (2014).

30. Martin (2014).

31. Ma (2013). See also World Resources Institute (2014b).

32. See, e.g., Myllyvirta (2014).

33. Personal communication with staff of the Global Commission on the Economy and Climate and the Climate Policy Initiative.

34. See Green and Stern (2014), part 3(c), for discussion. See also Garnaut (2014) and Myllyvirta (2014).

35. Chen and Reklev (2014).

36. See Khan (2014).

37. See Green and Stern (2014) for discussion. See also Garnaut (2014).

38. Green and Stern (2014).

39. Ibid.

40. World Resources Institute (2014a). Figures exclude land use change and forestry.

41. UNEP (2012).

42. Government of India (2008).

43. The report was prepared by an expert group set up by the Planning Commission. The major sectors examined in the report were power, transport, industry, buildings, and forestry, with a special emphasis on energy efficiency and renewable energy.

44. Government of India (2014), 86.

45. Mohan (2014); Yeo (2014).

46. Katakey and Chakraborty (2014).

47. Pearson and Chakraborty (2014).

48. Hamilton (2014).

49. World Resources Institute (2014a). Upper bound of emissions ranges includes emissions from land use change and forestry.

50. Accumulated deforestation in the Brazilian Amazon over the period 1988 to 2012 was 396,772 km^2 (Brazilian Ministry of Science and Technology 2013).

51. Bagnoli, Goeschl, and Kovács (2008).

52. GCEC (2014).

53. World Resources Institute (2014a). Figures exclude land use change and forestry.

54. UNEP (2010).

55. World Resources Institute (2014a). Upper bound of emissions range includes emissions from land use change and forestry.

56. Federal Democratic Republic of Ethiopia (2011). That cost estimate does not include co-benefits beyond emissions reductions.

57. World Resources Institute (2014a). Upper bound of emissions range includes emissions from land use change and forestry.

58. World Resources Institute (2014a). Upper bounds of ranges include emissions from land use change and forestry.

59. Canada's National Greenhouse Gas Inventory reports show that Canada's emissions were roughly 700 million tonnes per year at the end of 2012, or 18% above its 1990 emissions (591 million tonnes). Its Kyoto target was a 6% *reduction* below 1990 levels. See Environment Canada (2014).

60. Lies and Reklev (2013).

61. 549 U.S. 497 (2007).

62. See http://www.whitehouse.gov/climate-change and http://www.epa.gov/

63. I am grateful to Frank Ackerman for bringing this point to my attention.

64. C40/Arup (2014b).

65. C40/Arup (2014a).

66. Lagarde (2013).

67. IMF (2014).

68. The Bank's pioneering publications with the Potsdam Institute for Climate Impact Research on the expected impacts of a 4°C warmer world illustrate the challenges in great detail: see World Bank (2012b and 2013a).

69. World Bank (2014a).

70. See World Bank (2014c).

71. See https://climatehealthcommission.wordpress.com/.

72. IDDRI/SDSN (2014). See section 2.2 above for more on the DDPP.

73. IEA (2012e). Of these 2,860 billion tonnes of CO_2, around 63% is from coal, 22% from oil, and 15% from gas.

74. IPCC (2013).

75. Carbon Tracker (2013).

76. See, e.g., Gore and Blood (2014).

77. See GCEC (2014), chapter 6.

78. Shankleman (2014).

79. GCEC (2014).

80. Carbon Disclosure Project (2014).

Chapter 8

1. GCEC (2014).

2. See Stern and Rydge (2012).

3. See, for example, Barrett (2007).

4. Ross Garnaut, for example, has used the term "concerted unilateral mitigation" to describe the de facto system of global climate mitigation that has emerged from both international cooperation and domestic efforts in recent years (see, e.g., Garnaut 2011).

5. This section was prepared in collaboration with Fergus Green and draws on material first published in his Grantham Research Institute policy paper of October 2014 (Green 2014). See also Stern (2014c).

6. UNFCCC (2010), at paragraph [4].

7. Gurría (2013).

8. Figueres (2013).

9. GCEC (2014), chapter 8.

10. Gurría (2013).

11. See, e.g., Committee on Climate Change (2010).

12. Fankhauser (2012). See also IDDRI/SDSN (2014).

13. Fankhauser (2012).

14. See Green (2012).

15. See IPCC (2014b), chapter 13, p. 27 and literature there cited; and for a policymaker's perspective along similar lines, see T. Stern (2014).

