The Cyprus Institute

Solar Thermal Cogeneration of Electricity and Water

Research and Development Study for a Concentrated Solar Power - Desalinization of Sea Water (CSP–DSW) Project

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Solar Thermal Cogeneration of Electricity and Water

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EUROPEAN UNION THE REPUBLIC OF CYPRUS ΔΙΑΡΘΡΩΤΙΚΑ ΤΑΜΕΙΑ οι ιδέες μας, πράξη και ανάπτυξη DEPARTMENT OF CONTROL

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Abbreviations

CERA	Cyprus Energy Regulatory Authority
CMS	Cyprus Meteorological Survey
CSP	Concentrated Solar Power
CSP-DSW	Concentrated Solar Power - Desalinization of Sea Water
CSPonD	Concentrated Solar Power on Demand
CUT	The Cyprus University of Technology
CyI	The Cyprus Institute
EAC	The Electricity Authority of Cyprus
kWe, MWe	Power units in terms of Electrical Equivalent
MED	Multi-Effect Distillation
MED-TVC	Multi-Effect Distillation with Thermal Vapour Compressor
MIT	The Massachusetts Institute of Technology
MSF	Multistage Flash Distillation
PV	Photovoltaic
RO	Reverse Osmosis
UIUC	The University of Illinois at Urbana Champaign
WDD	The Water Development Department

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Attribution and Disclaimers

The report at hand is for the benefit of the Cyprus Government, and is intended as reference in its plans to develop a co-generation pilot plant based on CSP technologies and in its general strategy to promote renewable sources in Cyprus.

The responsibility of any opinions, findings, and recommendations expressed in the report, which are based on the results of the collaboration between The Cyprus Institute and its partners, rests with the Cyprus Institute.

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Table of Contents

Research and Development Study for a Concentrated Solar Power - Desalinization of Sea Water

(CSP–DSW) Project

Abbreviations 5
Acknowledgements 6
Attribution and Disclaimers 6

TABLE OF CONTENTS 8

LIST OF FIGURES 13

LIST OF TABLES 16

CHAPTER 1. EXECUTIVE SUMMARY 19

1.1. Preamble: Objectives 19
1.2. Recent Developments 21
1.3. Suitability of CSP Technologies in Cyprus 23
1.4. State of Technological know-how 24
1.4.1. Assessment of CSP Technologies - Trough, Tower, Parabolic Dishes and Fresnel Technologies. 24
1.4.2. Assessment of Desalination Technologies - Reverse Osmosis and Thermal Desalination 26
1.4.3. Assessment of Power Generation Technologies – Rankine, Brayton and Stirling Engines 27
1.4.4. Design of a CSP-DSW Pilot Co-Generation Plant 27
1.4.5. Consideration on the Placement (siting) of the CSP-DSW pilot facility 29
1.4.6. Pilot Plant Capacity 30
1.5. Conclusions – Recommendation 30

CHAPTER 2. THE CSP-DSW PROJECT 34

2.1. State of Affairs at the beginning of the Study 36
2.2. Themes 37
2.2.1. Policy & Techno economic Assessment 38
2.2.2. Light Harvesting 39
2.2.3. Thermal storage 39
2.2.4. Electricity Production 40
2.2.5. Desalination 40
2.2.6. Optimization and Integration 41
2.2.7. Siting 42
2.3. Partners and Participants 42
2.4. Structure of the Final Report 50

CHAPTER 3. CONCENTRATED SOLAR POWER TECHNOLOGIES 52

3.1. Introduction 52
3.2. The need for concentration 53

3.3. Salient features of CSP units as power generating systems 53
3.4. The Four Major Types of CSP technology 58
3.4.1. Parabolic trough 59
3.4.2. Linear Fresnel 61
3.4.3. Parabolic Dish 63
3.4.4. Central Receiver (Power Tower) 66
3.5. A few important aspects of CSP 71
3.5.1. Storage 71
3.5.2. Capacity factor 78
3.5.3. Major factors influencing performance 78
3.6. Discussion 81
3.7. Chapter References 82

CHAPTER 4. DESALINATION OF SEAWATER: TECHNOLOGY & STATE-OF-THE-ART (WITH EMPHASIS ON CYPRUS) 84

4.1. Motivation & Background: Desalination with Solar Energy 84
4.2. Reverse Osmosis (RO) 87
4.2.1. RO Technology 87
4.2.2. RO Energy Requirements 88
4.2.3. RO Energetics (closure) 91
4.3. Multi-Effect Distillation (MED) 92
4.3.1. MED Technology 92
4.3.2. MED Energy Requirements. 98
4.4. Chapter References 101

CHAPTER 5. POWER GENERATION 104

5.1. Introduction 104
5.2. Steam turbines currently integrated in CSP plants 105
5.2.1. Siemens SST-700DRH 105
5.2.2. Siemens SST-600 108
5.2.3. Siemens SST-900 109
5.2.4. GE Oil & Gas 110
5.2.5. MAN Turbo 110
5.3. Optimum selection of steam turbine 111
5.3.1. Simulation software 111
5.3.2. Design grid 112
5.3.3. Condensing turbine 113
5.3.4. Extraction turbine 117
5.3.5. Back pressure turbine 120
5.3.6. Discussion 121
5.4. Conclusions 122
5.5. Chapter References 124

CHAPTER 6. ELECTRICITY PRODUCTION AND DEMAND IN CYPRUS 125

6.1. Electricity Production 125
6.2. Energy Demand 128
6.3. Cost of Electricity 129
6.4. Chapter References 130

CHAPTER 7. WATER PRODUCTION AND DEMAND IN CYPRUS 131

7.1. Water Demand – Desalination 131
7.2. Note on Desalination Costs 136
7.3. Chapter References 137

CHAPTER 8. DESIGN AND MODELLING OF A SOLAR-POWERED CO-GENERATION OF ELECTRICITY AND DESALINATED SEAWATER PLANT 138

8.1. Introduction 139

8.2. Goals and Methodology 140
8.2.1. Goals 140
8.2.2. Tasks 141
8.2.3. Methodology 142
8.3. Technology 142
8.4. Modelling 144
8.4.1. Solar Irradiance 144
8.4.2. Heliostats 146
8.4.3. Receiver 147
8.4.4. Multi-effect Distillation 148
8.4.5. Reverse Osmosis 150
8.4.6. Power Block 154
8.5. Operation 157
8.6. Optimization of Short-term Operation 157
8.6.1. Design Parameters 158
8.6.2. Optimization Variables 159
8.6.3. Objective Function 159
8.7. Optimal Operating Conditions 161
8.7.1. Case Study 1: Maximum Income 161
8.7.2. Case Study 2: Maximum Weighted-Average Energetic Function 166
8.7.3. Case Study 3: Maximum Income Neglecting Feed-in Tariff 169
8.8. Results and Discussions 170
8.9. Conclusions 171
8.10. References 172

