

# TABLE OF CONTENTS

## **PART 1**

TECHNOLOGY AND  
THE GLOBAL ENERGY ECONOMY TO 2050

## **PART 2**

THE TRANSITION  
FROM PRESENT TO 2050

## **PART 3**

ENERGY TECHNOLOGY:  
STATUS AND OUTLOOK

|          |       |  |    |
|----------|-------|--|----|
|          |       | Introduction   | 1  |
| <b>1</b> | ..... | Scenarios  | 2  |
|          | ..... | Technology roadmaps  | 3  |
|          | ..... | Research, development and demonstration                                | 4  |
| <b>2</b> | ..... | Deployment and technology learning                                     | 5  |
|          | ..... | Investment issues  | 6  |
|          | ..... | Fossil fuel-fired power plants and CO <sub>2</sub> capture and storage | 7  |
|          | ..... | Nuclear  | 8  |
|          | ..... | Biomass and bioenergy  | 9  |
|          | ..... | Wind   | 10 |
|          | ..... | Solar  | 11 |
| <b>3</b> | ..... | Hydro, geothermal and ocean energy                                     | 12 |
|          | ..... | Electricity systems  | 13 |
|          | ..... | Methane mitigation   | 14 |
|          | ..... | Transport  | 15 |
|          | ..... | Industry   | 16 |
|          | ..... | Buildings and appliances   | 17 |
|          |       | Annexes  |    |

|                  |   |            |
|------------------|---|------------|
|                  | <b>Foreword</b> . . . . .   | <b>3</b>   |
|                  | <b>Acknowledgements</b> . . . . .   | <b>5</b>   |
|                  | <b>Table of contents</b> . . . . .  | <b>12</b>  |
|                  | List of figures . . . . .   | 22         |
|                  | List of tables. . . . .   | 31         |
|                  | <b>Executive summary.</b> . . . . .   | <b>37</b>  |
| <br>             |   |            |
| Chapter <b>1</b> | <b>Introduction</b> . . . . .   | <b>47</b>  |
|                  | <b>The political context.</b> . . . . .   | <b>48</b>  |
|                  | <b>The purpose and scope of this study.</b> . . . . .                           | <b>49</b>  |
|                  | <b>Implications of the scenarios for climate change</b> . . . . .               | <b>50</b>  |
|                  | <br>  |            |
|                  | <b>PART 1</b>   |            |
|                  | <b>Technology and the Global Energy Economy to 2050</b>                         |            |
| <br>             |   |            |
| Chapter <b>2</b> | <b>Scenarios</b> . . . . .  | <b>55</b>  |
|                  | <b>Scenario characteristics.</b> . . . . .                                      | <b>57</b>  |
|                  | <b>CO<sub>2</sub> emission trends</b> . . . . .                                 | <b>61</b>  |
|                  | <b>Reductions in CO<sub>2</sub> emissions by contributing factor.</b> . . . . . | <b>63</b>  |
|                  | Power generation . . . . .  | 68         |
|                  | CO <sub>2</sub> capture and storage (CCS) . . . . .                             | 69         |
|                  | Fuel switching in end-use sectors . . . . .                                     | 70         |
|                  | End-use energy efficiency improvements . . . . .                                | 71         |
|                  | <b>Energy demand and CO<sub>2</sub> emissions by sector</b> . . . . .           | <b>77</b>  |
|                  | Electricity generation . . . . .  | 83         |
|                  | Transport . . . . .   | 91         |
|                  | Buildings . . . . .   | 99         |
|                  | Industry . . . . .  | 106        |
|                  | <b>Energy demand by fuel.</b> . . . . .   | <b>113</b> |
|                  | Coal . . . . .  | 115        |
|                  | Oil . . . . .   | 115        |

|                          |            |
|--------------------------|------------|
| Natural gas              | 118        |
| Electricity              | 119        |
| Biomass                  | 121        |
| <b>Beyond 2050</b> ..... | <b>122</b> |

