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# Clean Ironmaking and Steelmaking Processes

Efficient Technologies for Greenhouse  
Emissions Abatement



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# Preface

World steel demand and production is continuously growing. Being a high energy-intensive and high-impact industry, the energy consumption and the greenhouse gases emissions are destined to double by 2050 if the actual processing routes are *completely* preserved. To avoid this, new paradigms must be developed and approached in order to transform the sector, making it sustainable in the future and compatible with the global warming reduction. By introducing and optimizing energy-efficient solutions to the actual route, only a maximum of 25% of global saving is expected; this target is insufficient for the goals, leading to global warming control and reduction. So, based on current climate change forecast, it is predicted that the steel industry will face greater challenges which cannot be solved with the past incremental technologies in the future. US and European reports underline that if the global warming should be avoided, the only way is to develop and apply breakthrough technologies very fast. The book describes the main available technologies employed in the traditional or innovative routes capable of reducing the energy consumption and the dangerous greenhouse emissions as well as the research efforts that see many scientists involved all around the world from industry, academia, and research centers. Obviously, the energy topic is largely described, taking into account the direct and indirect consumption per each analyzed technology and suggested solution. Regarding coke making, the last years' technological innovations led to lowering air emissions and to the deep limiting of hazardous solid wastes. It is showed that the different technological choices are driven by regional and logistic issues. The treatment of wastewater as a very crucial issue in coke making is largely described. The development and the diffusion of technologies, such as coke dry quenching and coke stabilization quenching, are discussed. The use of coke oven gas in order to abate the dangerous emissions is largely taken into account. Those technologies leading to operational efficiency, coke quality, and productivity are underlined. Another fundamental process for raw materials preparation in the integrated ironmaking/steelmaking route is sintering. CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub>, PCDD/Fs, and particulate matters are continuously produced during the whole sintering cycle; this is because of the fuel combustion, carbon in the fed material,

and other carbonaceous sources such as limestone and dolomite. All those solutions leading to these dangerous compounds' abatement are described. The employment of biomass as inhibitor and the energy consumption reduction solutions are underlined. Heat recovery at the sinter plant is a means for improving the efficiency of sinter making. Exhaust gases are processed, adsorbed, decomposed, and/or collected as nontoxic by-products to increase the quantity and improve the quality of steam recovery, reaching high fuel savings; all the most efficient methods are reviewed. Computer control technologies for the sintering process were developed along with sinter technology, as sinter quality requirements for the blast furnace were upgraded. Many parameters are involved during sintering. The optimization of these parameters control can lead to the increase in productivity and in the quality of the sintered ores. All the emissions optimized sintering technologies are largely described. The technological evolution of the blast furnace plants led to high efficient reactors very close to their thermodynamic limits. The blast furnace-based production route covers the majority of the steel production all around the world with hundreds of plants. One of the main disadvantages of the integrated route is the necessity of a coke plant with high energy intensity and very high emissions levels. In the direction of reducing these impacts, the injection of carbon-bearing reductants at the tuyere level has given new impetus to blast furnace operational practice to reduce the coke consumption significantly. Another important innovation is represented by the top gas recovery technologies. In the new-generation blast furnaces, oxygen is employed as substitute of the air. Many online process monitoring and control are in use or under development with the overall goal of increasing the process efficiency and fuel consumption and environmental impact reduction. Conversion operations are necessary in the integrated steel plant. Large effort has been devoted to the energy efficiency improvement and to the greenhouse gases emissions reduction. The actual converting technologies are based on a combination of blowing oxygen from the top laces and inert gas or oxygen plus inert gases from the bottom of the reactors. Today's highly efficient electric arc furnaces consume roughly 300 kWh/t-steel. The appropriate greenhouse gas reduction strategy is strongly influenced by the source of electricity generation (i.e., fossil fuel or nuclear). Reduction of indirect emissions requires reducing electrical energy consumption. The current trend toward increased addition of fuel and oxygen has resulted in chemical energy sources supplying a greater proportion of the furnace's energy inputs. Oxyfuel burners in the furnace have become a necessity to increase the rate of scrap melting in cold spots and thereby make scrap melting more uniform and to reduce the electricity needing for the metal fusion. Waste gases recovery and utilization as well as foamy slag practices allow to reduce energy consumption. The bottom stirring practice is getting more and more important and even essential, especially for the furnaces having big temperature gradient in the bath, such as big shell furnace. Modern controls which use a multitude of sensors help to achieve power saving and precise process monitoring to a greater extent than older controls. Direct reduced iron production is destined to increase in the next and far future. This is due to the continuous innovations of the plants leading to less energy consumption and carbon dioxide emissions. In this direction, the technological solutions push

toward the waste energy recovery and the use of CO and H<sub>2</sub> as reductant agents. The gas-based processes are located in those regions where natural gas is available in abundance and at reasonable prices. Hydrogen production from water electrolysis to obtain the reducing agent is under development and appears exceptionally promising for the zero-emissions ironmaking. The current CO<sub>2</sub> capture and usage solutions that are available or under development are reviewed. Only the capture of CO<sub>2</sub> will be responsible for the achievement of the goals of the Blue scenario. Intergovernmental Panel on Climate Change (IPCC) scenarios associated with a more than even chance of achieving the 2 °C target are characterized by average capture rates of 10 GtCO<sub>2</sub> per year in 2050, 25 GtCO<sub>2</sub> per year in 2100, and cumulative storage of 800–3000 GtCO<sub>2</sub> by the end of the century. Carbon capture, storage, and utilization are recognized as crucial in climate change mitigations and in particular in a NET contest to limit warming well below the 2 °C scenario. The capture technologies are grouped as chemical/physical absorption, solid adsorbents capture, membranes or molecular sieves physical separation, cryogenics separation, and carbonation. Obviously, this best available technology could be applied globally at current production levels, taking into account precise energy balances, economic feasibility, transition rates, and regulatory and social factors. The principal iron ore electrolysis routes under investigation and development are the molten oxide electrolysis and the electrowinning. Since electrolysis produces no CO<sub>2</sub>, it could theoretically be zero-carbon but only if the electricity needed to power the process is produced without generating CO<sub>2</sub> emissions (renewable sources). They are very promising even if at a basic research and pre-industrialization stage.

My special thanks to all the Springer editorial office people for their professionalism. Finally, I would like to dedicate the work to my “miracle” son Alessandro.

