Contents

Preface Short biographies				xiii xv	
1		Introduction Christos A. Frangopoulos			
	1.1	Defini	ition of cogeneration	1	
	1.2		rical development of cogeneration	1	
	1.3		ure of the text	2	
	Refe	erences		4	
2		rgy use ob Klim	e in the world and the benefits of cogeneration stra	5	
	2.1	Energ	y and the global economy	5	
		-	Introduction	5	
		2.1.2	The growth pattern in energy use	5	
	2.2	Fuel u	use for electricity generation, heating, transportation		
			idustrial processes	8	
	2.3	Fuel r	esources and depletion	10	
	2.4	Energ	y savings potential with cogeneration	13	
	2.5 Capabilities for back-up for renewables				
	Acr	Acronyms			
	Refe	erences		16	
	Further Reading			16	
3		enerati	ion technologies stra	17	
	3.1	Introd	uction	17	
	3.2	Gas-tı	urbine-based cogeneration systems	18	
		3.2.1	The gas turbine concept and its fuel efficiency	18	
		3.2.2	Exhaust gas emissions limits for gas turbines	20	
		3.2.3	Controllability of the power and heat output	21	
			Maintenance aspects	24	
		3.2.5	The effect of ambient conditions on gas turbine		
			performance	24	
		3.2.6	Special designs	25	

	3.3	Recip	rocating internal combustion-engine-based cogeneration	
		systen	ns	26
		3.3.1	The background and basic concept	26
			The practical gas engine	28
			The fuel efficiency	29
			The heat sources	32
			Controllability of the electricity and heat output	34
			Fuel-air mixture preparation and control	36
		3.3.7	Maintenance aspects	38
			Exhaust gas emissions limits for reciprocating engines	39
			Response time to required load changes	39
	3.4		cell-based cogeneration systems	40
			The concept of a fuel cell	40
			The phosphoric acid fuel cell	42
			The molten carbonate fuel cell	42
			The solid oxide fuel cell	42
	3.5		ne and combined cycle cogeneration systems	43
			General overview	43
			Steam-based cogeneration	43
			The organic Rankine cycle	44
	3.6		llaneous technologies with minor potential for cogeneration	45
			Thermo-electric generators	45
			Thermo-photo-voltaic generators	45
			Thermo-ionic converters	45
		3.6.4	Stirling engines	46
	Refe	erences		46
4			engineering aspects	49
		s Östma		10
	4.1	-	neration plant electrical system overview	49
			Cogeneration plant electrical system	49
	4.0		Grid connection technologies	49
	4.2		of generators	51
		4.2.1	The synchronous generator	51
		4.2.2	The asynchronous generator	55
			The power-converter system	58
	4.2		Summary of electrical power conversion	61
	4.3		ork stability considerations	61
		4.3.1	The challenge of the future	61
		4.3.2	The role of inertia in a power system	62
	4 4	4.3.3	The role of a cogeneration unit in island operation	62
	4.4	-	neration unit active power control	64
		4.4.1	General overview	64
		4.4.2	Active power control strategies	65