16. It has been argued by US negotiators that the president has the authority to accept such an agreement as legally binding without Congressional consent: see Davenport (2014).

17. GCEC (2014). See also United States Government (2014) and T. Stern (2014).

18. Green and Stern (2014).

19. See, e.g., the US's submission to the negotiating process (United States Government 2014).

20. Bodansky and Diringer (2014).

21. And see, for example, Stern (2008 and 2009).

22. See, e.g., Bell et al. (2013).

23. For details about how this could work, see Green, McKibbin, and Picker (2010).

24. IEA (2013b).

25. The Global Commission on the Economy and Climate recommended a commitment to introduce no new unabated coal-fired power stations in developed countries, to be followed rapidly by the same commitment in other countries (see section 2.10 above).

26. IEA (2013b).

27. See http://www.unep.org/ccac/.

28. GCEC (2014), chapter 3.

29. See C40/Arup (2014b).

30. See GCEC (2014). The future price of fossil fuels will be uncertain, with both oscillations and trends, but that of renewables is likely to continue falling.

31. See IEA (2014a), figure 1.22.

32. See GCEC (2014), chapter 7.

33. IEA (2013d), table 5.2 and figure 5.3. For figures on India and China, see Kempener, Anadon, and Condor (2010).

34. Grubb, Hourcade, and Neuhoff (2014).

35. King et al. (forthcoming). The remainder of this paragraph draws on this pamphlet.

36. In the case of concentrated solar power, sunnier countries with suitable conditions for siting plants have a greater interest than cloudier ones with less suitable conditions. For low-carbon technologies not discussed here, there are typically a significant number of countries with renewable resource conditions suited to the deployment of each technology.

37. I have been a trustee of the International Food Policy Research Institute (IFPRI), one of the CGIAR institutions, and was actively involved in CGIAR as chief economist of the World Bank (2000–2003).

38. GCEC (2014), chapter 3.

39. GCEC (2014), chapter 8.

40. I was personally involved in key aspects of the process toward the G8 Gleneagles summit in 2005 as the lead in the writing of the report of the Commission for Africa.

41. According to the CAIT database of CO_2e emissions (World Resources Institute 2014a), the EU (28), China, and the US together emitted around 20 billion (44%) of the 45 billion tonnes of world emissions in 2011. Data for 2013 on CO_2 emissions from fossil fuel and cement put the EU's, US's, and China's combined share of those emissions at 52% (Global Carbon Project 2014).

Chapter 9

This chapter is based on Stern (2014b), which was published in *Economics and Philosophy* in November 2014.

1. IPCC (2014b), Technical Summary, figure TS.2(b), showing historical emissions from 1750 to 2010.

2. *United Nations Framework Convention on Climate Change*, opened for signature 9 May 1992, 1771 UNTS 107 (entered into force 21 March 1994), art. 3.

3. *Kyoto Protocol to the United Nations Framework Convention on Climate Change*, opened for signature 16 March 1998, 2303 UNTS 148 (entered into force 16 February 2005), arts. 4(1), (3).

4. World Bank (2014b). GDP measured in purchasing power parity at current international dollars. On this indicator, "high-income" countries' (as per World Bank classification) share of world output was around 72% between 1990 and 1992. Note that a more common definition of "developed" countries is the World Bank's "high-income OECD" classification, which is a subset of the "high-income" countries. When calculated on that definition, the developed country GDP share was just under two-thirds of world output in the early 1990s (falling to just under half in 2012)—this is the figure I normally quote for developed country GDP in the mid-1980s / early 1990s (e.g., elsewhere in this book and in my note as chair of the Economic Advisory Panel for the report of the Global Commission on the Economy and Climate). I use the wider, "high-income" definition here to ensure a like-for-like comparison with the IPCC's emissions data quoted here, which uses the "high-income" classification.

5. IPCC (2014b), chapter 1, figures 1.4 and 1.6. Figure 1.6 of the IPCC report shows that high-income countries (as defined by the World Bank) accounted for just under 50% of global GHG emissions (18.3 billion of 37.2 billion tonnes) in 1990.