Lecce, Italy

Pasquale Cavaliere

# Contents

<b>1</b>	<b>Clean Ironmaking and Steelmaking Processes: Efficient Technologies for Greenhouse Emissions Abatement . . . . .</b>	<b>1</b>
1.1	Introduction and Global Scenario . . . . .	1
1.2	Main Approaches to the Problem . . . . .	6
1.3	Technological Issues . . . . .	13
1.4	Main Solutions . . . . .	22
1.5	Conclusions . . . . .	32
	References . . . . .	33
<b>2</b>	<b>Coke Making: Most Efficient Technologies for Greenhouse Emissions Abatement . . . . .</b>	<b>39</b>
2.1	Introduction . . . . .	39
2.2	Wastewater Treatment . . . . .	40
2.3	Coke Dry Quenching (CDQ) . . . . .	50
2.4	Use of Coke Oven Gas . . . . .	57
2.5	Coke Making Control Systems . . . . .	79
2.6	Coal Stamp Charging Battery (CSCB) . . . . .	82
2.7	High-Pressure Ammonia Liquor Aspiration System (HPALA) . . . . .	87
2.8	Coal Moisture Control . . . . .	87
2.9	Non-Recovery Coke Ovens . . . . .	88
2.10	Variable Speed Drive Coke Oven Gas Compressors . . . . .	95
2.11	Coke Stabilization Quenching . . . . .	95
2.12	Single-Chamber System . . . . .	96
2.13	SCOPE 21 . . . . .	97
2.14	Use of Biomass and Waste Materials . . . . .	99
2.15	Conclusions . . . . .	103
	References . . . . .	104

<b>3</b>	<b>Sintering: Most Efficient Technologies for Greenhouse Emissions Abatement</b> . . . . .	111
3.1	Introduction . . . . .	111
3.2	Waste Heat Recovery in Sinter Plant . . . . .	118
3.3	Exhaust Gas Treatment . . . . .	121
3.4	Improved Process Control and Quality Assurance . . . . .	131
3.5	Improved Ignition Oven Efficiency with Multi-slit Burners . . . . .	134
3.6	Emissions Optimized Sintering (EOS) . . . . .	136
3.7	EPOSINT Process, Selective Waste Gas Recycling . . . . .	137
3.8	Improved Charging of Materials . . . . .	139
3.9	Low Emissions and Energy Optimized Sintering Process . . . . .	142
3.10	Sectional Gas Recirculation . . . . .	142
3.11	Curtain Flame Ignition System . . . . .	145
3.12	Utilization of Waste Fuels in Sintering . . . . .	146
3.13	Charcoal in Sintering . . . . .	147
3.14	Biomass in Sintering . . . . .	153
3.15	Conclusions . . . . .	159
	References . . . . .	161
<b>4</b>	<b>Blast Furnace: Most Efficient Technologies for Greenhouse Emissions Abatement</b> . . . . .	167
4.1	Introduction . . . . .	167
4.2	High-Quality Ore . . . . .	179
4.3	Pulverized Coal Injection . . . . .	181
4.4	Top-Pressure Recovery Turbines . . . . .	188
4.5	Increased Blast Furnace Top Pressure . . . . .	191
4.6	Improved Hot Stove Process Control . . . . .	191
4.7	Blast Furnace Process Control . . . . .	194
4.8	Heat Recuperation from Hot Blast Stoves . . . . .	200
4.9	Increased Hot Blast Temperature . . . . .	201
4.10	Injection of Coke Oven Gas . . . . .	202
4.11	Improved Recovery of Blast Furnace Gas . . . . .	206
4.12	Injection of Oil . . . . .	208
4.13	Natural Gas (NG) Injection . . . . .	209
4.14	Plastic Waste Injection . . . . .	216
4.15	Oxy-Oil Injection . . . . .	221
4.16	Injection of Residues . . . . .	221
4.17	Biomass Combustion in the BF . . . . .	223
4.18	Charging Carbon Composite Agglomerates (CCA) . . . . .	232
4.19	COURSE50 . . . . .	240
4.20	Top Gas Recycling Blast Furnace (TGRBF) . . . . .	243
4.21	Slag Heat Recovery . . . . .	254
4.22	Conclusions . . . . .	262
	References . . . . .	264

