

Contents

	Authors' Biographies	<i>xv</i>
	Preface	<i>xvii</i>
	Acknowledgement	<i>xix</i>
	Nomenclature	<i>xxi</i>
1	History of steelmaking	1
1.1	How it all began	1
1.2	First attempts at steelmaking	2
1.3	Steelmaking process development	2
1.3.1	Micro-alloyed steels	3
1.3.2	Stainless steels	4
1.3.3	Tubes	4
1.3.4	Seamless tubing	5
1.3.5	Plates and sheets	5
1.3.6	Timeline of steel production processes	5
1.4	Casting	9
1.4.1	Forging	9
1.4.2	Foundry	10
1.4.3	Who and where are now the biggest steel producers?	10
1.4.4	Which industries is steel being produced for?	10
	References	11
2	Steelmaking processes	15
2.1	Introduction	15
2.2	Raw materials	16
2.2.1	Iron ore and coal extraction	16
2.2.2	Coal	17
2.2.2.1	Coal coking	19
2.2.3	Lime	20
2.2.4	Oxygen	21
2.3	Iron ore sintering	23
2.4	Iron ore direct reduction	25

2.5	Hydrogen direct reduction (HDR)	25
2.6	Blast furnace and the transformation process of ironmaking	26
2.7	Basic oxygen furnace operation	27
2.8	Electric arc furnace operation	28
2.9	Smelting reduction	29
2.10	Electric arc furnace efficiency improvements	30
2.11	Improvements in energy consumption and production: energy and emissions	31
2.12	Exergy analysis	33
2.13	Greater energy independence with sustainable steel production	38
2.14	Heat loss recovery – energy- and CO ₂ -saving protocols	44
2.15	Retrofitting renewable energy technologies on-site	46
2.16	Precombustion CO ₂ avoidance	51
2.17	Steelmaking process improvements	51
2.18	Post-combustion CO ₂ capture	51
2.19	Conclusions	54
	References	56
3	Introduction to the Bio Steel Cycle	67
3.1	Introduction	67
3.2	Importance of demonstrating all carbon emissions along the steelmaking process	69
3.3	BF/BOF route carbon capture	70
3.3.1	CO ₂ capture mechanisms	70
3.3.2	Carbon capture, utilisation and storage	72
3.4	BF/BOF off-heat utilisation	85
3.5	Renewable energy technologies	85
3.6	DAC woodlands	86
3.7	Biogas, biomass and hydrogen	87
3.8	CEPS	89
3.9	Industrial filters: carbon capture and sequestration	90
3.10	Anaerobic digestion, sewage treatment and geothermal units	90
3.10.1	Anaerobic digestion	90
3.10.2	Sewage treatment and steel slag reutilisation	91
3.10.3	Geothermal energy and ground-source heat pumps	91
3.11	CAT, CCS and CCUS	92
3.11.1	CO ₂ avoidance with production process improvement	95
3.11.2	CO ₂ and off-heat utilisation in food production	99
3.11.3	CO ₂ utilisation in the building industry	99
3.11.4	DAC and agricultural waste for anaerobic digestion	100
3.11.5	Anaerobic digestion, sewage treatment and hydrogen from biogas	100
3.11.6	Renewable energy technologies' utilisation	101
	References	102

4	Key components of the Bio Steel Cycle	119
4.1	Introducing the BiSC key components for net-zero carbon steel manufacturing	119
4.2	BF/BOF route carbon capture	120
4.3	BF/BOF off-heat utilisation in iron and steelmaking	123
4.3.1	Off-heat utilisation in anaerobic digestion and sewage treatment	123
4.3.2	CO ₂ and off-heat utilisation in food production	124
4.4	Renewable energy technologies	125
4.4.1	Renewable energy technologies utilisation	125
4.4.2	Wind energy	125
4.4.3	Solar energy	128
4.4.4	Hydropower	128
4.5	DAC woodlands and plant matter	129
4.6	CEPS	132
4.7	Geomimetic process	133
4.8	Anaerobic digestion	135
4.9	Sewage treatment	136
4.10	Biogas, biomass and hydrogen	136
4.10.1	Biogas	136
4.10.2	Biomass and green hydrogen utilisation	136
4.11	Multi-criteria decision analysis (MCDA) of BiSC	137
4.11.1	Introduction	137
4.11.2	Basics of MCDA of BiSC	137
4.11.3	MCDA of BiSC	139
4.11.4	MCDA sensitivity analysis to variation in scores or weighting	139
4.11.5	MCDA examination and analysis of the derived results	145
4.11.6	MCDA conclusions and discussion	146
4.11.7	The Bio Steel Cycle implementation stages, support schemes and cost	147
4.11.8	Conclusions and discussion	149
	References	152
5	The CAT and reducing effects of the BiSC key components implementation	165
5.1	Introduction	165
5.2	BF/BOF route carbon capture	166
5.2.1	Steelmaking process improvements: CO ₂ emissions avoiding, reducing and capturing technologies and processes	166
5.2.2	Discussion	166
5.2.3	CO ₂ capture mechanisms	167
5.3	Renewable energy technologies	168
5.4	DAC woodlands	168
5.5	CEPS and the Geomimetic [®] process	168