		4.4.3 Traditional droop control	65		
		4.4.4 Fixed output control	66		
		4.4.5 Fixed output control with frequency bias	67		
		4.4.6 Isochronous control	68		
		4.4.7 Conclusion on active power control strategies	69		
	4.5		69		
		4.5.1 General overview	69		
		4.5.2 Reactive power control strategies	69		
		4.5.3 Voltage droop control	70		
		4.5.4 Power factor control	71		
		4.5.5 Constant reactive power control	72		
		4.5.6 Conclusion on reactive power control strategies	72		
	Acre	onyms	72		
	Refe	erences	73		
5	App	plications of cogeneration	75		
	Jaco	ob Klimstra			
	5.1	Introduction to applications of cogeneration	75		
	5.2	8	75		
	5.3	Cogeneration in the industrial sector	77		
		5.3.1 Cogeneration for a paper mill	78		
		5.3.2 Cogeneration in the dairy and bakery industry	78		
		5.3.3 Cogeneration in the beer brewery industry	79		
		5.3.4 Cogeneration in a sewage sludge incineration plant	80		
	5.4	- 8	81		
		5.4.1 Cogeneration in hotels	81		
		5.4.2 Cogeneration in hospitals	82		
		5.4.3 Cogeneration for data centres	83		
	5.5	8 8	84		
		5.5.1 Greenhouse applications	84		
		5.5.2 Product drying	85		
	5.6	8	85		
	5.7	Cogeneration and desalination	86		
	Refe	erences	87		
6	Fuels for cogeneration systems				
		ob Klimstra	20		
	6.1	Introduction	89		
	6.2	Types and properties of fuels	89		
		6.2.1 Gaseous fuels	89		
		6.2.2 Liquid fuels	94		
	()	6.2.3 Solid fuels	96		
	6.3	Fuel- and combustion-related emissions	98		
		6.3.1 Greenhouse gas emissions	99		

	6.	3.2	NO_x emissions	100
	6.	3.3	SO ₂ emissions	101
	6.	3.4	CO, aldehydes and ash emissions	102
	Acrony	ms		103
	Referen	ices		103
7	Therm	odyı	namic analysis	105
	Christo	s A.	Frangopoulos	
	7.1 In	trod	uction to thermodynamic analysis of cogeneration	
	sy	sten	18	105
	7.2 In	dexe	es of thermodynamic performance	105
	7.	2.1	Efficiencies based on energy	106
	7.	2.2	Efficiencies based on exergy	110
	7.	2.3	Electricity to heat ratio	111
	7.	2.4	Primary energy savings	112
	7.3 Pr	oced	dure for determination of electricity cogenerated	
	W	ith u	seful heat	120
	7.	3.1	What is the issue?	120
	7.	3.2	Distinction between cogeneration systems without	
			loss and with loss of work production due to useful	
			heat production	120
	7.	3.3	Splitting the cogeneration unit in CHP and	
			non-CHP parts	121
	7.	3.4	Procedure to calculate the cogenerated electricity	
			and related parameters	122
	Nomen	clatu	ire	128
	Append	lix 7	.A Fundamentals of exergy	130
	7.	A.1	Definition of exergy	130
	7.	A.2	Exergy of work and heat	131
	7.	A.3	Exergy of a closed system	131
	7.	A.4	Flow exergy	132
	7.	A.5	Physical flow exergy of ideal gas and of mixture	
			of ideal gases	133
	7.	A.6	Physical flow exergy of incompressible fluids	133
	Append	lix 7	.B Power-to-heat ratio in full cogeneration mode	134
	Referen			135
	Further	Rea	ding	136
8	Enviro	nme	ental impacts of cogeneration	137
	Wojcied	ch Si	tanek and Lucyna Czarnowska	
	8.1 In	trod	uction	137
	8.2 D	efini	tions and emissions impact categories	138
	8.3 Ef	ffect	s on air quality	139