**5 Basic Oxygen Furnace: Most Efficient Technologies for Greenhouse Emissions Abatement** . . . . . 275

5.1 Introduction . . . . . 275

5.2 Use of Metallized Iron . . . . . 280

5.3 BOF Heat and Gas Recovery . . . . . 281

5.4 Energy Issues . . . . . 287

5.5 BOF Bottom Stirring . . . . . 291

5.6 Improved Process Monitoring and Control . . . . . 293

5.7 Improved Ladle Preheating . . . . . 295

5.8 In-Furnace Post-Combustion . . . . . 296

5.9 Conclusions . . . . . 297

References . . . . . 298

**6 Electric Arc Furnace: Most Efficient Technologies for Greenhouse Emissions Abatement** . . . . . 303

6.1 Introduction . . . . . 303

6.2 Raw Materials . . . . . 316

6.3 Oxyfuel Burners . . . . . 322

6.4 Flue Gas Monitoring and Control . . . . . 326

6.5 Post-Combustion Optimization in Steelmaking . . . . . 328

6.6 Foamy Slag Practices . . . . . 332

6.7 Scrap Preheating . . . . . 337

6.8 Shaft Furnace Scrap Preheating . . . . . 339

6.9 Tunnel Furnace Preheating . . . . . 344

6.10 Bottom Stirring/Stirring Gas Injection . . . . . 346

6.11 Direct Current (DC) Arc Furnace . . . . . 351

6.12 Waste Heat Recovery for EAF . . . . . 352

6.13 Contiarc Furnace . . . . . 360

6.14 Twin-Shell DC Arc Furnace . . . . . 361

6.15 Post-Combustion of EAF Flue Gas . . . . . 364

6.16 Process Optimization and Control . . . . . 365

6.17 Conclusions . . . . . 368

References . . . . . 370

**7 Smelting Reduction: Most Efficient Technologies for Greenhouse Emissions Abatement** . . . . . 377

7.1 Introduction . . . . . 377

7.2 Corex Process . . . . . 381

7.3 FINEX Process . . . . . 402

7.4 HIs melt . . . . . 406

7.5 TecnoRed . . . . . 408

7.6 Flash Ironmaking Technology . . . . . 412

7.7 Conclusions . . . . . 413

References . . . . . 413

**8 Direct Reduced Iron: Most Efficient Technologies for Greenhouse Emissions Abatement** . . . . . 419

8.1 Introduction . . . . . 419

8.2 MIDREX<sup>®</sup> Process . . . . . 424

8.3 Hyl-ENERGIRON Process . . . . . 431

8.4 FASTMET<sup>©</sup> and FASTMELT<sup>©</sup> . . . . . 440

8.5 ITmk3<sup>®</sup> Process . . . . . 441

8.6 MXCOAL<sup>™</sup>: MIDREX<sup>©</sup> with Coal Gasification . . . . . 443

8.7 SL/RN Process . . . . . 448

8.8 Waste Heat Recovery for Rotary Kiln Direct Reduction . . . . . 449

8.9 FINMET Process . . . . . 450

8.10 Iron Carbide Process . . . . . 450

8.11 CIRCORED . . . . . 452

8.12 Redsmelt . . . . . 452

8.13 Hydrogen Reduction . . . . . 452

8.14 Conclusions . . . . . 478

References . . . . . 479

**9 Carbon Capture and Storage: Most Efficient Technologies for Greenhouse Emissions Abatement** . . . . . 485

9.1 Introduction . . . . . 485

9.2 Energy Issues . . . . . 495

9.3 Shift Reactions . . . . . 502

9.4 Chemical/Physical Adsorption . . . . . 503

9.5 Solid Adsorbents Capture . . . . . 511

9.6 Membrane Separation . . . . . 516

9.7 Cryogenics Separation . . . . . 518

9.8 Carbonization . . . . . 521

9.9 CHG Capture . . . . . 527

9.10 Post-combustion . . . . . 534

9.11 Chemical Looping . . . . . 538

9.12 Conclusions . . . . . 547

References . . . . . 549

**10 Electrolysis of Iron Ores: Most Efficient Technologies for Greenhouse Emissions Abatement** . . . . . 555

10.1 Introduction . . . . . 555

10.2 Molten Oxide Electrolysis . . . . . 557

10.3 Electrowinning . . . . . 566

10.4 Conclusions . . . . . 574

References . . . . . 575

**Index** . . . . . 577

# Abbreviations

A/O <sup>1</sup> /O <sup>2</sup>	Anoxic/aerobic <sup>1</sup> /aerobic <sup>2</sup>
A <sup>2</sup> /O	Anaerobic-anoxic-aerobic system
AA	Annual average
AC	Alternating current
ACARP	Australian Coal Industry's Research Program
AcC	Activated carbon
ADP	Aquatic depletion potential
AER	Adsorption-enhanced reforming
AFT	Adiabatic flame temperature
AISI	American Iron and Steel Institute
AOD	Argon oxygen decarburization
AOP	Advanced oxidation process
AP	Acidification potential
ARA	Auxiliary reducing agents
ASCM	Adsorption-selective carbon membrane
ASU	Air separation unit
BAT	Best available techniques
BET	Brunauer-Emmett-Teller
BF	Blast furnace
BFB	Bubbling fluidized bed
BFD	Blast furnace dust
BFR	Blast furnace route
BFS	Blast furnace slag
BFSG	Blast furnace shaft gas
BFTG	Blast furnace top gas
BHZ	Bottom heat exchange zone
BIS	Blast furnace inner reaction simulator
BM	Biomass
BOD	Biochemical oxygen demand
BOF	Basic oxygen furnace
BOFG	Basic oxygen furnace gas

BOFS	Basic oxygen furnace slag
BOP	Basic oxygen process
BOS	Basic oxygen steelmaking
BTP	Burn-through point
BTX	Benzene toluene xylene
CA	Chronoamperometry/chronoamperogram
CaL	Calcium looping
CAP	Long-term CO <sub>2</sub> capture scenario
CBP	Composite burnout potential
CC	Continuous casting
CCA	Carbon composite agglomerates
CCD	Charge-coupled device
CCF	Cyclone converter furnace
CCPP	Combined cycle power plant
CCS	Carbon capture and storage
CCSC CO <sub>2</sub>	Capture by slag carbonization
CCU CO <sub>2</sub>	Carbon capture and utilization
CCUS	Carbon capture use and storage
CDA	Carbon direct avoidance
CDLC	Coal direct chemical looping
CDQ	Coke dry quenching
CDRI	Cold direct reduced iron
CE	Counter electrode
CFB	Circulating fluidized bed
CFP	Carbon footprint
CHG	Compressed hydrogen gas
CHP	Combined heat and power
CLC	Chemical looping combustion
CLH	Chemical looping hydrogen
CMC	Coal moisture control
CMCP	Coal moisture control process
CMSM	Carbon molecular sieving membrane
CN	Cyanide
CNT	Carbon nanotube
COD	Chemical oxygen demand
COG	Coke oven gas
COS	Carbonyl sulfide
COSS	Continuous optimized shaft system
COURSE50 CO <sub>2</sub>	Ultimate reduction in the steelmaking process by innovative technologies for cool earth 50
CP	Coke plant
CP/C	Chronopotentiometry/chronopotentiogram
CRACCK CO <sub>2</sub>	Recycling and conversion to CO in Korea
CRI	Index of reactivity to CO <sub>2</sub>

CRR	Coke replacement rate
CRW	Cold-rolling wastewater
CS	Cold steel
CSCB	Coal stamp charging battery
CSN	Crucible swelling number
CSQ	Coke stabilization quenching
CSR	Coke strength after reaction
CTM	COG to methanol
CTMCR	COG to methanol with CO <sub>2</sub> recycle
CTMWOSC	COG to methanol without supplementary carbon
CTMWSC	COG to methanol with supplementary carbon
CV	Calorific value
CV/V	Cyclic voltammetry/voltammogram
CW	Combined water
CW-EDI	Concentrated water from electrodeionization
CWHS	Coke oven gas with H <sub>2</sub> separation
CWOHS	Coke oven gas without H <sub>2</sub> separation
CWQ	Coke wet quenching
CWW	Coke wastewater
DAC	Direct air capture
DAPS	Dry-cleaned and agglomerated pre-compaction system
DAV	Direct alloying with vanadium
DC	Direct current
DDQ	Double dry quenching
DEA	Diethylamine
DFB	Dual fluidized bed
DHE	Dynamic hydrogen electrode
DI	Deadman inlet
DIPA	Disopropanolamine
DIPAM	Tetrahydrothiopene
DMR	Dry methane reforming
DRI	Direct reduced iron
DRIP	Direct reduction iron plant
DSG	Dry slag granulation
DTCR	Dry-type top-gas cleaning and recovery
DTF	Drop tube furnace
DU	Drying unit
EAF	Electric arc furnace
EAFD	Electric arc furnace dust
EBF	Experimental blast furnace
EBT	Eccentric bottom tapping
EC	European Commission
ECOARC	Ecologically friendly and economical arc
ECS	Evaporative cooling system