5.6	Anaerobic digestion and sewage treatment	169
5.7	Biomass, biogas and hydrogen	169
5.8	CCUS	169
5.8.1	Introduction	169
5.8.2	Results of process simulations	171
5.8.3	Discussion	171
5.8.4	CCUS conclusions	171
5.9	Validating process flowcharts and simulations	172
5.9.1	Process flowchart in MS excel	173
5.9.2	Process simulations in Aspen+V12.1, Simul8 and INOSIM	173
5.9.3	Process simulations in Simul8	178
5.9.3.1	Results	184
5.9.3.2	Conclusions and discussion	184
5.10	Findings	184
5.10.1	Introduction	184
5.10.2	Mathematical analysis	185
5.10.3	Data modelling	192
5.10.4	Statistics: T-test	197
5.10.5	Total CO ₂ emissions from BF/BOF operating oxygen	198
5.10.6	Validation and verification of the preliminary research results	200
5.10.6.1	Simul8	203
5.10.6.2	Aspen+V12.1	204
5.10.6.3	INOSIM	210
5.11	Process simulations verification and validation	211
5.11.1	Validation and verification of the preliminary research results under the application of process simulation software models	215
5.11.1.1	Introduction	215
5.11.1.2	Verification of process simulations	215
5.11.1.3	Validation of simulation models	216
5.11.1.4	Validation of simulation models	217
5.11.1.5	Graphical display of simulation models validation results	218
5.11.1.6	Conclusions and discussion verification and validation	237
	References	243
6	Greater energy independence with sustainable steel production	257
6.1	Introduction	257
6.2	Materials and methods	258
6.3	Heat loss recovery – energy- and CO ₂ -saving protocols	265
6.4	Retrofitting renewable energy technologies on site	268
6.5	Conclusions	272
	References	274

7	Technological challenges to and opportunities of the BiSC concept implementation	281
7.1	Introduction	281
7.2	Challenges	281
7.2.1	Steelmaking process improvements: implementation of TGR in BF, BOF and EAF	281
7.2.2	Utilising excess heat from furnaces	282
7.2.2.1	Challenges of excess heat harvesting implementation	282
7.2.3	Biomass to replace coal and coke	284
7.2.4	CO ₂ capture technology and filtering systems	286
7.2.4.1	Direct air capture (DAC)	286
7.2.4.2	Enhanced rock weathering (ERW)	286
7.2.4.3	Aqueous amine-based CO ₂ capture	286
7.2.4.4	Membrane gas separation	287
7.2.4.5	Carbon capture and conversion	287
7.2.4.6	Bioenergy with carbon capture and storage (BECCS)	287
7.2.4.7	Chemical looping	287
7.2.4.8	Cryogenic carbon capture (CCC)	287
7.2.4.9	Carbon capture using nanotechnology	288
7.2.4.10	The current status quo	288
7.2.4.11	Barriers to deployment	289
7.2.4.12	Transportation challenges	290
7.2.4.13	Storage considerations	290
7.2.4.14	Uncertain public support	290
7.2.4.15	Leading carbon capture companies	290
7.2.4.16	CO ₂ filter systems	294
7.2.5	Challenges of renewable energy implementation	295
7.3	Opportunities	296
7.3.1	Utilising captured carbon	296
7.3.1.1	CO ₂ in agri-food production	296
7.3.1.2	CO ₂ utilisation in the chemical industry	297
7.3.1.3	CO ₂ in concrete production	297
7.3.1.4	CO ₂ in glass manufacturing	298
7.4	Conclusions	300
	References	300
8	Macroeconomic and microeconomic challenges to implementation of the BiSC concept	309
8.1	Introduction	309
8.2	Part I policy and BiSC implementation	309
8.2.1	CO ₂ mitigation and sustainability adaptation – US’ evolving policy framework	309