## **PART 2**

### **The Transition from Present to 2050**

|                  |   |            |
|------------------|---|------------|
| <b>Chapter 3</b> | <b>Technology roadmaps</b>  | <b>127</b> |
|                  | .....   |            |
|                  | <b>Overview</b> .....   | <b>127</b> |
|                  | <b>Roadmaps</b> .....   | <b>128</b> |
|                  | Limitations of the roadmaps   | 129        |
|                  | What is included in the roadmaps  | 129        |
|                  | How to use the roadmaps   | 130        |
|                  | List of technology roadmaps   | 131        |
|                  | <b>Next steps</b> .....   | <b>133</b> |
| <br>             |   |            |
| <b>Chapter 4</b> | <b>Research, development and demonstration</b>  | <b>169</b> |
|                  | .....   |            |
|                  | <b>Introduction</b> .....   | <b>169</b> |
|                  | Phases of technology development  | 169        |
|                  | The role of government in energy technology innovation  | 170        |
|                  | <b>RD&amp;D trends</b> .....  | <b>171</b> |
|                  | Government investment in energy RD&D  | 171        |
|                  | Trends in private sector RD&D   | 174        |
|                  | General trends in energy RD&D   | 178        |
|                  | <b>Technology RD&amp;D needs</b> .....  | <b>178</b> |
|                  | <b>Priority near-term RD&amp;D targets for the development of lower-carbon technologies</b> ..... | <b>180</b> |
|                  | Power generation technologies   | 181        |
|                  | Industry  | 181        |
|                  | Buildings and appliances  | 182        |
|                  | Transport   | 183        |

|                  |   |            |
|------------------|---|------------|
|                  | <b>RD&amp;D policies needed to achieve technology priorities . . . .</b>                        | <b>184</b> |
|                  | Supply-push and market-pull: a policy portfolio approach  | 184        |
|                  | RD&D spending   | 185        |
|                  | RD&D priority setting: a technology portfolio approach  | 187        |
|                  | Basic science   | 187        |
|                  | Applied R&D and demonstration   | 189        |
|                  | Gap between RD&D and deployment: the “valley of death”  | 191        |
|                  | Public–private partnerships: navigating applied R&D,<br>demonstration and the “valley of death” | 191        |
|                  | International collaboration   | 192        |
| <b>Chapter 5</b> | <b>Deployment and technology learning</b>   | <b>201</b> |
|                  | .....   |            |
|                  | <b>Overview . . . . .</b>   | <b>201</b> |
|                  | <b>Deployment and the role of technology learning . . . . .</b>                                 | <b>202</b> |
|                  | Deployment versus diffusion (commercialisation)   | 202        |
|                  | <b>Technology learning curves . . . . .</b>   | <b>203</b> |
|                  | Using learning curves to estimate deployment/diffusion costs                                    | 203        |
|                  | Technology learning and diffusion   | 207        |
|                  | <b>Deployment costs: investment implications of the scenarios . .</b>                           | <b>208</b> |
|                  | Deployment costs and learning investments   | 208        |
|                  | Supply-side costs: investment needs   | 209        |
|                  | Demand-side costs: investment needs   | 210        |
|                  | Limitations of this analysis  | 212        |
|                  | <b>Regional breakdown of deployment for key<br/>power generation technologies . . . . .</b>     | <b>212</b> |
|                  | Onshore wind  | 213        |
|                  | Offshore wind   | 213        |
|                  | Photovoltaics (PV)  | 213        |
|                  | CO <sub>2</sub> capture and storage (CCS)   | 214        |
|                  | Nuclear   | 214        |
|                  | <b>Barriers to technology diffusion . . . . .</b>   | <b>214</b> |
|                  | <b>Policy options to accelerate deployment . . . . .</b>  | <b>217</b> |
|                  | Analysis of renewable energy policy effectiveness   | 217        |
|                  | <b>International co-operation to promote technology deployment .</b>                            | <b>218</b> |
| <b>Chapter 6</b> | <b>Investment issues</b>  | <b>221</b> |
|                  | .....   |            |
|                  | <b>Investment needs in the Baseline scenario . . . . .</b>                                      | <b>223</b> |

|  |            |
|--|------------|
| <b>Additional investment needs in the ACT Map and BLUE Map scenarios. . . . .</b>    | <b>224</b> |
| Investment needs by sector   | 228        |
| Investment patterns over time  | 236        |
| Regional differences   | 239        |
| Investment needs and global investment flows   | 240        |
| <b>Financial barriers to investment in clean and efficient technologies. . . . .</b> | <b>244</b> |
| <b>Policy issues and options . . . . .</b>   | <b>245</b> |