ED	Electricity demand
EF	Anodic electro
EII	Energy-intensive industry
EINO	Emission index of NO
EMF	Electromotive force
EMS	Electromagnetic stirring
EMSy	Environmental management system
EOl	End of life
EOR	Enhanced oil recovery
EOS	Emissions optimized sintering
EP	Eutrophication potential
EPA	Environmental protection agency
EPB	Environment protection bureau
EPOSINT	Environmentally process optimized sintering
EQ	Equilibrium
EQS	Environmental quality standards
EROI	Energy return on investment
ESCS	Electrostatic space cleaner super
ESP	Electrostatic precipitator
ETC	Energy transitions commission
ETS	Emissions trading system
EU	European Union
EUA	European emission allowances
EUD	Energy utilization diagram
EW	Electrowinning
EWC	European waste catalogue
EWHR	Exergy of waste heat recovery
FA	Fly ash
FAETP	Freshwater aquatic ecotoxicity potential
FAF	Fuel arc furnace
FB	Fluidized bed
FC	Fixed carbon
ffs	Flame front speed
FGR	Flow gas recirculation
FGR	Flue gas recirculation
FGRS	Flue gas recirculation sintering
FIT	Flash ironmaking technology
FOG	Fluidized bed reactor's off-gas
FSCM	Fixed site carrier membranes
FST	Final sinter temperature
FT	Fischer-Tropsch
FWC	Freshwater consumption
GA	Genetic algorithm
GAC	Granular activated carbon

GaCTO	Coke-Oven Gas-Assisted Coal to Olefins
GBFS	Granulated blast furnace slag
CCSI	Global carbon capture and storage initiative
GHG	Greenhouse gas
GOD	Gas-oxidation degree
GR	Gas recycling
GSC	Gas switching combustion
GWP	Global warming potential
HAP	Hazardous air pollutants
HB	Hot blast
HBI	Hot briquetted iron
HC	Hydrocarbons
HCI	Hot compacted iron
HCMB	High-carbon metallic briquettes
HDPE	High-density polyethylenes
HDRI	Hot direct reduced iron
HECA	Hydrogen energy California
HF	Hearth furnace
HHF	Hearth heating furnace
HHV	Higher heating value
HM	Hot metal
HOD	Heat of decomposition
HPALA	High-pressure ammonia liquor aspiration system
HpCDD	Heptachlorodibenzo-P-dioxin
HpCDF	Heptachlorodibenzo-P-furan
HR	High reactivity
HRC	Hot rolled coil
HRT	Hydraulic retention time
HS	Hot stoves
HTIR	High-temperature indirect reduction
HTP	Human toxicity potential
HV	High volatile
HVM	Heating value of mixture
HW	Hardwood
HxCDD	Hexachlorodibenzo-p-dioxin
HxCDF	Hexachlorodibenzo-p-furan
ICHB	Iron coke hot briquette
IEA	International energy agency
IGAR	Injection de GAZ Réformé
IGCC	Integrated gasifier combined cycle
inj	Injected
IOSP	Iron ore sintering plant
IPCC	Intergovernmental panel on climate change
IR	Indirect reduction

ISF	Intensified sifting feeder
ISM	Integrated Steel Mill
ISO	International Organization for Standardization
I-TEF	International toxicity equivalent factors
JISF	Japan Iron and Steel Federation
JSM	Japanese Steel Mill
KET	Key enabling technology
KPI	Key performance indicators
LCA	Life cycle assessment
LD	Linz-Donawitz
LDG	Linz-Donawitz gas
LEEP	Low emission and energy optimized sinter process
LF	Lower furnace
LGMgO	Low-grade MgO
LHV	Low heating value
LIBS	Laser-induced breakdown spectroscopy
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LPM	Lignin-rich press mud
LPMC	Lignin-rich press mud-derived carbons
LPR	Liquid-phase reduction
LRI	Low-reduced iron
LS	Liquid steel
LSV	Linear scan voltammetry/voltammogram
LTIR	Low-temperature indirect reduction
LV	Low volatile
M	Moisture
M40	Percentage of coke remaining on the +40 mm round hole after 100 revolutions
MAC	Maximum allowable concentration
MAETP	Marine ecotoxicity potential
MBBR	Moving bed biofilm reactor
MBF	Magnetic braking feeder
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
MEEP	Moving electrode electrostatic precipitator
MES	Multifunctional energy system
MFA	Materials flow analysis
MLSS	Mixed liquor
MOE	Molten oxide electrolysis
MP	Medium pressure
MPO	Methane partial oxidation
MSFB	Magnetically stabilized fluidized bed
MSR	Methane steam reforming

MSWI	Municipal solid waste incineration
MTL	Metallization
MTO	Methanol to olefins
MWCNT	Multiwalled carbon nanotube
NEDO	New energy and industrial technology development organization
NET	Negative emissions technologies
NF	Nanofiltration
NG	Natural gas
NGO	Nongovernmental organization
NHE	Normal hydrogen electrode
NI	Normal Inlet
NMI	Nonmetallic inclusions
O&M	Operation and maintenance
OBF	Oxygen blast furnace
OBM	Oxygen bottom Maxhütte
OCDD	Octachlorodibenzodioxin
OCDF	Octachlorodibenzofuran
OCOG	Original coke oven gas
ODP	Ozone depletion potential
OECD	the Organisation for Economic Co-operation and Development
OEE	Overall equipment effectiveness
OGS	Operation guidance system
OP	Oxygen plant
OPC	Ordinary portland cement
OR	Oxidation ratio
OSD	One-step decarbonization
OS-RVFLNs	Online sequential random vector functional-link networks
OTI	Optical texture index
PAH	Polycyclic aromatic hydrocarbons
PARAFAC	Parallel factor analysis
PCB	Polychlorinated biphenyls
PCC	Post-combustion capture
PCDDs	Polychlorinated dibenzodioxins
PCDFs	Polychlorinated dibenzofurans
PCI	Pulverized coal injection
PCM	Phase change materials
PCOP	Photochemical oxidation potential
PCR	Pulverized coal ratio
PE	Polyethylene
PeCDD	Pentachlorodibenzo-p-dioxin
PeCDF	Pentachlorodibenzo-p-furan
PEM	Proton exchange membrane
PET	Polyethylene terephthalate