CHAPTER 9. PROPOSAL FOR THE RECEIVER AND STORAGE SYSTEM OF A CSP-DSW PLANT 176

9.1. Background 178
9.2. CSP with Collocated Receiver and Storage 179
9.3. Heliostats on a hill 182
9.4. Collocated receiver/storage system 183
9.5. Solar Simulator Testing of a Volumetric Salt Receiver 187
9.5.1. Volumetric Receiver Testing: Single Tank 187
9.5.2. Volumetric Receiver Testing: Divider Plate-Equipped Tank 189
9.6. Heat Extraction System 192
9.7. CSPonD Materials Durability & Compatibility 195
9.8. References 196

CHAPTER 10. THE HELIOSTAT SYSTEM FOR A CSP-DSW PLANT 199

10.1. Concentrating Solar Radiation with Heliostats 199
10.1.2. Engineering Aspects 203
10.1.3. Heliostats for the CSP-DSW 206
10.2. Placement of Heliostats on a Hillside 209
10.2.1. Model 210
10.2.2. Case Studies 216
10.2.3. Results 225
10.2.4. Conclusions 227
10.3. Chapter References 228

CHAPTER 11. DESALINATION SYSTEM FOR A CSP-DSW PLANT 230

11.1. Cyprus CSP-DSW - RO vs. MED 230
11.2. Thermodynamics and Design Considerations of CSP-DSW 233
11.3. System design of an improved CSP-DSW with MED-TVC 237
11.4. Conclusion 241
11.5. Chapter References 242

CHAPTER 12. FINANCIAL MODELLING 244

12.1. Introduction 244

12.2. METHODOLOGY 245
12.3. ASSUMPTIONS AND CONSIDERATIONS 245
12.3.1. Overall financial environment 245
12.3.2. Price for electricity and water 246
12.3.3. Benefit from the Clean Development Mechanism (CDM) 246
12.3.4. CSP-DSW Design options 246
12.3.5. Financial revenues estimates 248
12.3.6. Elements cost estimates 249
12.4. FINANCIAL ANALYSIS RESULTS 254
12.4.1. Financial analysis results for Case (A) 254
12.4.2. Results for the remaining cases 256
12.4.3. Financial Performance in a non-FIT environment 258
12.4.4. Electricity only plant 259
12.4.5. Levelized cost of production in the co-generation plant 260
12.5. SENSITIVITY ANALYSIS 261
12.5.1. Capital Cost sensitivity 261
12.5.2. Operation and Maintenance Cost sensitivity 262
12.5.3. Loan interest rate sensitivity 263
12.5.4. Effect of the change in Debt-Equity ratio 265
12.6. CONCLUSIONS 266
12.7. CHAPTER REFERENCES 268

CHAPTER 13. SITE CONSIDERATIONS 270

13.1. SITE SELECTION CHARACTERISTICS 270
13.2. POTENTIAL SITES 272
13.3. LICENCES/PERMITS REQUIRED TO CONSTRUCT AND OPERATE A CSP-DSW PLANT 276
13.4. RECOMMENDATION 278
13.5. CHAPTER REFERENCES 278

CHAPTER 14. CONCLUSIONS AND RECOMMENDATIONS 279

14.1. CONCLUSIONS 280
14.2. TECHNOLOGICAL CHOICES FOR A PILOT CSP-DSW CO-GENERATION PLANT 282
14.2.1. Solar Harvesting and Storage 283
14.2.2. Power Generation 284
14.2.3. Desalination 285
14.2.4. Financial Analysis 286
14.2.5. Location 287
14.3. PILOT PLANT CAPACITY 288
14.4. RECOMMENDATIONS 289

