

PLANNING OF OPTIMAL POWER SYSTEMS

ASKO VUORINEN

# PLANNING OF OPTIMAL POWER SYSTEMS

## CONTENTS

1	IN	$\Gamma \mathbf{R}$	$\cap$	DΤ	IC	$\Gamma I C$	N	
	111		. , ,	,,,			, I N	

	17 18
1.3 Diesel engines	
1 6	19
1 1	20
$\mathcal{L}$	20
J	21
1 1	22
1 1	23
1 11	25
J	26
1.12 Power system planning	27
2 FUNDAMENTALS OF POWER PLANTS	
$\mathcal{E}$	29
$\mathcal{E}$	40
2.3 Gas turbines	43
2.4 Conventional power plants	44
1 1	45
1 1	46
1 1	49
J	54
1	59
2.10 Operation characteristics	53
3 FUNDAMENTALS OF EMISSION CONTROL	
3.1 Ambient air	68
3.2 Emissions	59
3.3 Global warming	74
4 PLANNING OF NATIONAL POWER SYSTEMS	
	79
4.2 Minimisation of power system costs	90
4.3 Maximisation of profits	96
4.4 Summary and conclusions	100
5 PLANNING OF DECENTRALISED POWER SYSTEMS	
5.1 Municipal CHP systems	102
5.2 Planning of independent systems	117

5.3 Integration of wind and diesel plants	121
5.4 Integration of wind energy into a large system	124
5.5 Planning of micro-CHP systems	127
6 PLANNING OF POWER SYSTEM RESERVES	
(1 Decree contains account as a single contains	121
6.1 Power system reserve requirements	131
6.2 Adequacy of power system capacity	138
6.3 Frequency control reserves	145
6.4 Operating reserves	159
6.5 Voltage control and reactive reserves	165
6.6 Black start reserves	170
7 BUSINESS STRATEGIES IN ELECTRICITY MARKETS	
7.1 Business strategies for traditional energy markets	181
7.1 Business strategies for traditional energy markets 7.2 Business strategies for competitive energy markets	187
7.2 Business strategies for competitive energy markets 7.3 Revenues from capacity markets	199
7.4 Credits from transmission services and congestion	204
7.4 Credits from transmission services and congestion 7.5 Electricity trading	211
7.6 Benchmarking	214
7.0 Benchmarking	214
8 BUSINESS STRATEGIES IN ANCILLARY SERVICE MARKETS	
8.1 Ancillary service markets	219
8.2 Revenues from regulation reserve markets	223
8.3 Revenues from operating reserves	231
8.4 Optimisation algorithms for ancillary service markets	237
8.5 Net revenues of power plants in some electricity markets	245
6.3 Teet revenues of power plants in some electricity markets	243
9 EVALUATION OF THE PROFITABILITY OF NEW POWER PLANT	ALTERNATIVES
9.1 Methodology in profitability evaluation	256
9.2 The profitability of nuclear power plants	261
9.3 The profitability of wind power plants	265
9.4 The profitability of coal power plants	272
9.5 The profitability of combined cycle power plants	278
9.6 The profitability of combined heat and power plant	289
9.7 The profitability of gas-fired peaking power plant	294
9.8 The profitability of diesel-fired power plants	302
9.9 Summary	310
10 POWER SYSTEM PLAN FOR THE WORLD IN 2050	
10.1 Trends in power plant construction	312
10.2 A plan for the year 2050	326
10.3 The strategy for the future	337
11 THE ACTION IN AN	220
11 THE ACTION PLAN	339