PG	Process gas
PI	Pipe inlet
PID	Proportional integral derivative
PIT	Polymer injection technology
PLA	Waste plastics
PM	Particulate matter
PM <sub>10</sub>	Particulate pollution (10 μm)
PM <sub>2.5</sub>	Particulate pollution (2.5 μm)
PMDR	Point of minimum direct reduction
POP	Persistent organic pollutants
POR	Partial oxidation reforming
POSCO	Pohang Iron and Steel Company
POX	Partial oxidation
PP	Polypropylene
PS	Polystyrene
PSA	Pressure swing adsorption
PSu	Priority substance
PtCR	Post-combustion ratio
PU/TU	Pyrolysis/torrefaction unit
PVC	Polyvinylchloride
PwP	Power plant
Q-BOP	Bottom-blowing process
R&D	Research and development
R&I	Research and innovation
R/H	Reforming gas/hematite
RAC	Regenerated activated carbon
RAFT	Raceway adiabatic flame temperature
RC	Regression coefficient
RCA	Reactive coke agglomerate
RCAt	Rotary cup atomizer
RCLA	Rotary cylinder atomizer
RCOG	Reformed coke oven gas
RD	Reduction degree
RDI	Reduction disintegration
RE	Reference electrode
RHF	Rotary hearth furnace
RMP	Refractory material plant
RNG	Reformed natural gas
RPB	Rotating packed bed
RVI	Reduction velocity index
RWGS	Reverse water gas reaction
S/F	Sloping flue
S/S	Solidification/stabilization
SBR	Sequential batch reactor

SCF	Standard cubic feet
SCL	Syngas chemical looping
SCM	Supplementary cementitious material
SCNT	Thiocyanate
SCPS	Selective crystallization and phase separation
SCR	Selective catalytic reduction
SCS	Single chamber system
SDQ	Single dry quenching
SECOS	Sintering energy control system
SER	Secondary energy resource
SES	Synthesis energy system
SF	Sinter feed
SFu	Shaft furnace
SI	Shaft injection
Sil	Silicate
SL/RN	Stelco-Lurgi/Republic Steel-National Lead
SMR	Steam methane reforming
SMS	Steel melting shop
SNG	Syngas
SP	Specific Pollutant
SPARG	Sulfur passivated reforming
SPH	Scrap preheating
SR	Steam reforming
SRe	Smelting reduction
SS	Suspended solids
SSAB	Svenskt stål AB
SSB	Supersonic burner
SSDO	Solid-state diffusion of oxygen
SSW	Segregation slit wire
ST	Hot stoves
STA	Simultaneous thermal analysis
SW	Softwood
SWV	Square wave voltammetry/voltammogram
T	Tapping
TBF	Traditional blast furnace
TCDD	Tetrachlorodibenzodioxin
TCDF	Tetrachlorodibenzofuran
TCE	Thermal and chemical energy of hearth gases
TCLP	Toxicity characteristic leaching procedure
TCT	Theoretical combustion temperature
TEP	Terrestrial ecotoxicity potential
TFN	Technological fuel number
TG	Top gas
TGN	Technological greenhouse number

TGRBF	Top gas recycling blast furnace
THM	Ton of hot metal
THZ	Top heat exchange zone
TI	Tuyeres injection
TLS	Ton of liquid steel
TmI	Tumble index
TOC	Total organic carbon
TP	Torrefied pellets
TRL	Technology readiness level
TRM	Tri-reforming of methane
TRS	Thermal reactor system
TRT	Top-pressure recovery turbine
TRZ	Thermal reserve zone
TSG	Tata Steel Group
TSP	Total suspended particulates
TSPM	Total suspended particulate matter
TTN	Technological total number
TW	Terrified wood
TWC	Total water consumption
UBS	Unione di Banche Svizzere
UCS	Unconfined compressive strength
UF	Upper furnace
UHP	Ultrahigh power
ULCOS	Ultralow CO <sub>2</sub> steelmaking
UNFCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
UV	Ultraviolet
VAI	Voest-Alpine Industrieanlagenbau
VIU	Value in use
VLD	Vacuum ladle degasser
VM	Volatile matter
VOC	Volatile organic compounds
VODC	Vacuum oxygen decarburization converter
VPSA	Vacuum pressure swing adsorption
VSA	Vacuum swing adsorption
VSD	Variable speed drive
WAC	Waste acceptance criteria
WACC	Weighted average cost of capital
WB	Wind box
WCP	Water cooled panels
WE	Working electrode
WFD	Water framework directive
WFGD	Wet flue gas desulfurization
WGSR	Water gas shift reaction

WHRS	Waste heat recovery system
WISCO	Wuhan Iron and Steel Company
WL	Wind leg
WP	Wood pellets
WPI	Waste plastic injection
WRZ	Wüstite reserve zone
WTCR	Wet-type top-gas cleaning and recovery
YSZ	Yttria stabilized zirconia
ZR	Zero reformer

# List of Figures

Fig. 1.1	Global crude steel production (worldsteel.org) .....	2
Fig. 1.2	Primary and secondary steelmaking production in the main producer countries .....	2
Fig. 1.3	China crude steel production growing rate .....	3
Fig. 1.4	MFA of iron in the world for year 2000 presented as a standard MFA diagram .....	8
Fig. 1.5	World total industry final energy consumption of the iron and steel sector in 2013 .....	10
Fig. 1.6	Energy employed and wasted in the BF-BOF-CC route .....	11
Fig. 1.7	Wasted energy in the integrated route (all the numbers refer to GJ/ton steel) .....	12
Fig. 1.8	CO <sub>2</sub> emissions levels from the Chinese iron and steel industry .....	13
Fig. 1.9	Ironmaking and steelmaking processes .....	14
Fig. 1.10	Schematic of the different processing routes .....	15
Fig. 1.11	Major carbon flow in the integrated still mill .....	16
Fig. 1.12	Emissions type in the integrated steel mill .....	17
Fig. 1.13	CO <sub>2</sub> emissions in the integrated steel mill .....	18
Fig. 1.14	Temperature anomaly May 2018 (NASA.gov) .....	19
Fig. 1.15	CO <sub>2</sub> emissions depending on the technological structure .....	20
Fig. 1.16	Direct emissions reduction potential .....	25
Fig. 1.17	Pathways of technologies for GHG emissions abatement .....	26
Fig. 1.18	Energy-saving potential for the BAT applied to the integrated steel mill .....	32
Fig. 2.1	World coke production in 2015 .....	40
Fig. 2.2	Coal in Europe 2017 .....	41
Fig. 2.3	Materials flow and emission sources in coke making .....	42
Fig. 2.4	Water consumption in an integrated steel plant, FWC (a); TWC (b) .....	43
Fig. 2.5	COD removal efficiency .....	49
Fig. 2.6	Coke wet quenching .....	51