APPENDICES 293

APPENDIX A.1. CSP-DSW CONCEPT AND PARAMETERS 294

APPENDIX A.2 ANALYSIS OF SEA WATER IN CYPRUS 295

APPENDIX A.3. ENERGY REQUIREMENTS FOR SEAWATER DESALINATION. 296

APPENDIX A.4. LIST OF MAJOR COMMERCIAL SUPPLIERS OF WATER TREATMENT AND PURIFICATION TECHNOLOGIES. 297

APPENDIX A.5. LIST OF THE “DESALINATION PLAYERS” ACCORDING TO SUEZ ENVIRONMENT (2008). 298

APPENDIX B.1. COORDINATE SYSTEM AND GEOGRAPHICAL COORDINATE SYSTEM FOR THE USA. 299

APPENDIX C.1. LIST OF DESALINATION PLANT CAPACITY 300

APPENDIX D.1. THE AREA SOUTH OF THE TECHNOLOGICAL PARK AT PENTAKOMO 301

APPENDIX D.2. THE AREA SURROUNDING VASSILICOS POWER PLANT 302

APPENDIX D.3. THE AREA SURROUNDING MONI POWER PLANT 303

APPENDIX D.4. THE AREA SURROUNDING DHEKELIA POWER PLANT 304

APPENDIX D.5. APPLICATION FOR EXEMPTION FROM LICENSE FOR UNITS PRODUCING LESS THAN 5MW FROM RENEWABLE ENERGY SOURCES 305

APPENDIX D.6. ELECTRICITY TRANSMISSION NETWORK 306

APPENDIX D.7. MAJOR WATER WORKS 307

APPENDIX E. 1. CSP-DSW INTERNATIONAL WORKSHOP 308

List of Figures

FIGURE 3-1: STEAM TURBINE CAPACITY VS. COST 57

FIGURE 3-2: EXPECTED TURBINE EFFICIENCY RELATED TO ITS CAPACITY 58

FIGURE 3-3: PARABOLIC TROUGH TYPE CSP PLANT CONCEPT 60

FIGURE 3-4: ANDASOL PLANT SCHEMATIC 61

FIGURE 3-5: LINEAR FRESNEL MIRRORS] 62

FIGURE 3-6: SOLAR DISH POWER PLANT, ALMERIA, SPAIN 65

FIGURE 3-7: PS 10 PLANT SCHEMATIC 69

FIGURE 3-8: SOLAR TRES PLANT SCHEMATIC 71

FIGURE 3-9: DESERTEC MAP 71

FIGURE 3-10: TYPICAL CAPITAL COST STRUCTURE OF TWO TANK MOLTEN SALT SYSTEM 76

FIGURE 4-1: BASIC CSP-DSW CONCEPT 85

FIGURE 4-2: REVERSE OSMOSIS (RO) PROCESS FLOW. 87

FIGURE 4-3: ENERGY REQUIREMENTS OF RO 89

FIGURE 4-4: PROCESS FLOW DIAGRAM FOR MULTIPLE EFFECT DISTILLATION (MED) WITH TVC 93

FIGURE 4-5: SCHEMATIC AND PHOTO OF MED-TVC PILOT PLANT 94

FIGURE 4-6: MULTIPLE EFFECT DISTILLATION (MED) SYSTEM PROCESS FLOW. 96

FIGURE 4-7: MED ALFA-LAVAL HEAT EXCHANGER PRESSED PLATE FALLING FILM CONFIGURATION 97

FIGURE 4-8: MATHEMATICAL MODEL REPRESENTING MASS AND ENERGY BALANCES IN A SINGLE MED EFFECT 99

FIGURE 5-1: CONDENSING TURBINES AT 4,10,25,50,100 AND 100 WITH REHEAT MWE 114

FIGURE 5-2: CONDENSING TURBINE EFFICIENCIES. 116

FIGURE 5-3: EXTRACTION TURBINES AT 4,10,25,50,100 AND 100 MWE 118

FIGURE 5-4: TURBINE EFFICIENCY: EXTRACTION AND BACKPRESSURE AT 4,10,25, 50 AND 100 MWE. 119

FIGURE 5-5: EXTRACTION TURBINES AT 4,10,25,50 AND 100 MWE 121

FIGURE 6-1: VARIATION OF PEAK ENERGY DEMAND 128

FIGURE 6-2: FORECAST OF PEAK ELECTRICITY DEMAND UNTIL 2020 129

FIGURE 7-1: VARIATION OF RAINFALL DURING THE LAST CENTURY 132

FIGURE 7-2: SOURCES OF FRESH WATER 133

FIGURE 7-3: WATER DEMAND PROJECTIONS BASED ON CONSERVATIVE WATER USE OF 2008 135

FIGURE 7-4: COST OF DESALINATED WATER PRODUCED BY RO OVER THE LAST 25 YEARS. 136

FIGURE 8-1: CONCEPTUAL PROCESS FLOW DIAGRAM 140

FIGURE 8-2: MODEL PREDICTIONS FOR THE GLOBAL IRRADIANCE COMPARED WITH MEASUREMENTS ON GROUND. 146

FIGURE 8-3: SPECIFIC ENERGY REQUIREMENT OF THE RO SYSTEM 153

FIGURE 8-4: PLANT'S OVERALL SPECIFICATION BASED ON OPTIMIZATION RESULTS (MED SYSTEM).. 164
FIGURE 8-5: PLANT'S OVERALL PERFORMANCE BASED ON OPTIMIZATION RESULTS (HYBRID RO/MED SYSTEM) 165
FIGURE 8-6: SPECIFICATION OF THE MED SYSTEM SELECTED UNDER OPTIMAL OPERATING CONDITIONS (CASE STUDY 1) 163
FIGURE 8-7: PENALTY PAID FOR EXTRACTING STEAM AT 0.5 BAR. 166
FIGURE 8-8: : WEIGHTED OBJECTIVE FOR COGENERATION AS A FUNCTION OF GOR AND MED PLANT CAPACITY. 167
FIGURE 8-9: PLANT'S OVERALL SPECIFICATION BASED ON OPTIMIZATION RESULTS 170
FIGURE 9-1: IDEALIZED SKETCH OF HILLSIDE HELIOSTATS 183
FIGURE 9-2: LAVA CAVE: WHAT CSPOND MIGHT LOOK LIKE TO INCOMING SUNRAYS. 184
FIGURE 9-3: IDEALIZED SKETCH OF CSPOND VOLUMETRIC ABSORPTION MOLTEN SALT RECEIVER/STORAGE SYSTEM 185
FIGURE 9-4: CSPOND RECEIVER 186
FIGURE 9-5: SOLAR SIMULATOR: 188
FIGURE 9-6: EXPERIMENTAL SALT RECEIVER 189
FIGURE 9-7: TEMPERATURE DISTRIBUTION OF MOLTEN NITRATE SALT MIXTURE 189
FIGURE 9-8: EXPERIMENTAL RECEIVER WITH PLATE DIVIDER 190
FIGURE 9-9: VARIOUS PICTURES OF THE VOLUMETRIC RECEIVER 191
FIGURE 9-10: TEMPERATURE DISTRIBUTION OF MOLTEN NITRATE SALT MIXTURE AS A FUNCTION OF DEPTH 192
FIGURE 9-11: OPEN AIR NACL-KCL SALT BATH AT 900OC FOR METAL HEAT TREATING. 196
FIGURE 10-1: SCHEMATICS OF HELIOSTATS 201
FIGURE 10-2: HELIOSTAT COMPONENT COST BREAKDOWN. 202
FIGURE 10-3: SPECIFIC COST OF HELIOSTAT COLLECTION FIELD 203
FIGURE 10-4: SOLAR PATHS AS SEEN FROM PENTAKOMO. 204
FIGURE 10-5: SHADING AND BLOCKING LOSSES OF INCOMING SOLAR RADIATION 205
FIGURE 10-6: AVERAGE ANNUAL COSINE EFFICIENCY AS A FUNCTION OF HELIOSTAT POSITION 212
FIGURE 10-7: MINIMUM YEARLY SOLAR ALTITUDE VS SOLAR AZIMUTH 213
FIGURE 10-8: EXAMPLE HELIOSTAT FIELD SAMPLED LOCATIONS FOR EVALUATING SITE EFFICIENCY 216
FIGURE 10-9: DENSITY OVERLAY INDICATING AREAS OF HIGH EFFICIENCY POND RECEIVER SITES IN WHITE SANDS, NM 217
FIGURE 10-10: POTENTIAL SITE FOR POND RECEIVER WITH SECONDARY REFLECTOR IN WHITE SANDS, NM 218
FIGURE 10-11: POTENTIAL SITE FOR POND RECEIVER WITHOUT SECONDARY REFLECTOR IN WHITE SANDS, NM 218
FIGURE 10-12: DENSITY OVERLAY INDICATING AREAS OF HIGH EFFICIENCY POND RECEIVER SITES IN CHINA LAKE, CA 219
FIGURE 10-13: POTENTIAL SITE FOR POND RECEIVER WITH SECONDARY REFLECTOR IN CHINA LAKE, CA 219
FIGURE 10-14: POTENTIAL SITE FOR POND RECEIVER WITHOUT SECONDARY REFLECTOR IN CHINA LAKE, CA 220
FIGURE 10-15: PENTAKOMO SITE FOR PROPOSED POND RECEIVER CSP(INSTITUDE 2009) 221
FIGURE 10-16: ELEVATION CONTOURS OF 10 KWT DEMONSTRATION SITE WITH EFFICIENCY OVERLAY 222
FIGURE 10-17: PENTAKOMO 10 KWT CSPOND LAND POTENTIAL EVALUATION 222
FIGURE 10-18: FIELD EFFICIENCY VS DIRECT NORMAL INSOLATION 223
FIGURE 10-19: ELEVATION CONTOURS WITH SITE EFFICIENCY OVERLAY} 224
FIGURE 10-20: CYPRUS 4 MWE CSPOND LAND POTENTIAL EVALUATION 224
FIGURE 10-21: AVERAGE ANNUAL COSINE EFFICIENCY VS LATITUDE (DECREASING EFFICIENCY FOR INCREASING AZIMUTH) 226