#### **TABLES**

2 FUNDAMENTALS OF POWER PLANTS 2.10.1 Maximum step change of power plants 63 2.10.2 Maximum ramp rates of power plants 64 2.10.3 Synchronisation time of large diesel engines and gas turbines 65 2.10.4 Loading time from zero to full load 66 3 FUNDAMENTALS OF EMISSION CONTROL 3.1.1 WHO Ambient Air Quality Guidelines 68 3.2.1 Emission limit values for SO2 and NOx plant built after 2003 69 3.2.2 Emission limit values for SO2 and NOx plant built after 2008 69 3.2.3 Nitrogen oxide emission standards for internal combustion engines 70 3.2.4 Emission standards for particles 72 3.2.5 Carbon content of fuels 72 3.2.6 Carbon dioxide emissions of typical power plants 73 4 PLANNING OF NATIONAL POWER SYSTEMS 79 4.1.1 Power plant alternatives 4.1.2 Capital costs of power plan alternatives 81 4.1.3 Fixed operation and maintenance costs 82 4.1.4 Variable operation, maintenance, waste and emission costs 83 4.1.5 Levelised prices of fuels 85 4.1.6 Fuel costs of power plants 86 4.1.7 Fixed and variable generation costs 87 4.1.8 Lowest cost plants by full power hours 89 4.2.1 Optimum power generation capacity mix (MW) 94 4.2.2 Total generation costs of alternative power systems 94 4.2.3 Optimal power generation by energy (TWh) and emissions 95 4.2.4 Electricity prices in different cases 96 4.2.5 The net profits of alternative 10 000 MW power systems 97 5 PLANNING OF DECENTRALISED POWER SYSTEMS 103 5.1.1 Power plant alternatives 5.1.2 Economical evaluation of gas engine plant size 105 5.1.3 Economical optimisation of dual-fuel combined cycle plant size 107 5.1.4 Comparison of a CC gas engine plant and a gas engine plant 110 5.1.5 Optimisation of the coal-fired CHP plant size 111 5.1.6 Installed CHP capacity in the largest cities of Finland 115 5.1.7 Potential capacity of CHP plants in Finland 116 5.2.1 Capital costs of decentralised power plants 117 5.2.2 Generation costs of decentralised power plants 118 5.2.3 Generation costs by increasing size of diesel engine combined cycle 1 119

5.2.4 Optimal capacity mix in an independent 200 MW system

5.3.1 Optimal capacity mix in an interconnected 200 MW system

120

122

5.3.2 Optimal capacity mix in an independent 200 MW wind diesel system 5.4.1 Analysing the wind generation on 1 <sup>st</sup> of October 2008 5.5.1 Micro CHP plants	122 126 127
6 PLANNING OF POWER SYSTEM RESERVES	
6.1.1 Generating unit statistics 1999-2003	132
6.2.1 Finnish power system capacity	140
6.2.2 Available power system capacity and the peak load	140
6.4.1 Typical start-up times and ramp rates of power plants	161
7 BUSINESS STRATEGIES IN ENERGY MARKETS	
7.2.1 Capacities and costs of power plants	189
7.2.2 Energy revenues and generation costs at 300 MW load	193
7.4.1 Average weighting of transmission charges in Europe	204
7.4.2 Capacities and costs of power plants	205
7.4.3 Revenues and generation costs of power plants with transmission	207
7.4.4 Revenues and costs of power plants	209
7.6.1 Electricity prices in the EU in 1996	214
7.6.2 Electricity prices in the EU in 2005	215
8 BUSINESS STRATEGIES FOR ANCILLARY SERVICES	
8.2.1 Regulation reserve needs in Western Denmark	227
8.2.2 Secondary frequency control market prices in E.ON Netz	228
8.2.3 Profits of alternative 100 MW power plants in different markets	230
8.3.1 Profits from energy and spinning capacity	232
8.4.1 Profits of 160 MW gas engine plant with and without A/S	241
8.4.2 Profits of 160 MW gas engine CHP plant with and without A/S	242
8.4.3 Profits of 160 MW diesel engine plant with and without A/S	243
8.5.1 Net revenues of new entrants in California (\$/kW) in 2004	246
8.5.2 Electricity prices in California SP15 in the year 2005 (\$/MWh)	247
8.5.3 Number of start-ups and operation hours of a 160 MW gas plant	247
8.5.4 Revenues of a 160 MW gas engine plant in California SP15	248
8.5.5 Net revenues of a new gas turbine plant in PJM area	249
8.5.6 Net revenues of a new combined cycle plant in PJM area	249
8.5.7 Net revenues of a new gas turbine and CC plant in New England	251
8.5.8 Power reserves in Nordel	252
9 PROFITABILITY EVALUATION OF NEW POWER PLANT ALTERNATIVES	
9.1.1 Basic cash flow model of power plant investments	257
9.1.2 Generating costs of electricity in the model system	259
9.1.3 Prices of fuels, electricity and CO <sub>2</sub> -allowances in the year 2013	259
9.2.1 Performance of nuclear power plants	261
9.2.2 Cash flow analysis of a nuclear plant without ancillary services	262
9.2.3 Cash flow analysis of a nuclear plant with ancillary services	264
9.3.1 Performance of wind power plants	265