		8.3.1	Irreversibility, fuel use, and emissions	140
		8.3.2	Estimation of direct gaseous emissions	142
		8.3.3	Local and global balance of direct gaseous emissions	146
		8.3.4	The various substances that affect global warming	148
		8.3.5	Allocation of fuel and emissions of a cogeneration	
			system to its products	149
		8.3.6	Cumulative emissions—the case of greenhouse gases	154
		8.3.7	Dispersion and impacts of pollutants on the environment	
			and the society-the external environmental cost	157
		8.3.8	Thermo-ecological cost	160
		8.3.9	Thermo-ecological indicators of environmental benefits	
			and results for selected bio-CHPs	165
	8.4	Effect	s on water and soil quality	167
		8.4.1	Effects on water quantity and quality	167
		8.4.2	Effects on soil and water quality caused by	
			the emissions	168
	8.5	Legal	emission limits and emission trading	170
	8.6		and vibration	173
	Refe	rences		174
9	Reli	ability	and availability	179
	Jaco	b Klim	stra	
	9.1	Introd	uction	179
	9.2	Defini	tions	180
		9.2.1	Component reliability	180
		9.2.2	Operational availability	180
		9.2.3	System reliability	181
	9.3 Maintenance philosophies		182	
	9.4 Redundancy			
	Refe	rences		188 188
	Further Reading			
10	Ecol	nomic a	analysis of cogeneration systems	191
	Chri	stos A.	Frangopoulos	
	10.1		duction to economic analysis of cogeneration systems	191
	10.2	* 1	s of costs	191
		10.2.	I I I I I I I I I I I I I I I I I I I	191
		10.2.	1	195
	10.3		nition of economic parameters	198
		10.3.		198
		10.3.		199
		10.3.		199
		10.3.		200
		10.3.	5 Estimation of the value of money in time	201