- 8.2.2 CO₂ mitigation and sustainability adaptation – UK’s evolving policy framework 310
 - 8.2.2.1 The UK Government’s Green Industrial Revolution 310
 - 8.2.2.2 Offshore wind 310
 - 8.2.2.3 Hydrogen 311
 - 8.2.2.4 Nuclear 311
 - 8.2.2.5 Electric vehicles 311
 - 8.2.2.6 Public transport 311
 - 8.2.2.7 Jet zero 311
 - 8.2.2.8 Homes and public buildings 312
 - 8.2.2.9 Carbon capture 312
 - 8.2.2.10 Nature 312
 - 8.2.2.11 Innovation and finance 312
 - 8.2.2.12 Findings 312
 - 8.2.2.13 Research gaps 313
- 8.2.3 CO₂ mitigation and sustainability adaptation – Brazil’s evolving policy framework 317
- 8.2.4 CO₂ mitigation and sustainability adaptation – Russia’s evolving policy framework 318
- 8.2.5 CO₂ mitigation and sustainability adaptation – India’s evolving policy framework 319
- 8.2.6 CO₂ mitigation and sustainability adaptation – China’s evolving policy framework 319
- 8.2.7 CO₂ mitigation and sustainability adaptation – Australia’s evolving policy framework 320
- 8.2.8 CO₂ mitigation and sustainability adaptation – Canada’s evolving policy framework 321
- 8.2.9 CO₂ mitigation and sustainability adaptation – EU’s evolving policy framework 322
- 8.2.10 CO₂ mitigation and sustainability adaptation – Norway’s evolving policy framework 323
- 8.2.11 CO₂ mitigation and sustainability adaptation – US’ evolving policy framework 323
- 8.2.12 Sustainability, decarbonisation and carbon certifications 324
 - 8.2.12.1 EU’s CBAM 324
- 8.3 Part II markets analysis 328
 - 8.3.1 The United Kingdom 328
 - 8.3.2 EU 328
 - 8.3.3 International 329
- 8.4 PESTEL and SWOT analysis of green steel 329
 - 8.4.1 Introduction 329
 - 8.4.2 Political factors affecting the United Kingdom 329
 - 8.4.3 Economic factors affecting the United Kingdom 339
 - 8.4.4 Social factors affecting the United Kingdom 340
 - 8.4.5 Technological factors affecting the United Kingdom 340

8.4.6	Environmental factors affecting the United Kingdom	341
8.4.7	Legal factors affecting the United Kingdom	342
8.4.8	Emphasising strategic opportunity	342
8.5	SWOT analysis of the United Kingdom	343
8.5.1	Introduction	343
8.5.2	Strengths of the United Kingdom	343
8.5.3	Weaknesses of the United Kingdom	344
8.5.4	Opportunities for the United Kingdom	345
8.5.5	Threats to the United Kingdom	345
8.5.6	Conclusions – emphasising strategic opportunity for the UK	346
8.6	CO ₂ emissions for the entire steel production process	346
8.7	BiSC – steel production decarbonisation model and strategy	346
8.8	Higher degree of energy independence	347
	References	348
9	Skills set required within the different components and sectors	359
9.1	Introduction	359
9.2	Solar	359
9.2.1	Stages of producing solar panels	359
9.2.1.1	Solar photovoltaic panels	359
9.2.1.2	Thin-film PV	360
9.2.1.3	Racking systems	360
9.2.1.4	Power electronics	361
9.2.1.5	Solar thermal panels	361
9.3	Wind turbines	362
9.4	Hydro	364
9.5	Geothermal	366
9.6	Green hydrogen	367
9.7	Biomass	368
9.8	Biogas	369
9.9	Conclusion	370
	References	370
10	The future of green steel	375
10.1	Introduction	375
10.2	Evaluation of the United Kingdom and its NDCs	376
10.3	The United States of America	378
10.4	Brazil	380
10.5	Russian Federation	382
10.6	India	383
10.7	China	386
10.8	Australia	388
10.9	Canada	392
10.10	Norway	395

xiv | Contents

10.11 European Union (EU)–Germany 398

10.12 Discussion and conclusions 401

References 402

**11 An idealised timeline of possibilities for steel
decarbonisation 443**

11.1 Introduction 443

11.2 Political decision-making and legislative foundations 443

11.3 All-encompassing industrial response 444

11.4 Investment in people 446

11.5 Infrastructural improvements 446

References 447

12 Concluding remarks and suggestions 449

12.1 Discussion of findings 449

References 462

Index 473