Contents

Preface xiii

About the Authors xv

	Acronyms xvii
1	Introduction 1
2	Coal in the Industrial Revolution and Beyond 13
3	History of Petroleum Oil and Natural Gas 21
3.1	Oil Extraction and Exploration 26
3.2	Natural Gas 27
4	Fossil-Fuel Resources and Their Use 31
4.1	Coal 32
4.2	Petroleum Oil 38
4.3	Unconventional Oil Sources 43
4.4	Tar Sands 44
4.5	Oil Shale 46
4.6	Light Tight Oil 47
4.7	Natural Gas 48
4.8	Coalbed Methane 56
4.9	Tight Sands and Shales 56
4.10	Methane Hydrates 57
4.11	Outlook 60
5	Oil and Natural Gas Reserves and Their Limits 63
6	The Continuing Need for Hydrocarbon Fuels and Products 73
6.1	Fractional Distillation of Oil 77
6.2	Thermal Cracking and Other Downstream Processes 78
6.3	Petroleum Products 79
7	Fossil Fuels and Climate Change 85
7.1	Mitigation 95



8	Renewable Energy Sources and Atomic Energy 101
8.1	Hydropower 104
8.2	Geothermal Energy 108
8.3	Wind Energy 113
8.4	Solar Energy: Photovoltaic and Thermal 117
8.4.1	Electricity from Photovoltaic Conversion 118
8.4.2	Solar Thermal Power for Electricity Production 121
8.4.3	Electric Power from Saline Solar Ponds 125
8.4.4	Solar Thermal Energy for Heating 125
8.4.5	Economics of Solar Energy 126
8.5	Bioenergy 127
8.5.1	Electricity from Biomass 128
8.5.2	Liquid Biofuels 130
8.5.2.1	Biomethanol 135
8.5.3	Advantages and Limitation of Biofuels 135
8.6	Ocean Energy: Thermal, Tidal, and Wave Power 136
8.6.1	Tidal Energy 136
8.6.2	Wave Power 138
8.6.3	Ocean Thermal Energy 139
8.7	Nuclear Energy 140
8.7.1	Energy from Nuclear Fission Reactions 142
8.7.2	Breeder Reactors 146
8.7.3	The Need for Nuclear Power 148
8.7.4	Economics 149
8.7.5	Safety 151
8.7.6	Radiation Hazards 153
8.7.7	Nuclear By-products, Waste, and Their Management 154
8.7.8	Emissions 156
8.7.9	Nuclear Fusion 156
8.7.10	Nuclear Power: An Energy Source for the Future 160
8.8	Future Outlook 161
0	The Undream Franchy and Ital imitations 165
9 9.1	The Hydrogen Economy and Its Limitations 165 Hydrogen and Its Properties 166
9.1	The Development of Hydrogen Energy 168
9.3	Production and Uses of Hydrogen 171
9.3.1	Hydrogen from Fossil Fuels 172
9.3.2	Hydrogen from Biomass 174
9.3.3	Photobiological Water Cleavage and Fermentation 175
9.3.4	Water Electrolysis 175
9.3.4.1	Electrolyzer Types 176
9.3.4.2	Electricity Source 177
9.3.5	Hydrogen Production Using Nuclear Energy 179
9.4	The Challenge of Hydrogen Storage 180
9.4.1	Liquid Hydrogen 182
9.4.2	Compressed Hydrogen 182
943	Metal Hydrides and Solid Adsorbents 184

9.4.4	Chemical Hydrogen Storage 185
9.5	Centralized or Decentralized Distribution
	of Hydrogen? 186
9.6	Hydrogen Safety 188
9.7	Hydrogen as a Transportation Fuel 189
9.8	Fuel Cells 191
9.8.1	History 191
9.8.2	Fuel Cell Efficiency 192
9.8.3	Hydrogen-based Fuel Cells 194
9.8.4	PEM Fuel Cells for Transportation 197
9.8.5	Regenerative Fuel Cells 200
9.9	Outlook 203
10	The "Methanol Economy": General Aspects 205
11	Methanol and Dimethyl Ether as Fuels and
	Energy Carriers 211
11.1	Background and Properties of Methanol 211
11.1.1	Methanol in Nature 213
11.1.2	Methanol in Space 213
11.2	Chemical Uses of Methanol 214
11.3	Methanol as a Transportation Fuel 216
11.3.1	Development of Alcohols as Transportation Fuels 217
11.3.2	Methanol as a Fuel in Spark Ignition (SI) Engines 226
11.3.3	Methanol as a Fuel in Compression Ignition (Diesel) Engines
	and Methanol Engines 229
11.4	Dimethyl Ether as a Transportation Fuel 232
11.5	Biodiesel Fuel 238
11.6	Advanced Methanol-powered Vehicles 238
11.6.1	Hydrogen for Fuel Cells Based on Methanol Reforming 239
11.7	Direct Methanol Fuel Cell (DMFC) 245
11.8	Fuel Cells Based on Other Methanol-derived Fuels and
	Biofuel Cells 253
11.8.1	Regenerative Fuel Cell 253
11.9	Methanol and DME as Marine Fuels 253
11.10	Methanol for Locomotives and Heavy Equipment 261
11.11	Methanol as an Aviation Fuel 262
11.12	Methanol for Static Power, Heat Generation, and Cooking 263
11.13	DME for Electricity Generation and as a Household Gas 265
11.14	Methanol and DME Storage and Distribution 268
11.15	Price of Methanol and DME 271
11.16	Safety of Methanol and DME 273
11.17	Emissions from Methanol- and DME-powered Vehicles and
	Other Sources 278
11.18	Environmental Effects of Methanol and DME 283
11.19	The Beneficial Effect of Chemical CO ₂ Recycling to Methanol
	on Climate Change 285