FIGURE 10-22: US SOLAR RESOURCE MAP 226
FIGURE 11-1: SINGLE AND DUAL PURPOSE PLANT CYCLE, TEMPERATURE VS. ENTROPY OF WORKING FLUID (STEAM). 233
FIGURE 11-2: PLANT CONFIGURATION WITH ADVANCED MED DESIGN 239
FIGURE 11-3: MODULAR MED SYSTEM WITH COMPACT PARALLEL PLATE FALLING FILM HEAT EXCHANGERS 240
FIGURE 12-1: ANNUAL REVENUE BREAK UP FOR THE CASES (A) AND (D) 249
FIGURE 12-2: INITIAL CAPITAL COST BREAK UP FOR CASES (A) AND (D) 253
FIGURE 12-3: ANNUALIZED COSTS OF MAJOR COMPONENTS FOR CASE (A) 254
FIGURE 12-4: AFTER TAX CASH FLOW FOR CASE (A) WITHOUT THE GHG EMISSION REDUCTION BENEFIT 255
FIGURE 12-5: CUMULATIVE PAYBACK CASH FLOW FOR CASE (A) WITHOUT GHG EMISSION REDUCTION BENEFIT 256
FIGURE 12-6: AFTER TAX CASH FLOW FOR ALL CASES 257
FIGURE 12-7: CUMULATIVE AFTER TAX PAYBACK CASH FLOW FOR ALL CASES 258
FIGURE 12-8: SENSITIVITY OF NPV ON CAPITAL COST 262
FIGURE 12-9: SENSITIVITY OF IRR ON CAPITAL COST 262
FIGURE 12-10: SENSITIVITY OF NPV ON O&M COST 263
FIGURE 12-11: SENSITIVITY OF IRR ON O&M COST 263
FIGURE 12-12: SENSITIVITY OF NPV ON RATE OF INTEREST 264
FIGURE 12-13: SENSITIVITY OF IRR ON RATE OF INTEREST 264
FIGURE 12-14: SENSITIVITY OF NPV ON DEBT-EQUITY RATIO 266
FIGURE 12-15: SENSITIVITY OF IRR ON DEBT-EQUITY RATIO 266
FIGURE 13-1: AREAL VIEW OF PENTAKOMO SITE 272
FIGURE 13-2: AREAL VIEW OF VASSILIKO SITE 273
FIGURE 13-3: AREAL VIEW OF MONI SITE 273
FIGURE 13-4: AREAL VIEW OF DHEKELIA SITE 274
FIGURE 13-5: MAP OF THE PENTAKOMO AREA. 275
FIGURE 14-1: HORIZONTAL COORDINATE SYSTEM 299
FIGURE 14-2: GEOGRAPHIC COORDINATE SYSTEM FOR THE CONTIGUOUS UNITED STATES 299