Fig. 2.7	Coke dry quenching plant .....	53
Fig. 2.8	Carbon flow analyses .....	56
Fig. 2.9	Energy recovery and use in the integrated steel plant .....	58
Fig. 2.10	Energy balance for a coke plant (European IPPC Bureau 2011, values in MJ/t coke) .....	59
Fig. 2.11	Coke oven gas utilization .....	61
Fig. 2.12	Separation of coke oven gas by employing a PSA System .....	65
Fig. 2.13	Integrated COG-DRI plant .....	66
Fig. 2.14	Process flow diagram of syngas processing units of GaCTO .....	67
Fig. 2.15	Schematic diagram of GaCTO process .....	67
Fig. 2.16	Schematic of the CWOHS and CWHS processes (units in kmol-C/h) .....	75
Fig. 2.17	Energy balance of the CWOHS and CWHS processes (units in MW) .....	76
Fig. 2.18	Hydrogen Energy California (HECA) Facility Process .....	78
Fig. 2.19	Coke temperature monitoring .....	81
Fig. 2.20	Coal stamp process .....	83
Fig. 2.21	Compressive strength as a function of the coal density .....	85
Fig. 2.22	Coal charge density in different coke making technologies .....	86
Fig. 2.23	Coal moisture control plant .....	88
Fig. 2.24	Non-recovery coke plant .....	89
Fig. 2.25	Non-recovery and recovery coke ovens .....	90
Fig. 2.26	Coke properties for non-recovery coke oven products .....	91
Fig. 2.27	Annual emissions for non-recovery coke ovens compared to conventional ovens .....	92
Fig. 2.28	CSQ .....	96
Fig. 2.29	Schematic diagram of the single-chamber system .....	97
Fig. 2.30	SCOPE 21 plant .....	98
Fig. 2.31	Energy saving trend in Japan ironmaking .....	99
Fig. 2.32	Energy intensity vs. country for ironmaking operations .....	99
Fig. 3.1	Sintering operations .....	112
Fig. 3.2	Longitudinal section of the sinter bed .....	113
Fig. 3.3	Reaction zones vs. temperature during the sintering process .....	114
Fig. 3.4	Energy-saving solutions in sintering .....	118
Fig. 3.5	Heat recovery in the WHRS system .....	120
Fig. 3.6	Activated coke method .....	122
Fig. 3.7	Gas treatment through selective catalytic reduction .....	122
Fig. 3.8	Dust after ESP vs. alkali input .....	124
Fig. 3.9	Activated carbon adsorption performance .....	126
Fig. 3.10	Adsorption of PCDD/Fs on activated carbon .....	126
Fig. 3.11	PCDD/Fs adsorption efficiency for activated carbon and MWCNTs .....	127
Fig. 3.12	Regenerated activated carbon system .....	128
Fig. 3.13	Low-temperature plasma treatment .....	129

Fig. 3.14	Additive injection and bag filter dedusting .....	129
Fig. 3.15	SIMETAL schematic .....	132
Fig. 3.16	Ignition control system .....	134
Fig. 3.17	Multi-slit burner .....	135
Fig. 3.18	Emissions optimized sintering plant .....	136
Fig. 3.19	EPOSIT process configuration plant .....	138
Fig. 3.20	Improving charging system .....	140
Fig. 3.21	Pre-reduced agglomerates .....	141
Fig. 3.22	Energy optimized sintering process .....	142
Fig. 3.23	Sectional gas recirculation .....	143
Fig. 3.24	BFG employment in the sinter process .....	148
Fig. 3.25	Concentrations of CO and CO <sub>2</sub> during sintering with 0%, 20%, 50%, and 100% replacement of coke breeze energy with charcoal .....	150
Fig. 3.26	Concentrations of targeted PCDD/F congeners observed during sintering with coke breeze and with 20% and 50% replacement of the coke energy with charcoal .....	151
Fig. 3.27	Effects of biochar replacing coke breeze on yield and quality of sinter .....	156
Fig. 3.28	Effects of biochar replacing coke on pollutant concentration of flue gas .....	157
Fig. 3.29	Technological solutions for environment impact mitigation .....	159
Fig. 4.1	Blast furnace plant .....	168
Fig. 4.2	Low reducing agent rate operation of blast furnace .....	169
Fig. 4.3	Approaches for lowering carbon in blast furnace .....	171
Fig. 4.4	Coke rate range predicted in various processes .....	172
Fig. 4.5	Dependence of the gas mixture and the solid-phase equilibrium composition on the temperature .....	174
Fig. 4.6	Gas-phase equilibrium of hematite reduction by CO and H <sub>2</sub> .....	175
Fig. 4.7	Solid-phase equilibrium of hematite reduction by CO (a) and H <sub>2</sub> (b) .....	176
Fig. 4.8	Gas-phase equilibrium of reactions relating to hydrogen, carbon, and oxygen .....	177
Fig. 4.9	BF main reactions .....	177
Fig. 4.10	CO <sub>2</sub> emissions in the traditional iron and steel production process .....	179
Fig. 4.11	Fossil fuel and materials flows in the BF-BOF steelmaking system .....	180
Fig. 4.12	Pulverized coil injection .....	182
Fig. 4.13	BF tuyeres .....	184
Fig. 4.14	Heat balance in the BF .....	186
Fig. 4.15	VIU for BF injectants .....	187
Fig. 4.16	Top gas recovery system .....	189
Fig. 4.17	Top-pressure control system .....	192