9.3.2 Cash flow analysis of a 30 x 5 MW onshore wind plant without A/S	266
9.3.3 Cash flow analysis of a 30 x 5 MW offshore wind plant without A/S	267
9.3.4 Cash flow analysis of a 30 x 5 MW offshore wind power plant with	
green certificates without A/S	268
9.3.5 Cash flow analysis of an onshore wind plant with fast reserves	270
9.3.6 Cash flow analysis of an offshore wind plant with fast reserves	271
9.4.1 Performance of coal fired power plants	272
9.4.2 Cash flow analysis of a coal plant (Coal 500 SC) without A/S	273
9.4.3 Cash flow analysis of a coal plant (Coal 500 USC) without A/S	274
9.4.4 Cash flow analysis of a coal plant (Coal 330 CSS) without A/S	275
9.4.5 Cash flow analysis of a coal plant with regulation reserves	277
9.5.1 Performance of dual-fuel and gas turbine combined cycle plants	278
9.5.2 Cash flow analysis of a 170 MW DFCC plant in base load	280
9.5.3 Cash flow analysis of a 170 MW DFCC plant in intermediate load	281
9.5.4 Cash flow analysis of a 170 MW DFCC plant with non-spin reserves	282
9.5.5 Cash flow analysis of a 170 MW GECC plant with A/S service	283
9.5 6 Cash flow analysis of a 330 MW GTCC plant in energy service	285
9.5.7 Cash flow analysis of a 500 MW GTCC plant in energy service	286
9.5.8 Cash flow analysis of a 330 MW GTCC plant in regulation service	287
9.5.9 Cash flow analysis of a 500 MW GTCC plant in regulation service	288
9.6.1 Performance of gas engine CHP plant	289
9.6.2 Cash flow diagram of a gas engine CHP plant in energy service	291
9.6.3 Cash flow diagram of a gas engine CHP plant with non-spin	292
9.6.4 Cash flow diagram of a gas engine CHP plant with spin and non-spin	293
9.7.1 Performance of dual fuel and gas engine peaking plants	294
9.7.2 Cash flow of a 160 MW gas engine plant operating 819 h/a	296
9.7.3 Cash flow of a 160 MW gas engine plant with regulation	297
9.7.4 Cash flow of a 160 MW gas engine plant with non-spin	298
9.7.5 Cash flow of a 160 MW gas engine plant with reg. and non-spin	299
9.7.6 Cash flow of a 160 MW gas turbine plant regulation and non-spin	301
9.8.1 Performance of LFO-fired peaking plants	302
9.8.2 Cash flow of a 160 MW diesel engine plant in energy service	304
9.8.3 Cash flow of a 160 MW diesel engine plant with non-spin	305
9.8.4 Cash flow of a 160 MW diesel engine plant with reg. and non-spin	306
9.8.5 Cash flow of a 160 MW diesel engine plant in non-spinning service	307
9.8.6 Cash flow of a LFO gas turbine plant in non-spinning service	308
9.8.7 Cash flow of a LFO gas turbine plant with regulation and non-spin	309
9.9.1 Internal rate of return of alternative power plants	310
5.5.1 Internal rate of revain of alternative power plants	210
10 POWER SYSTEM PLAN FOR THE WORLD IN 2050	
10.1.1 Increase of coal consumption in the world	319
10.2.1 Electricity consumption in the world	329
10.2.2 Electricity generation with three scenarios	335
10.2.3 Costs and emissions of different scenarios	335
10.2.4 CO <sub>2</sub> - emissions of different scenarios	336