List of Tables

TABLE 3-1: SEGS PLANT DETAILS 60

TABLE 3-2: A FEW DISH TYPE CSP INITIATIVES 66

TABLE 3-3: A FEW CENTRAL RECEIVER TYPE CSP PLANTS 68

TABLE 3-4: SOME OF THE EXISTING STORAGE SYSTEMS WITH CSP PROJECTS 74

TABLE 3-5: COMPARISON OF STORAGE SYSTEMS FOR A HYPOTHETICAL 200 MW PLANT 75

TABLE 3-6: STRENGTH AND WEAKNESSES OF THE TWO COMMON CSP STORAGE SYSTEMS 76

TABLE 4-1: INPUTS AND OUTPUTS OF HIGH-GOR MED-TVC SIMULATIONS 100

TABLE 4-2: INPUT CONDITIONS FOR MED-TVC SIMULATION 100

TABLE 5-1: STEAM TURBINES EMPLOYED IN CSP PLANTS 107

TABLE 5-2: STEAM TURBINES TO BE INTEGRATED IN ANNOUNCED CSP PLANTS 107

TABLE 5-3: POSSIBLE INTERFACES BETWEEN STEAM PLANT AND DESALINATION PLANT 113

TABLE 5-4: OPTIMUM CONDENSING TURBINE DESIGNS 116

TABLE 5-5: OPERATING PARAMETERS OF DESALINATION PLANTS 117

TABLE 6-1: CURRENT AND FUTURE ELECTRICITY PRODUCTION CAPACITY 127

TABLE 7-1: DESALINATION CAPACITY 2007-2012 134

TABLE 8-1: KEY INPUTS USED WITH THE SOLAR IRRADIANCE MODEL 145

TABLE 8-2: KEY INPUT PARAMETERS USED FOR THERMAL ENERGY RECEIVER AND STORAGE 148

TABLE 8-3: INPUT PARAMETERS OF THE MED MODEL 150

TABLE 8-4: CONSTANTS USED WITH THE RO MODEL 152

TABLE 8-5: COMPARISON OF JACOBIAN RO MODEL WITH FILMTEC'S ROSA SOFTWARE 154

TABLE 8-6: MODEL PREDICTIONS UNDER FULL-LOAD AND PARTIAL-LOAD OPERATION COMPARED WITH ST PRO MODELS 156

TABLE 8-7: KEY DESIGN PARAMETERS 159

TABLE 8-8: CONSTRAINTS OF OPTIMIZATION 161

TABLE 8-9: RESULTS OF OPTIMIZATION 162

TABLE 8-10: THE POWER LOST DUE TO EXTRACTING STEAM TEAM AT VARIOUS PRESSURES 167

TABLE 8-11: TYPICAL STEAM FLOW RATE, NUMBER OF EFFECTS, AND GOR FROM EXISTING PLANTS 168

TABLE 9-1: BASIC PARAMETERS OF THE CSPOND CONFIGURATION 182

TABLE 9-2: DIVIDER PLATE SYSTEM PARAMETERS. 187

TABLE 10-1: CATALOGUE OF SOLAR HELIOSTATS 201

TABLE 10-2: COSINE EFFICIENCY TABLE - RANGE AND RESOLUTION 211

TABLE 11-1: COMPARISON BETWEEN CSP-DSW WITH RO AND MED 235

TABLE 11-2: ENERGETICS COMPARISON BETWEEN CSP-DSW WITH RO AND MED 236

TABLE 12-1: KEY FEATURES OF THE FOUR DIFFERENT DESIGNS OF CSP-DSW PLANT 248
TABLE 12-2: YEARLY REVENUE STREAM BREAK UP FOR FOUR CASES 249
TABLE 12-3: CAPITAL AND O&M COST REQUIREMENTS 251
TABLE 12-4: FINANCIAL PERFORMANCE KEY INDICATORS FOR ALL CASES EXCLUDING GHG BENEFITS 257
TABLE 12-5: FINANCIAL PERFORMANCE WITH 10 CENT/KWH TARIFF 259
TABLE 12-6: KEY FINANCIAL PERFORMANCE OF ELECTRICITY ONLY PLANT 260
TABLE 12-7: LEVELIZED COST OF ELECTRICITY AND WATER 261
TABLE 14-1: LIST OF MAJOR COMMERCIAL SUPPLIERS OF WATER TREATMENT AND PURIFICATION TECHNOLOGIES 297
TABLE 14-2: LIST OF THE “DESALINATION PLAYERS” ACCORDING TO SUEZ ENVIRONNEMENT 298

Chapter 1. Executive Summary

1.1. Preamble: Objectives

The report at hand constitutes the final deliverable of the Research and Development Study for the Concentrated Solar Power - Desalinization of Sea Water (CSP-DSW) study pursued by the Cyprus Institute for the benefit of the Cyprus Government. This Final Report is the final report to be produced as prescribed in the terms of the contract agreement signed between the Directorate of Control of the Ministry of Communications and Works and the Cyprus Institute.

The CSP-DSW study proceeded according to the initial planning with a few corrective adjustments mainly due to the innovative design and dynamic interaction of various engineering subsystems of the CSP-DSW unit. The research results and the conceptual design are most encouraging in that they indicate that the proposed technology is very promising for Cyprus in particular, and island environments in general. A detailed technical analysis for the implementation of the design indicates that the industrial components needed to realize any of the suitable designs are mostly untested for the harsh costal humid saline environments and in few cases unavailable.

This Final Report contains a comprehensive summary of all the research and analysis that has been carried out and the final findings throughout the duration of the study. It includes a detailed implementation design for a possible prototype CSP-DSW plant to be situated in Cyprus, which we judge as most promising for an island environment for the intermediate and long term.

We present in this report:

1. The current state of technological developments concerning the production of electricity using CSP and a detailed cataloguing of alternative technologies and an assessment of their advantages and disadvantages vis-à-vis their employment for a CSP-DSW facility.
2. The current state of technological developments concerning the available desalination technologies. Detailed cataloguing of alternative technologies and an assessment of their advantages and disadvantages vis-à-vis their employment for a CSP-DSW facility.
3. An assessment of the maturity of the available technologies for implementation in a pilot plant and in a commercial (industrial) plant.
4. Characteristics of suitable locations and land requirements for the construction of a pilot plant in Cyprus.
5. An innovative design for a Pilot plant, that is most suited to the needs and conditions of Cyprus, with proposals for its various subsystems: Solar harvesting, Energy Storage, and Power and Water production units.
6. Operational parameters, capacity both in terms of electricity and water production and an operational plan of the proposed pilot plant.
7. An Economic Assessment of the proposed technology through a Discounted Cash Flow (DCF) business model.
8. Final conclusions for the direction that the engineering studies towards the construction of the pilot plant should take.
9. Recommendations towards achieving the objective of economically competitive and technologically robust CSP co-generation plants for electricity and Sea Water desalination

All ideas, concepts and tentative conclusions presented in earlier reports are presented anew in this final report appropriately adjusted in the light of the most recent findings.

1.2. Recent Developments

Since the launching of the CSP-DSW project, the interest in renewable technologies in general and for energy production in particular has grown impressively. A number of reasons, political, economic and technological have contributed significantly to this growth, principally among them the following:

- The growing realization that climate change is occurring at a faster pace than originally anticipated and carbon emissions need to be reduced.
- The new administration of B. Obama in the US has reversed the policies of the previous (G. W. Bush) administration, placing central importance to reducing dependence on fossil fuels. Substantial funds are being allocated in the US for research in renewable technologies and demonstration projects.
- The most important initiative of the newly founded Union for the Mediterranean (UfM) has been the launching of the Mediterranean Solar Plan (MSP) which aims to increase the already installed capacity based on renewable sources by 20 GW at an estimated budget of 40 to 50 Billion Euros. In particular a subset of this initiative called “DESERTEC” aims to install high capacity CSP plants in the Sahara desert providing electricity through a High Voltage Direct Current (DCHV) supergrid to Europe and North Africa. International Organizations (e.g. World Bank, European Investment Bank etc.) are on record that they will finance big components of the project. The MSP has a small but important provision relevant to this study concerning Mediterranean islands.
- In a number of stimulus packages, particular that of the US, emphasis is placed on using funds to cultivate new “green” technologies, in particular solar. This sector of the economy is projected to grow rapidly and become one of the main industries of the 21st century. Already substantial research funds from the US Government and the European Union are earmarked and are being dispensed towards Research and Development of these initiatives.
- The European Commission, acknowledging the need for small scale co-generation units based on renewable technologies and especially solar, has

launched through the 7th Framework programme, a call for the partial funding of a co-generation demonstration unit for deployment in coastal or island environment (Demonstration of innovative multi-purpose solar power plant - ENERGY.2010.2.9-1).