## **PART 3**

### **Energy Technology: Status and Outlook**

|  |            |
|--|------------|
| <b>Chapter 7 Fossil fuel-fired power plants and CO<sub>2</sub> capture and storage . . . . .</b> | <b>251</b> |
| <b>Overview . . . . .</b>  | <b>252</b> |
| <b>The current status of coal and natural gas-fired electricity generation . . . . .</b>         | <b>253</b> |
| Power generation efficiency  | 255        |
| CO <sub>2</sub> emissions  | 257        |
| Age profile of the capital stock   | 258        |
| <b>Technology status/development . . . . .</b>   | <b>259</b> |
| Advanced steam cycles  | 259        |
| Fluidised bed combustion (FBC)   | 260        |
| Natural gas combined-cycle (NGCC)  | 260        |
| Integrated gasification combined-cycle (IGCC)  | 261        |
| Combined heat and power (CHP)  | 262        |
| Fuel cells   | 266        |
| <b>CO<sub>2</sub> capture and storage (CCS) . . . . .</b>  | <b>268</b> |
| CO <sub>2</sub> capture  | 269        |
| Transporting CO <sub>2</sub>   | 271        |
| Geological storage   | 272        |
| Prospects for CCS  | 273        |
| Current status of CCS: major projects  | 274        |
| International efforts to accelerate deployment of CCS  | 275        |
| Barriers to large-scale deployment of CCS  | 279        |

|                  |   |            |
|------------------|---|------------|
| <b>Chapter 8</b> | <b>Nuclear</b>  | <b>283</b> |
|                  | .....   |            |
|                  | <b>Overview</b> .....                                       | <b>284</b> |
|                  | <b>The current status of nuclear power generation</b> ..... | <b>284</b> |
|                  | <b>The cost of nuclear power</b> .....                      | <b>286</b> |
|                  | Construction costs  | 286        |
|                  | Operating (O&M and fuel cycle) costs                        | 287        |
|                  | Back-end costs  | 289        |
|                  | Cost reduction opportunities: existing plants               | 289        |
|                  | New nuclear power plant costs                               | 290        |
|                  | Nuclear power cost sensitivity                              | 291        |
|                  | External costs  | 294        |
|                  | <b>Safety</b> .....   | <b>294</b> |
|                  | <b>Proliferation of nuclear weapons</b> .....               | <b>296</b> |
|                  | <b>High-level waste disposal</b> .....                      | <b>297</b> |
|                  | <b>New nuclear build and construction rates</b> .....       | <b>298</b> |
|                  | <b>Future technology options</b> .....                      | <b>303</b> |
|                  | Small- and medium-scale nuclear plants                      | 303        |
|                  | <b>Alternative uses of nuclear power</b> .....              | <b>304</b> |
|                  | <b>Future prospects</b> .....                               | <b>305</b> |
| <br>             |   |            |
| <b>Chapter 9</b> | <b>Biomass and bioenergy</b>                                | <b>307</b> |
|                  | .....   |            |
|                  | <b>Introduction and scenario results</b> .....              | <b>308</b> |
|                  | Scenarios   | 309        |
|                  | Costs   | 311        |
|                  | Policy options  | 311        |
|                  | <b>Biomass supply and demand: by use and region</b> .....   | <b>313</b> |
|                  | Crop yields and plant breeding                              | 314        |
|                  | Harvesting, logistics and pre-treatment of biomass          | 314        |
|                  | Energy crops  | 319        |
|                  | Biomass potential   | 320        |
|                  | <b>Biomass conversion technologies</b> .....                | <b>321</b> |
|                  | Power generation: combustion                                | 321        |

|                                |     |
|--------------------------------|-----|
| Power generation: gasification | 326 |
| Combined heat and power (CHP)  | 328 |
| Carbon-dioxide mitigation      | 330 |
| Biofuels for transport         | 331 |

## Chapter 10 **Wind** **339**

|   |            |
|---|------------|
| <b>Wind power overview</b>                                | <b>340</b> |
| Scenario highlights                                       | 343        |
| Technology developments                                   | 345        |
| Cost developments   | 345        |
| Market overview   | 346        |
| Environmental factors                                     | 348        |
| <b>Onshore wind power</b>                                 | <b>348</b> |
| Overview  | 348        |
| Efficiency improvements                                   | 349        |
| Onshore wind power costs                                  | 349        |
| <b>Offshore wind power</b>                                | <b>352</b> |
| Overview  | 352        |
| Offshore wind power costs                                 | 353        |
| <b>Further technology development</b>                     | <b>356</b> |
| Wind turbine technology                                   | 356        |
| Superconducting generators                                | 357        |
| Smart rotors  | 357        |
| Novel concepts  | 357        |
| New offshore concepts                                     | 357        |
| <b>Wind power research, development and demonstration</b> | <b>359</b> |
| RD&D international frameworks                             | 359        |
| RD&D priorities   | 360        |
| <b>System aspects</b>                                     | <b>361</b> |
| Additional costs of wind integration                      | 362        |