x Cogeneration: technologies, optimisation and implementation

	10.4	Measure	s of economic performance	206	
		10.4.1	Net present value of the investment	206	
		10.4.2	Net present cost and present worth cost	207	
		10.4.3	Internal rate of return	207	
		10.4.4	Payback period	208	
	10.5	Procedur	re for economic analysis of cogeneration systems	209	
			Estimation of the initial cash flow (F_0)	210	
		10.5.2	Estimation of the net cash flow for the years		
			of analysis $(F_n, n \ge 1)$	210	
	10.6	Costing	of thermal and electrical and/or mechanical energy	214	
		10.6.1	Statement of the problem	214	
		10.6.2	Methods of cost allocation	215	
	10.7	Internali	zation of external environmental costs and their		
		effect or	the economic performance of cogeneration systems	217	
			Introductory remarks and definitions	217	
		10.7.2	Evaluation and internalization of external		
			environmental costs	217	
	10.8		es of economic analysis of cogeneration systems	218	
	Nome	nclature		229	
	Refer	ences		231	
	Furthe	er Readin	g	232	
11			d legal framework of cogeneration	233	
	Costas G. Theofylaktos				
	Costa	s G. Theo	ofylaktos		
				233	
	11.1	Introduc	tion	233 234	
		Introduc Europea	tion n policy on energy efficiency and on cogeneration	234	
	11.1	Introduc Europear 11.2.1	tion n policy on energy efficiency and on cogeneration The general framework	234 234	
	11.1 11.2	Introduc Europear 11.2.1 11.2.2	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries	234	
	11.1	Introduc Europeat 11.2.1 11.2.2 Regulate	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries ory and legal framework in countries outside Europe	234 234 241	
	11.1 11.2	Introduc Europear 11.2.1 11.2.2 Regulato 11.3.1	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries	234 234 241	
	11.1 11.2	Introduc Europeat 11.2.1 11.2.2 Regulato 11.3.1	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries ory and legal framework in countries outside Europe Regulatory and legal framework in the United States of America	234 234 241 245	
	11.1 11.2	Introduc Europeat 11.2.1 11.2.2 Regulato 11.3.1 11.3.2	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries ory and legal framework in countries outside Europe Regulatory and legal framework in the United States of America Policy development of cogeneration in PR of China	234 234 241 245 245	
	11.1 11.2 11.3	Introduc Europeat 11.2.1 11.2.2 Regulato 11.3.1 11.3.2 11.3.3	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries ory and legal framework in countries outside Europe Regulatory and legal framework in the United States of America Policy development of cogeneration in PR of China Policy development of cogeneration in Japan	234 234 241 245 245 245 247 248	
	11.1 11.2	Introduc Europeat 11.2.1 11.2.2 Regulato 11.3.1 11.3.2 11.3.3 Impact of	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries ory and legal framework in countries outside Europe Regulatory and legal framework in the United States of America Policy development of cogeneration in PR of China Policy development of cogeneration in Japan of electricity and gas liberalisation on cogeneration	234 234 241 245 245 245 247 248 250	
	11.1 11.2 11.3	Introduc Europeat 11.2.1 11.2.2 Regulato 11.3.1 11.3.2 11.3.3 Impact of 11.4.1	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries ory and legal framework in countries outside Europe Regulatory and legal framework in the United States of America Policy development of cogeneration in PR of China Policy development of cogeneration in Japan of electricity and gas liberalisation on cogeneration Introduction to EU electricity and gas liberalisation	234 234 241 245 245 245 247 248	
	11.1 11.2 11.3	Introduc Europeat 11.2.1 11.2.2 Regulato 11.3.1 11.3.2 11.3.3 Impact of 11.4.1	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries ory and legal framework in countries outside Europe Regulatory and legal framework in the United States of America Policy development of cogeneration in PR of China Policy development of cogeneration in Japan of electricity and gas liberalisation on cogeneration Introduction to EU electricity and gas liberalisation EU energy liberalisation and its impact on cogeneration	234 234 241 245 245 245 247 248 250 250	
	11.111.211.311.411.5	Introduc Europeat 11.2.1 11.2.2 Regulato 11.3.1 11.3.2 11.3.3 Impact of 11.4.1 11.4.2 Conclusio	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries ory and legal framework in countries outside Europe Regulatory and legal framework in the United States of America Policy development of cogeneration in PR of China Policy development of cogeneration in Japan of electricity and gas liberalisation on cogeneration Introduction to EU electricity and gas liberalisation EU energy liberalisation and its impact on cogeneration	234 234 241 245 245 247 248 250 250 252 254	
	11.1 11.2 11.3	Introduc Europeat 11.2.1 11.2.2 Regulato 11.3.1 11.3.2 11.3.3 Impact of 11.4.1 11.4.2 Conclusio	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries ory and legal framework in countries outside Europe Regulatory and legal framework in the United States of America Policy development of cogeneration in PR of China Policy development of cogeneration in Japan of electricity and gas liberalisation on cogeneration Introduction to EU electricity and gas liberalisation EU energy liberalisation and its impact on cogeneration	234 234 241 245 245 247 248 250 250 252	
12	 11.1 11.2 11.3 11.4 11.5 Acror Reference 	Introduc Europear 11.2.1 11.2.2 Regulato 11.3.1 11.3.2 11.3.3 Impact of 11.4.1 11.4.2 Conclusion ences	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries ory and legal framework in countries outside Europe Regulatory and legal framework in the United States of America Policy development of cogeneration in PR of China Policy development of cogeneration in Japan of electricity and gas liberalisation on cogeneration Introduction to EU electricity and gas liberalisation EU energy liberalisation and its impact on cogeneration ions	234 234 241 245 245 247 248 250 250 252 254 255	
12	 11.1 11.2 11.3 11.4 11.5 Acror Reference Select 	Introduc Europear 11.2.1 11.2.2 Regulato 11.3.1 11.3.2 11.3.3 Impact of 11.4.1 11.4.2 Conclusion ences	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries ory and legal framework in countries outside Europe Regulatory and legal framework in the United States of America Policy development of cogeneration in PR of China Policy development of cogeneration in Japan of electricity and gas liberalisation on cogeneration Introduction to EU electricity and gas liberalisation EU energy liberalisation and its impact on cogeneration ions	234 234 241 245 247 248 250 250 252 254 255 256	
12	 11.1 11.2 11.3 11.4 11.5 Acror Reference Select 	Introduc Europea 11.2.1 11.2.2 Regulato 11.3.1 11.3.2 11.3.3 Impact of 11.4.1 11.4.2 Conclusion ences tion, integration for the second second Klimstra	tion n policy on energy efficiency and on cogeneration The general framework Examples of policy development in European countries ory and legal framework in countries outside Europe Regulatory and legal framework in the United States of America Policy development of cogeneration in PR of China Policy development of cogeneration in Japan of electricity and gas liberalisation on cogeneration Introduction to EU electricity and gas liberalisation EU energy liberalisation and its impact on cogeneration ions	234 234 241 245 247 248 250 250 252 254 255 256	