These considerations and motivating factors as well as other economic considerations are expected to further enhance in the near future the demand for CSP, leading to more rapid development and reduced cost.

The 2009 United Nations Climate Change Conference which took place in Copenhagen in December, failed to bring the participating nations together in adopting a common policy to mitigate climate change. What was seen as an extraordinary opportunity for the development of renewable energy sources as the primary instrument for reducing carbon emissions providing further and enhanced economic incentives for their employment, did not materialize in some formal agreement. Part of the failure of the Copenhagen Summit was attributed to the recent global economic crisis from which a number of nations, including Cyprus, have yet to recover. Nevertheless as global economic recovery is currently underway, the first signs of increased demand for oil and natural gas have driven market prices high again, and have placed renewables once again in a competitive track. Many countries (including Germany, France and the US) have indeed seen the development of "green technologies", such as the use of Concentrated Solar Power, as a growth area which could lead to a restructuring of the Economy. Based on the investigations pursued during the course of this study we conclude and recommend that this opportunity presents itself strongly in Cyprus and appropriate policies should be implemented to capture it.

Through the duration of the study, the debate on the various forms of renewable energy sources evolved in parallel and it is fair to say that it is now a well-accepted fact that in the intermediate (2015-2025) and especially in the long term (2025 and beyond) solar power will become the dominant component in the basket of the renewable sources. For the southern Europe and the Mediterranean basin, especially the Eastern Mediterranean it is viewed that very few other alternatives exist. Solar energy is expected to be the dominant, but definitely not the exclusive, source of energy from renewable sources.

Finally, the choice between the two principal modalities of solar energy, photovoltaic (PV) or Concentrated Solar power (CSP) has recently tilted towards the CSP. This is due to two primary reasons: a) CSP is considerably less expensive and b) it provides a proven way to remove its intermittency (due to temporary cloud coverage) and to extend its operation into the evening hours of peak demand by thermal storage. The same technology holds the promise to provide continuous operation (24-hour operation). As in the case of the mixture of renewable energy sources, in the long term both CSP and PV will be employed, the exact mixture will depend largely to technological developments.

1.3. Suitability of CSP Technologies in Cyprus

For the case of Cyprus, particular considerations further argue for the employment of principally solar and in particular CSP technologies. The fact that Cyprus is isolated from any continental power grid from which to draw power when intermittent renewable sources (e.g. wind or photovoltaic) cannot produce power (due to lack of sustained winds or because of cloudiness) necessitates the employment of renewable sources which allow for energy storage. CSP is the only technology available to Cyprus that meets this requirement.

CSP is a technology that is on the verge of becoming mature for industrial employment – a conclusion which is widely accepted. However, local geographical conditions are important and do play an important role in our considerations. Most CSP plants require substantial amounts of water to operate (primarily for cooling) and although dry-cooling methods can be employed they induce heavy penalties in both production efficiency and electricity consumption. The CSP-DSW concept overcomes this drawback and turns it into an advantage by incorporating desalination. Nevertheless, like all solar technologies CSP requires substantial amounts of flat land, which is expensive, especially given that it needs to be located near the sea. In addition conditions near the coast offer a hostile environment for a number of components (at least different hostile environment than of that of the desert). The high salinity conditions as well as the intermittent high wind loads present a distinct obstacle to implementation, which needs to be addressed.

1.4. State of Technological know-how

The study has thoroughly examined the various available CSP technologies with particular emphasis on those which are currently at a mature level, or on the verge of becoming mature. A summary of these assessments follows.

1.4.1. Assessment of CSP Technologies - Trough, Tower, Parabolic Dishes and Fresnel Technologies.

A thorough review of the available Concentrated Solar Power (CSP) technologies has been conducted and an evaluation of the emerging trends has been performed. An extensive summary and assessment is present in Chapter 3 where an overview of the CSP concept is presented, salient features of commercially available CSP technologies are reviewed and the influencing key factors to the CSP plant's performance is discussed.

The four primary types of CSP technology:

1. Parabolic Troughs,
2. Fresnel Systems,
3. Central Receivers (Heliostat arrays), and
4. Parabolic Dishes

were considered, presented and discussed. It is concluded that Fresnel Systems and Parabolic Dishes (especially when coupled to Stirling Engines) hold promise for the future but they are not mature enough for implementation. Parabolic Troughs and to a lesser degree Heliostat-Central Receiver systems comprise ***relatively*** safe technologies, ready for pilot plant implementation. Proponents of the CSP electricity production claim that these technologies are mature enough for industrial mass-scale production, without however claiming base-load operation without the employment of a backup combined cycle system. None of the above technologies has ever being employed in a co-generation plan.

The Heliostat-Central Receiver configuration offers great potential in terms of power cycle efficiency (it is the technology that can reach the highest temperature), and with the ability to be deployed on hilly land and be coupled to a thermal storage system. Future anticipated developments of specialized gas turbines suitable for renewables will need to operate at these temperatures. It also offers the greatest potential for storage at high temperatures (essential for 24 hour operation, a principal technological goal of our design objectives) and it is receiving increasing research attention both in Europe and the US.

A most important advantage of the Heliostat – Central Receiver system over the Parabolic Trough system, critical for the application we are considering, concerns the flexibility it offers for the placement of the heliostat field on a hilly terrain. As it will be discussed later in the main body of the report, the utilization of flat terrain required by current trough technology puts heavy restrictions for the implementation of a CSP-DSW plant in an island environment (troughs could in principle be deployed on gentle slopes with a constant gradient and the correct orientation, a rather infrequent combination of conditions).

For the case of Cyprus, we have carefully considered the available Central Receiver technologies available today. The Heliostat - Central Receiver technology was chosen amongst the various technologically proven options for CSP, as the most fitting, especially when combined with a thermal storage solution in order to achieve 24-hour, independent (no fossil fuel assisted) operation.

It was concluded that although a number of such systems have been constructed there is currently, no system which is completely independent, operating only through its storage solution. All systems employ a solar-fossil hybrid cycle which provides power when weather conditions are unfavourable or the heat transfer from storage fails. This emphasises both the importance of storage for continuous operation and the lack of a dependable storage system ready for ***base-load*** and most crucially ***peak-load*** operation at present. In this context, this study has conducted innovative research and is proposing a novel way of storage which minimizes technical complexity.