6. World Bank (2014b). GDP measured in purchasing power parity at current international dollars. On this indicator, low-income and middle-income countries were together responsible for 43% of world output in 2012. If "high-income non-OECD" countries are added to the low-income and middle-income figures, the developing country share in 2012 rises to over 50%.

7. IPCC (2014b), chapter 1, figures 1.4 and 1.6, showing emissions to 2010. Figure 1.6 of the IPCC report shows that low-income to upper-middle-income countries (as defined by the World Bank) accounted for 61% of global GHG emissions (29.6 billion of 48.3 billion tonnes) in 2010. Given the falling developed-country emissions in 2010–2014 and rising emissions from developing countries, the fraction could now (2014) be around two-thirds.

8. IPCC (2014b), chapter 1, figure 1.4 shows that low-income and lower-middle-income countries' per capita emissions were around one-third those of high-income countries in 2010; upper-middle-income countries' per capita emissions were around half of high-income countries'. China's emissions per capita are likely already similar to EU levels.

9. See the New Climate Economy report (GCEC 2014) and chapter 2 of this book.

10. As explained in section 1.4, we could cut emissions less now and more later. For example, with strong assumptions about the ability to go to zero or negative emissions in the second half of the century, the 35 billion tonnes in 2030 might be raised to 42.

11. IEA (2010a and 2013b).

12. These are the most up to date and easily available GHG and CO_2 data with some consistency across countries. The main points we draw from these data about broad histories and cross-country comparisons would not likely be altered by more recent data. Note that CO_2e data are not easily available for time series for a large cross-section of countries, so we use CO_2. The broad picture for CO_2e is likely to be similar.

13. See section 7.3.2 (section on China).

14. Based on World Resources Institute (2014a). See section 7.3.2 (section on China), which explains why China's emissions are likely to be more like 9 tonnes of CO_2e per capita in 2014.

15. See, for example, Allen et al. (2009) or IPCC (2013).

16. New important reports such as from the IPCC (2014b) estimate the remaining "space" to be in the region of 1–1.5 trillion tonnes of CO_2 emissions consistent with 2°C trajectories (bearing in mind that data limitations restrict calculating "CO_2 budgets" as opposed "CO_2 equivalent budgets"—this is, as discussed in chapter 2, because CO_2 is the strongest driver of radiative forcing and the gas that is easiest to measure). To a rough approximation, this is equivalent at the very most to current annual world emissions over a 40-year period. Given that emissions are rising, this space would be exhausted well before 40 years without strong action.

17. For example, market prices of $50 or more may be necessary to sustain CCS, which itself is likely to be an important part of a path for holding to 2°C.

18. See, for example, Agarwal and Narain (1991); Jamieson (2001); Baer (2002); Höhne, den Elzen, and Weiss (2006); Singer (2010b).

19. Probably of the order of half a trillion tonnes CO_2e.

20. See, for example, Sen (1999 and 2009).

21. Some appear to advocate equal per capita emissions as a "pragmatic" expression of equal right to development on the grounds that emissions are necessary for development. But, as I have argued, while energy may be necessary, there is no rigid relationship between energy and income/output or between energy and emissions. The challenge is indeed to break the relationship between energy and emissions and use energy much more efficiently. Further, the insistence on such a formula is not "pragmatic" if the formulation leads to deadlock (see below).

22. I was part of the panel discussion during which he made the remark.

23. One could complicate by building in various incentive and response structures to transfer payments, but the basic point of the direction and magnitude of transfers being strongly influenced by the social marginal utility of income would stand.

24. See Caney (2010) for a discussion.

25. See, for example, Tata Institute of Social Sciences (2010).

26. Or "isolationist" in the Caney sense.

27. Stern (2009).

28. See, for example, Drèze and Stern (1990), or more generally the *Journal of Public Economics* (for example). The arguments go back at least to James Meade and Paul Samuelson in the 1950s, and are expressed with great lucidity in Meade (1955) and its mathematical supplement.

29. See GCEC (2014).

30. See, for example, Jackson (2009).

31. See Romani, Rydge, and Stern (2012).

Chapter 10

1. The science of psychology has yielded many insights into the psychological mechanisms at work in the course of communication, some of which I discuss further below. Yet our understanding of the basic elements of effective communication, at least in spoken form, can still learn much from Aristotle's treatise *Rhetoric*, from the fourth century BC: it requires (i) ethos—credible, trusted messengers who can combine (ii) logos—appeals to logic with (iii) pathos—appeals to emotion.