12	Production of Methanol from Still Available Fossil-Fuel
	Resources 287
12.1	Methanol from Fossil Fuels 290
12.1.1	Production via Syngas 290
12.1.2	Syngas from Coal 294
12.1.3	Syngas from Natural Gas 295
12.1.3.1	Steam Reforming of Methane 295
12.1.3.2	Partial Oxidation of Methane 296
12.1.3.3	Autothermal Reforming and Combination of Steam Reforming
	with Partial Oxidation 296
12.1.3.4	Syngas from CO ₂ Reforming of Methane 297
12.1.4	Syngas from Petroleum Oil and Higher Hydrocarbons 297
12.1.5	Economics of Syngas Generation 298
12.1.6	Alternative Syngas Generation Methods 298
12.1.6.1	Tri-reforming of Natural Gas 298
12.1.6.2	Bi-reforming of Methane for Methanol Production 298
12.1.6.3	Oxidative Bi-reforming of Methane for Methanol Production:
12.11.0.0	Methane Oxygenation 300
12.1.7	Other High-Temperature Processes Based on Methane to Convert
12.1.7	Carbon Dioxide to Methanol 300
12.1.7.1	Carnol Process 300
12.1.7.1	Combination of Methane Decomposition with Dry Reforming or
12.1.7.2	Steam Reforming 302
12.1.7.3	Addition of CO_2 to Syngas from Methane Steam Reforming 303
12.1.8	Coal to Methanol Without CO ₂ Emissions 303
12.1.9	Methanol from Syngas Through Methyl Formate 305
12.1.9	
	Methanol from Methane Without Producing Syngas 306 Direct Oxidation of Methane to Methanol 306
	Catalytic Gas-Phase Oxidation of Methane 307
	Liquid-Phase Oxidation of Methane to Methanol 309
12.1.10.4	Methane to Methanol Conversion Through Monohalogenated
10 1 11	Methanes 311
12.1.11	Microbial or Photochemical Conversion of Methane
10.0	to Methanol 313
12.2	Dimethyl Ether Production from Syngas or Carbon Dioxide Using
	Fossil Fuels 314
	Doler CD III Made I I DAMEC DE II
13	Production of Renewable Methanol and DME from Biomass and
10.1	Through Carbon Capture and Recycling 319
13.1	Biomass- and Waste-Based Methanol and DME – Biomethanol
	and Bio-DME 319
13.1.1	Gasification 321
13.1.1.1	Sources of Heat for the Gasification 322
13.1.2	Biocrude 322
13.1.3	Combination of Biomass and Coal 324
13.1.4	Excess CO ₂ in the Gas Mixture Derived from Biomass 324
13.1.5	Methanol from Biogas 329

13.1.6	Limitations of Biomass 332
13.1.7	Aquaculture 335
13.1.7.1	Water Plants 336
13.1.7.2	Algae 336
13.2	Chemical Recycling of Carbon Dioxide to Methanol 340
13.3	Heterogeneous Catalysts for the Production of Methanol from CO ₂
10.0	and H_2 340
13.4	Production of DME from CO ₂ Hydrogenation over Heterogeneous
13.4	Catalysts 342
10 5	Reduction of CO_2 to Methanol with Homogeneous
13.5	
12.6	Catalysts 343
13.6	Practical Applications of CO ₂ to Methanol 344
13.7	Alternative Two-Step Route for CO ₂ Hydrogenation
10.0	to Methanol 346
13.8	Where Should the Needed Hydrogen Come From? 346
13.9	CO ₂ Reduction to CO Followed by Hydrogenation 347
13.10	Electrochemical Reduction of CO ₂ 348
13.10.1	Direct Electrochemical CO ₂ Reduction to Methanol 349
13.10.2	Methods for High-Rate Electrochemical CO ₂ Reduction 350
13.10.3	Syngas (Metgas) Production from Formic Acid Synthesized by
	Electrochemical Reduction of CO ₂ 352
13.11	Thermochemical and Photochemical Routes to Methanol 352
13.11.1	Solar-Driven Thermochemical Conversion of CO ₂ to CO
	for Methanol Synthesis 352
13.11.2	Direct Photochemical Reduction of CO ₂ to Methanol 354
13.12	Sources of CO ₂ 355
13.12.1	Separating Carbon Dioxide from Industrial and Natural Sources
	for Chemical Recycling 356
13.12.2	CO ₂ Capture from Seawater 359
13.12.3	CO ₂ Capture from the Air 359
13.13	Atmospheric CO ₂ to Methanol 363
13.14	Cost of Producing Methanol from CO ₂ and Biomass 365
13.15	Advantages of Producing Methanol from CO ₂ and H ₂ 369
13.16	Reduction in Greenhouse Gas Emissions 369
13.17	Anthropogenic Carbon Cycle 372
14	Methanol-Based Chemicals, Synthetic Hydrocarbons, and
	Materials 375
14.1	Methanol-Based Chemical Products and Materials 375
14.2	Methyl-tert-butyl Ether and DME 377
14.3	Methanol Conversion to Light Olefins and Synthetic
	Hydrocarbons 378
14.4	Methanol to Olefin (MTO) Processes 380
14.5	Methanol to Gasoline (MTG) Processes 383
14.6	Methanol-Based Proteins 384
14.7	Plant Growth Promotion 385
14.8	Outlook 386
11.0	CHICON JOU

15	Conclusion and Outlook 387	
15 1	Where Do We Stand? 387	

15.1 Where Do We Stand? 387
15.2 The "Methanol Economy": Progress and Solutions for the Future 390

Further Reading and Information 395 References 409 Index 459