An important finding of this study has been the large room for improvement and innovation in the field of Heliostats. Currently only a handful of commercial companies exist which construct heliostats, but they seem to occupy the two ends of the spectrum, i.e. very large (around 100 m^2) or very small (a few m^2) heliostats. There is a significant gap than needs to be covered and unfortunately for a pilot plant in Cyprus, given the choice of a hill deployment and beam-down configuration (see discussion below), there exists no ready-made heliostat solution to satisfy these conditions. Moreover, heliostats have so far been developed for deployment away from coastal environments. The corrosive conditions combined with high-wind loads experienced in near-sea areas dictates that a new design approach is needed for Heliostat use in small islands.

1.4.2. Assessment of Desalination Technologies - Reverse Osmosis and Thermal Desalination

There exist a number of methods for desalination using renewable resources however two classes are considered proven and most promising for the CSP-DSW process: membrane-based methods, such as Reverse Osmosis (RO), and thermal desalination methods, such as Multiple Effect Distillation (MED). In Chapter 4. the state of development, the current state of knowledge and research for these technologies and their comparative advantages and disadvantages are being reviewed. The technological constraints that determine the energetic requirements of each class separately, with the aim of determining the most favourable option for the development of the co-generation plant on the island is also considered in some detail. It is concluded that while both options offer viable alternatives for single purpose desalination plants, MED seems to be the technology of choice for the co-generation plant under certain circumstances (see also discussion in Section on Design of the Pilot Plant below). It is to be noted that while MED has been identified as the leading choice, a hybrid solution employing both MED and RO technologies demands further consideration.

For the case of Cyprus, we have carefully considered the MED technologies available today. Given a fixed thermal energy source (i.e. CSP) and a Rankine-cycle or any other suitable power cycle (e.g. Brayton Cycle) power plant, performing seawater desalination via a Multiple-Effect Distillation- with a Thermal Vapour compression (MED-TVC) with an absorption heat pump is a superior option than using the electricity from the power plant to drive a Reverse Osmosis (RO) plant. However, in the literature, in the considered scale for the pilot plant, only moderate sized MED units are explored with limited production capacity. This is by no means restrictive in designing an extended MED unit, but is not considered the norm. In Chapter 11. an advanced design of a MED-TVC system is presented, with enhanced water production performance that could be employed in a CSP-DSW pilot plant.

1.4.3. Assessment of Power Generation Technologies – Rankine, Brayton and Stirling Engines

A comprehensive review of the available power generation technologies was conducted in the preceding months and an evaluation of the emerging trends has been performed. Comprehensive report and assessment is presented in Chapter 3. where an overview of the available technologies suitable for a CSP plant can be found. It is concluded that at the current stage of development only Rankine Cycle (steam turbine) Engines should be considered for a pilot plant. These engines are highly efficient and extremely reliable for high power ratings (in excesses of 30 MW), while renewable sources such as CSP, are in need of smaller more efficient engines in the 1 to 10 MW range, and especially in island environments (due to land availability and optical efficiency considerations). Promising new technologies, well adapted to CSP are actively being researched, especially variants of the classical Stirling Engine. It is judged that these concepts are not mature for implementation even at pilot plants and it is inconceivable to consider them for industrial application at the present time.

1.4.4. Design of a CSP-DSW Pilot Co-Generation Plant

The conceptual and implementation design of the co-generation Plant has been studied extensively. ***It is concluded that for the specific needs and conditions of Cyprus, there is no sufficient maturity in certain components that are required for the construction of a pilot unit. Further research and development is needed in these components and their integration and extensive field testing in realistic island-coastal environment before the investment for the construction of a full scale demonstration plant will be warranted.***

In this Final Report we present one of the most promising combination of technologies for a pilot unit to be constructed in Cyprus, following extensive research and testing in some of its subsystems. The design presented here is the product of intense research carried out by the Cyprus Institute and its collaborators. The proposed design is original, truly innovative and bespoken to Cyprus' needs and conditions.

In Chapter 8 a design for a pilot plant is presented having the following components:

- Light (solar energy) will be harvested by a field of Heliostats on a hilly, south facing, location near the sea.
- The solar energy will be captured by a central receiver and converted to heat and stored in a salt container of novel design at high temperatures (500 to 600^{o} C). A second, more advanced and technologically far more challenging design for the storage unit, employing very high operating temperatures (600 – 1000^{o} C) has also been studied, providing an excellent future solution for use with a supercritical CO_2 cycle.
- Steam will be generated from the heat reservoir of the salt container (or possibly from alternative thermal storage concepts); this production is augmented by collecting "waste" heat from the various subsystems of the entire unit.
- Electricity will be produced using commercially available Steam extraction turbine. Desalinated water will be produced using an innovative Multiple Effect Distillation (MED) with a Thermal Vapour Compressor, principally from the heat output of the steam turbine and other heat sources of the system. A hybrid solution (with the inclusion of a Reverse Osmosis branch) has also been considered, which might introduce further flexibility and efficiency in the system.

Detailed engineering parameters, optimization considerations and the current detailed design are being presented in Chapter 8.

It should be stressed that variants and similar concepts both in the receiver technology (e.g. conventional tower technology) and in storage (e.g. storage in concrete blocks, pursued by DLR and collaborators) are actively being researched by a number of international teams and their development should be monitored closely.

The considered conceptual design corresponds to a competitive and economically viable pilot plant which will have the capability of operating continuously (24 hour) and independently (without co-firing assistance). It is worth noting that this has not been achieved yet anywhere.

An extended Financial Assessment of the proposed pilot plant has been modelled and is presented in Chapter 12. suggesting that such a unit will produce both electricity and desalinated water simultaneously at economically viable prices given the currently adapted

CSP feed-in tariff structure of the Republic. The business model reveals a fundamental deficiency in the current policy for the encouragement of the use of renewable energy sources for water production. Unless it is supplemented by a tandem policy for feed-in tariff for the production of desalinated water market distortions will result defeating the very goal of the policy. The introduction of incentives for renewables with storage and inflation-adjusted tariffs should also be considered.