		12.1.2	Measurement equipment for determining			
			the energy flows	261		
		12.1.3	Fuel options	262		
	12.2	Integrat	ion of cogeneration in heat supply systems	262		
		12.2.1	Matching size and demand	263		
		12.2.2	Hydraulic integration	264		
	12.3	Summa	ry of possible integration problems	271		
	Refere	ences		272		
	Furthe	er Readir	ng	272		
13	Simu	lation ar	nd optimisation of synthesis, design and operation			
		,	on systems	273		
	Christ	tos A. Fr	rangopoulos			
	13.1	Introdu	ction to simulation and optimisation of			
	10.1		ation systems	273		
	13.2	-	pment of simulation models	273		
			nance evaluation of cogeneration systems	275		
	13.4		natical optimisation of cogeneration systems	276		
	1011	13.4.1	Definition of optimisation	276		
		13.4.2	*	276		
			Levels of optimisation	277		
		13.4.4	1	278		
		13.4.5				
			optimisation problem	279		
		13.4.6	Formulation and solution methods of the dynamic			
			optimisation problem	284		
		13.4.7	* *			
			cogeneration systems	287		
		13.4.8	Sensitivity analysis	288		
	13.5	Optimis	sation examples	289		
	Refere	-	1	309		
14	Exam	ples of o	cogeneration projects	313		
	Costas G. Theofylaktos					
	14.1	Introdu	ction	313		
	14.2	Cogene	ration in district heating	313		
		0	The Siekierki CHP plant, Warsaw, Poland	313		
		14.2.2	The Ziepniekkalns CHP plant, Riga, Latvia	314		
	14.3	Industri	al cogeneration plants	314		
		14.3.1	Cogeneration in the pulp and paper industry: The			
			UIPSA CHP plant, La Pobla de Claramunt, Barcelona	314		
		14.3.2	Cogeneration in the primary metal industry: The			
			Aughinish Alumina CHP plant, Askeaton,			
			Limerick, Ireland	315		

	14.4	Cogener	ration in the commercial (building) sector	316
		14.4.1	CHP plant in Hospital Central de la Defensa	
			"Gomez Ulla," Madrid, Spain	316
		14.4.2	"Hypo Alpe Adria" Trigeneration System,	
			Tavagnacco, Italy	317
		14.4.3	Micro-CHP plant in De Clare Court, Haverfordwest,	
			Pembrokeshire, UK	318
	14.5	Cogener	ration in the agricultural sector	318
		14.5.1	The Agritex Energy S.A. CHP plant, Alexandria, Greece	318
	Refere	ences		319
15	Resea	rch and	development on cogeneration	321
			angopoulos	
	15.1	Introduc	tion	321
	15.2	Advance	ements in cogeneration technologies	321
		15.2.1	Steam systems	321
		15.2.2	Combined cycles	321
		15.2.3	Organic Rankine cycles	322
		15.2.4	Fuel cells and hybrid systems	322
		15.2.5	Thermoelectric generators	322
		15.2.6	Nuclear plants	322
	15.3	Cogener	ration and renewable energy	323
		15.3.1	Biomass	323
		15.3.2	Solar energy	323
		15.3.3	Geothermal energy	324
	15.4	Storage	of thermal and electric energy	324
		15.4.1	Storage of thermal energy	324
		15.4.2	Storage of electric energy	324
	15.5	Reduction	on of emissions	325
	Refere	ences		325
16	Summ	nary and	l conclusions	329
	Christ	tos A. Fra	angopoulos	

Index

333