# **FIGURES**

## 1 INTRODUCTION

1.1 An old farm windmill in the Middle of Finland	23
2 FUNDAMENTALS OF POWER PLANTS	
2.1.1 The Carnot engine	29
2.1.2 The Carnot cycle is the ideal cycle of engines	29
2.1.3 Otto cycle of spark-ignition engines	31
2.1.4 The Diesel cycle has constant pressure	32
2.1.5 Gas turbine process (Brayton cycle)	34
2.1.6 Brayton cycle with constant pressure in heat input and rejection	35
2.1.7 Steam turbine (Rankine) process diagram	36
2.1.8 TS-diagram of Rankine cycle or water steam cycle	37
2.1.9 Diesel or Gas Engine Combined Cycle (DECC/GECC) power plant	38
2.1.10 Gas Turbine Combined Cycle (GTCC) power plant	38
2.6.1 Wind forecast	46
2.6.2 Output curve of a wind turbine	47
2.6.3 Monthly average wind generation in E.ON Netz in 2008	48
2.7.1 Output as a function of ambient temperature	50
2.7.2 Output as a function of altitude from sea level	51
2.7.3 Output deterioration of gas turbines	52
2.8.1 Electrical efficiency of IC engines and gas turbines	56
2.8.2 Correction factor of ambient temperature for efficiency	57
2.8.3 Correction factor of part load operation for efficiency	58
2.9.1 Engine main flow diagram	59
2.9.2 Heat balance of a 10 MW diesel engine	60
3 FUNDAMENTALS OF EMISSION CONTROL	
3.3.1 Millennial Northern Hemisphere temperature reconstruction	74
3.3.2 Average annual concentration of carbon dioxide	76
3.3.3 Annual increase of carbon dioxide concentration in Hawaii	76
3.3.4 Concentration of carbon dioxide has an actually an increasing trend	77
4 PLANNING OF OPTIMAL CAPACITY MIX	
4.1.1 Import prices of fuels	84
4.1.2 Trends in fuel prices during the operation life	85
4.1.3 Generation costs of power plants	88
4.2.1 Load duration curves in Finland and California	90
4.2.2 Optimum generation mix with all options open	92
4.2.3 Optimum generation mix without nuclear plants	92
4.2.4 Optimum generation mix without nuclear and coal plants	93
4.2.5 Optimum generation mix with renewable plants	93
4.2.6 Annual costs of alternative power systems	94
4.2.7 Nuclear and liquid biofuel (LBF) engine mixed power system	98

4.2.8 Nuclear and gas engine mixed power system	98
4.2.9 Wind and LBF diesel engine mixed power system	99
4.2.10 Wind and gas engine mixed power system	99
5 PLANNING OF DECENTRALISED POWER SYSTEMS	
5.1.1 Load duration curve of a city with 100,000 inhabitants	102
5.1.2 Heat duration curve of a city with 100,000 inhabitants	102
5.1.3 Electrical load duration of a 224/224 MW gas engine plant	106
5.1.4 Heat load duration curve of a 224/224 MW gas engine plant	106
5.1.5 Electrical load duration curve of a 234/213 MW DFCC plant	108
5.1.6 Heat load duration curve of a 234/213 MW DFCC plant	109
5.1.7 Electrical load duration curve of a 120/240 MW coal CHP plant	112
5.1.8 Heat load duration curve of a 120/240 MW coal CHP plant	112
5.2.1 DECC plant and LFO diesel plant capacity mix	119
5.3.1 Optimal capacity mix in an integrated wind energy system	121
5.3.2 Load duration curve of an isolated wind-diesel system	123
5.4.1 Residual load (load-wind) will fluctuate more than actual load	124
5.4.2 Power generation in E.On Netz without wind power plants	125 125
5.4.3 Power generation in E.On Netz with 30 % wind power	123
6 PLANNING OF POWER SYSTEM RESERVES	
6.1.1 Reserve margin requirements as a function of a number of plants	135
6.2.1 Finnish electricity consumption during the first week in 2003	138
6.2.2 Peak load trend in Finland and 1/10 maximum and minimum peaks	139
6.2.3 Electricity consumption in Finland	141
6.3.1 Daily load variations	145
6.3.2 Commitment of frequency control reserves (UCTE manual)	146
6.3.3 Power control of two generators with different droops	148
6.3.4 Frequency drop after power plant trip	148
6.3.5 Primary control of reserves in UCTE	149
6.3.6 System frequency control diagram (UCTE manual)	152
6.3.7 Secondary control of reserves (UCTE manual)	152
6.3.8 Tertiary control of reserves in UCTE	154
6.3.9 The net efficiency of power plants at the regulation range	157
6.3.10 Net efficiency of a plant in high efficiency and regulation modes	157
6.4.1 Maximum wind power decrease in E.ON Netz in Germany in 2008	162 163
6.4.2 Monthly wind forecast error in E.ON Netz in Germany in 2008 6.4.3 Start-up sequence of power plants after wind decrease of 800 MW	163
6.5.1 Generator excitation	165
6.5.2 Generator voltage control with brushless excitation	166
6.5.3 Generator PQ-diagram	166
6.5.4 Single line diagram of a high voltage power line	167
6.6.1 Energization of a power line after a blackout	174
6.6.2 Diagram of an induction motor	175
6.6.3 Equivalent single line diagram of a motor at starting phase	176