## Chapter 11 **Solar** **365**

|                      |            |
|----------------------|------------|
| <b>Introduction</b>  | <b>366</b> |
| <b>Photovoltaics</b> | <b>368</b> |



|                   |  |            |
|-------------------|--|------------|
|                   | Current situation and market trends  | 368        |
|                   | Technology description/status  | 370        |
|                   | Costs and potential for cost reduction   | 373        |
|                   | Future R&D efforts   | 375        |
|                   | <b>Concentrated solar power</b> . . . . .  | <b>378</b> |
|                   | Technology description/status  | 380        |
|                   | Costs and potential for cost reduction   | 383        |
|                   | Future R&D efforts   | 384        |
| <b>Chapter 12</b> | <b>Hydro, geothermal and ocean energy</b> . . . . .                                      | <b>387</b> |
|                   | <b>Hydropower</b> . . . . .  | <b>389</b> |
|                   | Status   | 389        |
|                   | Costs  | 390        |
|                   | Future R&D efforts   | 391        |
|                   | Challenges to future deployment  | 391        |
|                   | <b>Geothermal</b> . . . . .  | <b>392</b> |
|                   | Status   | 392        |
|                   | Costs  | 393        |
|                   | Future R&D efforts   | 394        |
|                   | Challenges to future deployment  | 395        |
|                   | <b>Ocean energy</b> . . . . .  | <b>396</b> |
|                   | Status   | 396        |
|                   | Costs  | 398        |
|                   | Future R&D efforts   | 399        |
|                   | Challenges to future deployment  | 399        |
|                   | Cost overview  | 400        |
| <b>Chapter 13</b> | <b>Electricity systems</b> . . . . .   | <b>401</b> |
|                   | <b>Overview</b> . . . . .  | <b>401</b> |
|                   | <b>Load duration curves and their impact on CO<sub>2</sub> mitigation cost</b> . . . . . | <b>403</b> |
|                   | <b>Transmission and distribution technology</b> . . . . .                                | <b>404</b> |
|                   | Distribution   | 406        |
|                   | <b>Electricity storage systems</b> . . . . .   | <b>407</b> |

|                   |  |            |
|-------------------|--|------------|
|                   | Storage and variability  | 410        |
|                   | <b>Distributed generation</b> . . . . .  | <b>411</b> |
| <b>Chapter 14</b> | <b>Methane mitigation</b> . . . . .  | <b>413</b> |
|                   | <b>Overview</b> . . . . .  | <b>413</b> |
|                   | <b>Current major sources of anthropogenic methane and emission reduction options</b> . . . . . | <b>414</b> |
|                   | Natural gas and oil supply   | 414        |
|                   | Coal mines   | 416        |
|                   | Solid waste management   | 418        |
|                   | <b>Modelling approach and results</b> . . . . .  | <b>419</b> |
|                   | Characterisation of scenario analysis  | 419        |
|                   | Modelling of methane mitigation  | 419        |
|                   | Scenario results   | 420        |
|                   | <b>Challenges to deployment</b> . . . . .  | <b>422</b> |
| <b>Chapter 15</b> | <b>Transport</b> . . . . .   | <b>423</b> |
|                   | <b>Overview</b> . . . . .  | <b>425</b> |
|                   | Current status and trends  | 426        |
|                   | Scenario results   | 427        |
|                   | <b>Alternative fuels: status and prospects</b> . . . . .                                       | <b>432</b> |
|                   | Electricity  | 432        |
|                   | Hydrogen   | 432        |
|                   | <b>Light-duty vehicles</b> . . . . .   | <b>434</b> |
|                   | Status and trends  | 434        |
|                   | LDV technology   | 437        |
|                   | <b>Modal shift to transit and non-motorised modes</b> . . . . .                                | <b>447</b> |
|                   | <b>High speed rail</b> . . . . .   | <b>450</b> |
|                   | <b>Truck and rail freight transport</b> . . . . .  | <b>451</b> |
|                   | Trucking technical efficiency  | 453        |
|                   | <b>Aviation</b> . . . . .  | <b>457</b> |
|                   | Historical trends and baseline projections   | 458        |
|                   | Aviation technologies  | 461        |