Fig. 4.18	Hot blast stove control .....	192
Fig. 4.19	BF control system .....	195
Fig. 4.20	Process monitoring .....	195
Fig. 4.21	Example of process monitoring and control .....	196
Fig. 4.22	Measurements at tuyeres level .....	197
Fig. 4.23	Torpedo infrared monitoring .....	198
Fig. 4.24	BF stack status monitoring .....	199
Fig. 4.25	Stove hot gas recovery .....	200
Fig. 4.26	Hot blast use .....	202
Fig. 4.27	Coke oven gas injection in the BF .....	203
Fig. 4.28	IGAR schematic .....	208
Fig. 4.29	Comparison of the coke rate, CO <sub>2</sub> intensity, and coke replacement rate (CRR) relative to the baseline case, for 180 kg/t-HM direct reduced iron in the furnace feed, 180 kg/t-HM cold CH <sub>4</sub> injected through the tuyere, 180 kg/t-HM CH <sub>4</sub> (preheated to 1200 K) partially combusted with O <sub>2</sub> (1200 K) to yield hot CO + 2H <sub>2</sub> and then injected in the furnace shaft, and 180 kg/t-HM CH <sub>4</sub> (preheated to 1200 K) injected through the tuyeres .....	210
Fig. 4.30	Comparison of the gas flow rate into the furnace and the heat transfer required to preheat the blast air and injectants for these cases, together with the net calorific value of the blast furnace top gas .....	212
Fig. 4.31	Plastic waste injection plant .....	216
Fig. 4.32	Flame temperature as a function of the injection rate .....	217
Fig. 4.33	Reduction potential of different plastics .....	218
Fig. 4.34	Residue injection scheme .....	222
Fig. 4.35	Comparison of PCI and biomass injection .....	224
Fig. 4.36	Reducing agent rates in different injection cases .....	225
Fig. 4.37	Thermochemical conversion products from woody biomass .....	226
Fig. 4.38	Emissions reduction potential through the employment of charcoal in primary ironmaking .....	227
Fig. 4.39	Life cycle CO <sub>2</sub> emissions of various biomass .....	228
Fig. 4.40	Schematic of biomass pretreatment setup in the simulated steel plant .....	229
Fig. 4.41	Combustion behavior of char, pulverized coal, and coke by rapid heating .....	231
Fig. 4.42	Change of biomass composition and effect of CO <sub>2</sub> reduction by carbonization .....	232
Fig. 4.43	Model of the CCB reaction .....	234
Fig. 4.44	Results for the CCB model .....	235
Fig. 4.45	Gas generation rate from iron carbon ore composite .....	236
Fig. 4.46	Gas generation rate from different iron carbon ore composites .....	237
Fig. 4.47	Schematic of reduction of iron ore by biomass carbon .....	238

Fig. 4.48	Reacted fraction of a volatile carbon and b nonvolatile carbon at different temperatures during reduction .....	239
Fig. 4.49	COURSE50 technologies scheme .....	241
Fig. 4.50	Iron reduction with H <sub>2</sub> use .....	242
Fig. 4.51	Schematic gas flow .....	242
Fig. 4.52	CO <sub>2</sub> emissions in BF with different solutions .....	244
Fig. 4.53	Scheme of the TGR-OBF plant .....	245
Fig. 4.54	BF configuration .....	246
Fig. 4.55	Hydrogen reduction to the entire indirect reduction of iron-bearing burdens .....	246
Fig. 4.56	Carbon consumption for direct reduction in TBF .....	249
Fig. 4.57	Pilot plant for the top gas recycling OBF .....	250
Fig. 4.58	Carbon consumption for direct reduction in OBF .....	250
Fig. 4.59	Carbon consumption vs. degree of direct reduction in OBF .....	252
Fig. 4.60	Conventional BF vs. advanced oxygen BF .....	253
Fig. 4.61	Slag heat recovery .....	256
Fig. 4.62	Slag granulation .....	260
Fig. 5.1	BOF process .....	276
Fig. 5.2	BOF reactions .....	277
Fig. 5.3	Melt composition variation .....	278
Fig. 5.4	Slag composition variation .....	278
Fig. 5.5	Materials flow and emission sources during the BOF process ...	280
Fig. 5.6	Sensible heat in iron and steelworks, (1) cooler exhaust gas; (2) main exhaust gas; (3) main exhaust gas after heat recovery; (4) coke oven flue gas after heat recovery; (5) COG sensible heat; (6) COG ammonia water; (7) BF slag sensible heat; (8) hot stove gas; (9) slag granulation tank water; (10) BOF slag sensible heat; (11) BOF gas sensible heat .....	281
Fig. 5.7	BOF gas recovery .....	283
Fig. 5.8	RecoDust schematic .....	289
Fig. 5.9	Energy saving potential .....	290
Fig. 5.10	Inert gas injection .....	292
Fig. 5.11	Censoring for process parameters monitoring .....	294
Fig. 5.12	Ladle preheating .....	295
Fig. 5.13	High-volume ladles preheating .....	296
Fig. 6.1	Electric arc furnace .....	304
Fig. 6.2	Percentage of electric steel production in the different regions (2017) .....	305
Fig. 6.3	Energy sources for ironmaking and steelmaking in the different regions .....	306
Fig. 6.4	Scrap charging .....	308
Fig. 6.5	Major technology developments in the EAF .....	310
Fig. 6.6	EAF electricity consumption as a function of the charged DRI .....	318

Fig. 6.7	Energy consumption for the DRI addition in the EAF .....	318
Fig. 6.8	Energy consumption for the DRI by varying the temperature ...	320
Fig. 6.9	EAF outputs as a function of DRI charge .....	321
Fig. 6.10	Burners for the EAF .....	323
Fig. 6.11	EAF electrodes at high temperature .....	325
Fig. 6.12	Energy saving as a function of the adopted solution .....	327
Fig. 6.13	Consteel furnace .....	330
Fig. 6.14	Preheating schematic .....	337
Fig. 6.15	Scrap heating through waste gas (direct from Tenova) .....	338
Fig. 6.16	Direct and indirect GHG sources for two cases. Top, convention EAF using Canadian electricity generation source distribution; bottom, scrap preheating EAF .....	340
Fig. 6.17	Bottom stirring effect in EAF .....	346
Fig. 6.18	Bottom gas stirring .....	346
Fig. 6.19	Electromagnetic stirring (direct from Tenova) .....	347
Fig. 6.20	EAF performances with EMS .....	348
Fig. 6.21	Single electrode furnace .....	352
Fig. 6.22	EAF energy balance .....	353
Fig. 6.23	Waste heat recovery .....	354
Fig. 6.24	Waste heat recovery strategies in a Consteel furnace .....	359
Fig. 6.25	Contiarc furnace .....	360
Fig. 6.26	iEAF system .....	368
Fig. 7.1	Smelting schematic and smelting reactor .....	378
Fig. 7.2	Classification of smelting reduction processes .....	380
Fig. 7.3	Fluidized bed schematic .....	381
Fig. 7.4	RHF-Smelter schematic .....	382
Fig. 7.5	Corex process .....	383
Fig. 7.6	Melter-gasifier schematic .....	384
Fig. 7.7	Bauer-Glaessner diagram .....	384
Fig. 7.8	Calculations of Bauer-Glaessner and Bogdandy-Engel diagrams .....	385
Fig. 7.9	Melter-gasifier reaction zones .....	387
Fig. 7.10	Thermodynamic model of the melter-gasifier in Corex .....	389
Fig. 7.11	Thermodynamic model of the reduction shaft in Corex .....	390
Fig. 7.12	Reducing gas requirement in reduction shaft and gas generation in smelter gasifier with different degrees of metallization for different types of coal .....	391
Fig. 7.13	Upstream and downstream CO <sub>2</sub> emission at different carbon rates .....	392
Fig. 7.14	Metallization degree as a function of gas composition and temperature .....	394
Fig. 7.15	Desulfurizer preparation .....	395
Fig. 7.16	Large-scale plant .....	396