#### 7 BUSINESS STRATEGIES FOR ENERGY MARKETS

7.1.1 Traditional competition has been in the transmission network level	181
7.2.1 Unbundling of energy services	187
7.2.2 Power system with size plants and one load	189
7.2.3 Supply curve of a power system with six plants	189
7.2.4 Demand forecast for the following day	190
7.2.5 Prices are found at crossing points of supply and demand	191
7.2.6 Energy prices for the next day	191
7.2.7 A system with two loads	192
7.2.8 Reduced supply curve, when the highest cost plant has taken out	194
7.4.1 Two area power system with a limited transmission line capacity	205
7.4.2 Transmission capacity is limited to 100 MW	206
7.4.3 Transmission line has a 100 MW limit and 100 MW of spinning	208
7.5.1 Electricity prices in Finland	212
7.6.1 Changes in average prices of electricity from 1996 to 2005	215
7.6.2 Natural gas prices in some EU-countries in 1995 and 2004	216
8 BUSINESS STRATEGIES FOR ANCILLARY SERVICE MARKETS	
8.2.1 Regulation market prices in California	225
8.2.2 Regulation up price duration curve in Finland in 2006	226
8.2.3 Maximum regulation reserve needs in E.ON Netz area in 2008	228
8.2.4 Energy supply curve including 100 MW power plants	229
8.2.5 Regulation power supply curve of 100 MW plants	229
8.3.1 Prices of operating reserves in California	231
8.4.1 Electricity prices and variable costs of alternative plants	239
8.4.2 Operation of the power plants without ancillary services	239
8.4.3 Operation of the power plants with ancillary services	240
8.4.4 Operating profit of a 160 MW plant with ancillary services	241
8.4.5 Operating profit of a 160 MW plant without ancillary services	241
8.4.6 Operating profits of a 160 MW CHP plant with A/S services	242
8.4.7 Operating profits of a 160 MW CHP plant without A/S services	243
8.4.8 Operating profit of a 160 MW diesel plant with A/S services	244
8.4.9 Operating profit of a 160 MW diesel plant without A/S services	244
8.5.1 Electricity and gas price duration curve in California	247
9 PROFITABILITY EVALUATION OF NEW POWER PLANT ALTERNATIVES	
9.1.1 Cash flow diagrams	257
10 POWER SYSTEM PLAN FOR THE WORLD IN 2050	
	212
10.1.1 Orders of gas turbines have been in average 60 000 MW annually	312
10.1.2 Orders of gas and dual-fuel fired gas turbines have increasing trend	313
10.1.3 Orders of oil fired gas turbines	313
10.1.4 Orders of small (1-60 MW) gas turbines	314
10.1.5 Orders of (1-60 MW) IC engines are approaching 30000 MW	315
10.1.6 Orders of 0.5 – 1 MW IC engines are approaching 15000 MW	315

	10.1.7 Orders of oil-fired IC-engines are approaching 20 000 MW	316
	10.1.8 Orders of gas and dual-fuel fired IC-engines are increasing rapidly	316
	10.1.9 Installation of large stationary fuel cells	317
	10.1.10 Installation of small stationary fuel cells	318
	10.1.11 Consumption of coal in the world started to rise in 2003	320
	10.1.12 Capacity additions of nuclear power plants in the world markets	321
	10.1.13 Construction starts of new nuclear power plants	321
	10.1.14 Capacity additions of wind turbines in the world markets	323
	10.1.15 Four-year trend of capacity additions of wind turbines	323
	10.1.16 Capacity additions of competing technologies	325
	10.2.1 The electrical load duration curve in 2005	328
	10.2.2 Electricity consumption in the world until 2050	328
	10.2.3 Capacity additions in Scenario a) Business as usual	331
	10.2.4 The load duration curve of the power system in 2050, Scenario a)	331
	10.2.5 Capacity additions in Scenario b) Nuclear Expansion	332
	10.2.6 The load duration curve of the power system in 2050, Scenario b)	332
	10.2.7 Capacity additions in Scenario c) Optimal system in 2050	333
	10.2.8 The load duration curve of the power system in 2025, Scenario c)	333
11 T	HE ACTION PLAN	
	11.1.1 Electricity generation by energy sources	342
APP	ENDICES	345
1	Probability that at least $n - m$ units are in operation (R=90%)	346
2	Probability that at least $n - m$ units are in operation (R=95%)	346
3	Probability that at least $n - m$ units are in operation (R=97%)	347
4	Probability that at least $n - m$ units are in operation (R=99%)	347
5	Normal distribution	348
6	Conversion factors	349