2. See, e.g., Kasser and Crompton (2009); Corner and Roberts (2014); Marshall (2014).

3. Brulle, Carmichael, and Jenkins (2012). The study also found that two other factors were important influences on Americans' concerns about climate change: the prominence of other issues (economic downturn, foreign wars); and

"elite cues" (i.e., from political leaders), with the latter being the most important factor.

4. Kahneman (2011) calls this the "availability" heuristic. In a famous study conducted by Paul Slovic and colleagues (Lichtenstein et al. 1978), respondents were asked to compare the frequency of various pairings of "causes of death"—one frequently reported in the media, the other not. Respondents' answers were systematically, and incorrectly, biased in favor of the media-reported causes—for example, tornadoes were seen as more frequent killers than asthma, though the latter caused 20 times more deaths. See discussion in Kahneman (2011) at p. 138.

5. Although it should be recognized that direct causation can sometimes be established.

6. Painter (2013).

7. See, e.g., Oosterhof, Heuvelman, and Peters (2009).

8. O'Neill et al. (2013).

9. Boykoff and Boykoff (2004).

10. Interestingly, climate change skepticism in the media appears to be a largely Anglophone phenomenon: Painter (2011).

11. For a good survey of the relevant issues and literature, see American Psychological Association (2010).

12. See Kahneman (2011); Cialdini (1993).

13. Joireman et al. (2010).

14. Li, Johnson, and Zaval (2011).

15. Risen and Critcher (2011).

16. See, e.g., Leiserowitz (2007).

17. Kahan et al. (2012).

18. Ibid.

19. See Kahneman and Tversky (1979); Kahneman, Knetsch, and Thaler (1991); Kahneman (2011).

20. See, e.g., Coggan (2013); Wilks-Heeg, Blick, and Crone (2012); Gilens and Page (2014).

21. See, e.g., Kay (2012).

22. McCright and Dunlap (2011a).

23. World Health Organization (2014).

24. Lovei (1998).

25. Ibid.

26. See http://www.madd.org/about-us/history/.

27. See, e.g., Appiah (2011); Bicchieri (2006); Brennan et al. (2013); Pinker (2011).

28. Greene et al. (2001).

29. Gauri (2012).

30. Cialdini (1993).

31. This discussion of “packaging” reforms draws on Ahmad and Stern (1991) and Green and Stern (2014).

32. Hills (2012).

33. Vatican Radio (2014).

34. I had the privilege of working closely with Bob Geldof when leading the writing of the Report of the Commission for Africa in 2004–2005.

35. Such calculations of loss of life in terms of GDP are standard but can be problematic. The point here is that the loss of life and health costs are very large.

36. See Hamilton (2014).

37. See https://climatehealthcommission.wordpress.com/ucl-lancet-commission/.

38. See, e.g., the front cover and editorial in the 5 April edition of the *British Medical Journal* and the letter to *The Times* by 60 medical professionals on 29 March 2014.

39. See www.caringforclimate.org. The other two actions that businesses are invited to undertake under the Criteria are setting an internal carbon price and communicating progress.

40. See World Bank (2014c).

41. Business Green (2014). See section 1.4 of this book for a discussion of carbon budgets and the remaining carbon space.

42. See http://www.wemeanbusinesscoalition.org/.

43. C40, http://www.c40.org/why_cities.

44. C40, http://www.c40.org/why_cities.

45. C40/Arup (2014b).

46. There is a powerful moral argument here. Further, some psychologists argue there is strong evidence that the idea of reciprocity—others helped us so we should help others (Cialdini 1993)—is often persuasive in shaping action.

47. This song, written by Graham Nash and first released on the Crosby, Stills, Nash & Young album *Déjà Vu* in 1970, has a particular resonance for me, as it was played at the ceremony at which I received the 2013 Stephen H. Schneider Award for Outstanding Climate Science Communication. When it came to “teaching our children well”—along with teaching a great many adults—about the science of climate change, there was no one better than Steve Schneider.

Why Are We Waiting?

The Logic, Urgency, and Promise of Tackling Climate Change

By: Nicholas Stern

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