Fig. 7.17	CO <sub>2</sub> emission of BF ironmaking system and COREX as function of power generation efficiency and electricity CO <sub>2</sub> emission factor .....	401
Fig. 7.18	FINEX process .....	402
Fig. 7.19	BF and FINEX integration .....	404
Fig. 7.20	CO <sub>2</sub> saving due to the use of LRI and PSA gas in the BF .....	406
Fig. 7.21	HIsmelt plant .....	407
Fig. 7.22	Coal consumption as a function of production rate .....	407
Fig. 7.23	Tecnored plant .....	409
Fig. 7.24	Tecnored furnace .....	410
Fig. 7.25	Charification of solid fuel .....	411
Fig. 8.1	Main reduction volume capacity .....	420
Fig. 8.2	Different types of DRI (direct from Midrex) .....	421
Fig. 8.3	Relationship between iron resources and reductants in various ironmaking processes (the production scale is million ton/year) .....	421
Fig. 8.4	Classification of direct reduction processes .....	424
Fig. 8.5	Midrex process .....	425
Fig. 8.6	Midrex plant with gasification and CO <sub>2</sub> removal equipment ...	425
Fig. 8.7	Used and wasted energies in the coal-based and the gas-based DRI plants .....	427
Fig. 8.8	Hyl-ENERGIRON process .....	432
Fig. 8.9	DRI use in BF .....	436
Fig. 8.10	Furnace model .....	437
Fig. 8.11	Energy balance .....	438
Fig. 8.12	FASTMELT process .....	441
Fig. 8.13	ITmk3 process .....	442
Fig. 8.14	CO <sub>2</sub> emissions for Fastmelt and ITmk3 vs. BF .....	442
Fig. 8.15	MXCOAL™ process .....	443
Fig. 8.16	Reduction rate of oxidized pellets .....	444
Fig. 8.17	Global natural gas producers .....	445
Fig. 8.18	DRI production in 2015 by region (direct from Midrex) .....	447
Fig. 8.19	SL/RN process .....	448
Fig. 8.20	Rotary kiln DRI process .....	449
Fig. 8.21	FINMET process .....	450
Fig. 8.22	Iron carbide reduction process .....	451
Fig. 8.23	CIRCORED process .....	453
Fig. 8.24	Redsmelt process .....	454
Fig. 8.25	DRI reduction through H <sub>2</sub> .....	459
Fig. 8.26	Midrex process with H <sub>2</sub> addition .....	459
Fig. 8.27	Midrex H <sub>2</sub> process .....	460
Fig. 8.28	Production costs due to H <sub>2</sub> transition .....	466

Fig. 8.29	Baur-Glaessner type diagram for mixed gases depending on fraction, C, of carbonaceous gas molecules. R denotes unoxidized gas species ( $\text{CO} + \text{H}_2$ ), and RO denotes the oxidized gas species ( $\text{CO}_2 + \text{H}_2\text{O}$ )	469
Fig. 8.30	Water-gas shift reaction (WGSR) equilibrium diagram in general and definition of gas variables	470
Fig. 8.31	Water electrolysis plant (www.thyssenkrupp-industrial-solutions.com)	475
Fig. 8.32	Flowsheet for hydrogen-based DRI production	476
Fig. 8.33	Hydrogen value chains by thyssenkrupp (www.thyssenkrupp-industrial-solutions.com)	476
Fig. 9.1	Global emissions from the seven most $\text{CO}_2$ -intensive industrial sectors	486
Fig. 9.2	$\text{CO}_2$ emissions per ton of crude steel	488
Fig. 9.3	$\text{CO}_2$ emissions for selected countries	489
Fig. 9.4	Carbon capture and utilization pathways	492
Fig. 9.5	Aqueous ammonia plant	506
Fig. 9.6	$\text{CO}_2$ capture and storage system process flow	509
Fig. 9.7	Principle of the PSA $\text{CO}_2$ -scrubbing techniques and various domains of application and performances of the variant techniques, PSA, VPSA, and VSA	512
Fig. 9.8	Steelanol schematic	513
Fig. 9.9	Block diagrams that outline the modeling blocks and the COG, BFG, OBFG, and PG connections: base case	514
Fig. 9.10	Block diagrams that outline the modeling blocks and the COG, BFG, OBFG, and PG connections: $\text{CO}_2$ capture case	515
Fig. 9.11	Phase diagram of pure $\text{CO}_2$	519
Fig. 9.12	Costs and $\text{CO}_2$ emissions for different capture technologies applied to various processing routes	523
Fig. 9.13	Fans capture scheme of the proposed technology	524
Fig. 9.14	Proposed process chemistry	524
Fig. 9.15	Industrial scheme of the plant	525
Fig. 9.16	Prototype module capable of capturing 100 kt $\text{CO}_2$ /year	526
Fig. 9.17	Prototype module capable of capturing 100 kt $\text{CO}_2$ /y	534
Fig. 9.18	Oxyfuel combustion scheme	537
Fig. 9.19	Principle of CaL process	539
Fig. 9.20	Simulated CaL process	541
Fig. 9.21	Energy integration of the CaL treating BFG	542
Fig. 9.22	Simplified scheme of the Ca-Cu looping process	546
Fig. 9.23	Cost comparison of different steel production decarbonization technologies depending on price of zero-carbon electricity	548
Fig. 10.1	Scoring criteria (with equally distributed weighting)	557
Fig. 10.2	Electrical energy required per ton of liquid iron as a function of the electrical conductivity of the molten oxide electrolyte	558