|                   |   |            |
|-------------------|---|------------|
|                   | Aircraft alternative fuels potential  | 464        |
|                   | <b>Maritime transport</b> . . . . .   | <b>466</b> |
|                   | Efficiency technologies   | 468        |
|                   | Changes in propulsion systems   | 469        |
|                   | Shifts to alternative fuels   | 469        |
| <b>Chapter 16</b> | <b>Industry</b> . . . . .   | <b>471</b> |
|                   | <b>Overview</b> . . . . .   | <b>471</b> |
|                   | <b>Industrial energy use and CO<sub>2</sub> emissions profile</b> . . . . . | <b>473</b> |
|                   | <b>Iron and steel</b> . . . . .   | <b>482</b> |
|                   | Scenarios   | 482        |
|                   | Processing overview   | 483        |
|                   | Energy efficiency: BAT  | 485        |
|                   | Energy and materials efficiency: improved and new process technologies      | 485        |
|                   | Fuel and feedstock substitution   | 488        |
|                   | CO <sub>2</sub> capture and storage (CCS)                                   | 489        |
|                   | <b>Non-metallic minerals</b> . . . . .                                      | <b>489</b> |
|                   | Scenarios   | 490        |
|                   | Processing overview   | 490        |
|                   | Energy efficiency: BAT  | 491        |
|                   | Energy and materials efficiency: new process technologies                   | 493        |
|                   | Fuel and feedstock substitution   | 493        |
|                   | CO <sub>2</sub> capture and storage (CCS)                                   | 495        |
|                   | <b>Chemicals and petrochemicals</b> . . . . .                               | <b>495</b> |
|                   | Scenarios   | 496        |
|                   | Processing overview   | 497        |
|                   | Energy efficiency: BAT  | 499        |
|                   | Energy and materials efficiency: new process technologies                   | 499        |
|                   | CO <sub>2</sub> capture and storage (CCS)                                   | 502        |
|                   | Process intensification   | 503        |
|                   | <b>Pulp and paper</b> . . . . .   | <b>503</b> |
|                   | Scenarios   | 503        |
|                   | Processing overview   | 503        |
|                   | Energy efficiency: BAT  | 505        |
|                   | Energy and materials efficiency: new process technologies                   | 506        |
|                   | CO <sub>2</sub> capture and storage (CCS)                                   | 508        |

|                   |   |            |
|-------------------|---|------------|
|                   | <b>Non-ferrous metals</b> . . . . .   | <b>508</b> |
|                   | Scenarios   | 509        |
|                   | Processing overview   | 510        |
|                   | Energy efficiency: BAT  | 510        |
|                   | Energy and materials efficiency: new process technologies   | 511        |
|                   | <b>General equipment and recycling</b> . . . . .  | <b>512</b> |
|                   | Steam supply  | 512        |
|                   | Electric motor-drive systems  | 514        |
| <b>Chapter 17</b> | <b>Buildings and appliances</b> . . . . .   | <b>519</b> |
|                   | <b>Overview</b> . . . . .   | <b>520</b> |
|                   | <b>Low building stock turnover: the need for energy efficiency refurbishment</b> . . . . .                | <b>521</b> |
|                   | <b>Status and trends in the global buildings sector</b> . . . . .   | <b>524</b> |
|                   | Demand drivers in the scenario analysis   | 525        |
|                   | <b>Global results of the Baseline scenario</b> . . . . .  | <b>526</b> |
|                   | <b>The Baseline scenario results by sector and region</b> . . . . .                                       | <b>528</b> |
|                   | OECD countries  | 529        |
|                   | Non-OECD countries  | 531        |
|                   | <b>The ACT Map and BLUE Map scenarios</b> . . . . .   | <b>534</b> |
|                   | <b>Key technologies and measures to reduce CO<sub>2</sub> emissions in the buildings sector</b> . . . . . | <b>539</b> |
|                   | The building shell, hot water heating and system issues   | 539        |
|                   | Cooling systems: air conditioning   | 542        |
|                   | Appliances  | 544        |
|                   | Lighting  | 546        |
|                   | Heat pumps  | 548        |
|                   | Solar thermal heating   | 551        |
|                   | Passive houses and zero-energy buildings  | 555        |
|                   | Bioenergy technologies  | 557        |
| <b>Annex A</b>    | <b>IEA Energy Technology Collaboration Programme</b>  | <b>561</b> |
| <b>Annex B</b>    | <b>Framework assumptions</b>  | <b>569</b> |
| <b>Annex C</b>    | <b>Technology development needs</b>   | <b>579</b> |
| <b>Annex D</b>    | <b>Comprehensive list of key new energy technologies</b>  | <b>591</b> |
| <b>Annex E</b>    | <b>Definitions, abbreviations, acronyms and units</b>   | <b>601</b> |
| <b>Annex F</b>    | <b>References</b>   | <b>615</b> |