1.4.5. Consideration on the Placement (siting) of the CSP-DSW pilot facility

A comprehensive review of the considerations that are traditionally being taken into account in the placement of CSP facilities was performed and critically examined. The conventional wisdom, for which there is very little, if any, documented justification (beyond the obvious ease of access and serviceability), is that CSP facilities are being placed on flat terrain. This requirement presents difficulty in being implemented in Cyprus, for such terrain is generally either limited and of high agricultural and/or commercial value or it is away from the sea shore, thus not suitable for desalination. Detailed examination revealed that this bias has limited justification (primarily in terms of serviceability of the light gathering hardware) and can be overcome for heliostat technologies. Hilly terrain near the sea facing south, such as that in the south coast of Cyprus can be used and in certain cases it offers substantial advantages.

The placement near the sea and the co-generation concept itself (CSP-DSW) solves one of the major problems that CSP plants face: their cooling and maintenance demands substantial quantities of water. The site at Pentakomo (adjacent to the area earmarked for the Technology Park) is a good example of a location that can incorporate hilly terrain in the planning. A software tool which can assess the solar potential of an area and identify the most promising spots for the placement of a CSP plant (see Chapter 10. on a hillside was developed, and could be used to identify in the whole of Cyprus the most promising areas to install the pilot plant. This software tool requires detailed geographical data which were not available to us for at the time of the Study's conclusion. Should this data become available, the assessment of the solar potential of hills in various regions in Cyprus would be a relatively easy task.

A very important conclusion of the study concerns the size of the plants. Geography in Cyprus and similarly in other islands puts very difficult constraints on the placement of CSP plants. The space requirements for an optimally sized CSP plant (in excess of 20 MWe) are prohibitive. The development of efficient electricity generation (need of new generation of turbines) in the range of 0.5 to 2.5 MWe will be of a tremendous significance to the employment of CSP and CSP-DSW in many part of the world, including Cyprus.

1.4.6. Pilot Plant Capacity

In our considerations we took as the primary purpose of the Pilot Plant to test and demonstrate on a realistic scale the technological feasibility and economic viability and competitiveness of a CSP-DSW co-generation Plant. A detailed investigation of the desired pilot plant capacity revealed a number of conflicting considerations and requirements. We took into consideration the morphology of terrain, the size of the solar field, the efficiency of electric production and the efficiency of desalination production.

The above considerations which are discussed in detail in the main body of this document dictate that a minimum plant capacity of 4.0 MWe (nominal) should be aimed. This is solely driven by the requirements of reasonable efficiency in electricity production. Most other considerations demand a smaller rather than larger Pilot Plant. A plant of this size, which we tentatively propose and for which we provide a conceptual design report, should be able to co-generate desalinated water in excess of 1000 cubic meters per day (very conservative estimate) and possibly as much 5000 Cubic meters per day (if new technologies are incorporated).

A rather optimistic, but nevertheless realistic, cost assessment of such a facility is in excess of 25 Million Euros. Our business model indicates that this plant will be quite profitable but as we indicated earlier the risk in unproven components is high.

1.5. Conclusions – Recommendation

After a thorough examination of all available technologies, it is concluded that for island and coastal environments and for Cyprus in particular no technological solution for certain components exists at the desired level of maturity which will allow us to recommend the construction of a pilot plant without the introduction of considerable financial risk. This lack of maturity in certain components also restrains their efficient integration under a specific design. There is currently no commercially available proven storage technology that can be used for a CSP-DSW pilot plant operating as a base-load unit. The two-tank molten salt solution currently employed by a few Central Receiver systems is still evolving and in general is employed in a combined cycle for power production. No field-proven heliostat solution yet exists for deployment on a hillside able to withstand the corrosive and windy coastal environment. Rankine cycle turbines after decades of development which has focused on improving efficiency on large scales are extremely reliable although mismatched to a degree in size to the requirements of the CSP-DSW project.

Based on the extensive and thorough study that has been performed, our research has shown that the concept of the co-generation of Electricity and Desalinated Water is technically feasible and economically competitive in comparison to separate desalination and electricity production from renewable sources, but not yet at the maturity level that allow the immediate launching of a pilot construction. Most importantly, thermal storage, power generation and desalination have not yet been fully integrated and as a result the system does not exploit the advantages afforded by a dual purpose plant (efficiency, economy of scale, etc.).

The recommended co-generation scheme is very well suited to the geographical and technological realities of the island but inconsistent with the current policies on renewables and feed-in tariffs established in Cyprus. Although power production from renewables is handsomely rewarded with a premium feed-in tariff, desalination of sea water from renewables is not. Therefore the co-generation, whilst economically viable and financially profitable, is suffering a heavy penalty due to this imbalance, urging for electricity-only production to maximize profit. It must also be pointed out that the lack of a connection between the feed-in tariff and the inflation rate is a considerable deterrent for investing in renewable projects in Cyprus.

The choices recommended and the detailed information provided in the chapters that follow provides a sound basis for the commencement of research and engineering studies for a 4 MWe CSP-DSW demonstration plant, a size we tentatively propose as appropriate.

Based on our results, we recommend that the Cyprus Government proceeds with the construction of such a plant after a number of key components are subjected to test and verification in a realistic environment. We identify the need of experimental demonstration of critical subsystems in order to assess the robustness and suitability of the technologies chosen in an island environment. We recommend that these experiments be launched immediately. We expect that a three-year period will be required to perform these experiments and tests. The abovementioned findings have met the approval and support of the participating scientists and stakeholders of the international CSP-DSW Workshop, which was organized on June 23rd 2010, in Nicosia, Cyprus and where the results of the CSP-DSW study were presented.

At this stage of the study, and based on thorough and detailed studies which are presented in the main body of this report we conclude that the:

- International political, economic and technological developments have further enhanced the rationale and firmed up the technological arguments for pursuing a Co-generation Plant for the production of Electricity and desalinated water in Cyprus.
- We recommend that based on the detailed technological choices presented in this document and summarized above, that the Government of Cyprus develops a strategy for the development of the CSP-DSW Pilot Plant. This will require a comprehensive program of research and development to refine, assess and prove the performance and especially the reliability of a number of key components of the system. This program, expected to last three years, will reduce the financial-technological risk significantly.
- A rationalized tariff structure needs to be implemented to support the production of Desalinated Sea Water from renewable energy sources. It will be necessary in order to incentivise the commercial installation of CSP-DSW plants. Additional considerations should be made for the introduction of incentives for renewables employing storage options. Finally, a time-dependant strategy (such as linkage to the inflation) of feed-in tariffs should be introduced which would make investments in renewables much more attractive.

We have completed a study with the dual goals of gauging the maturity of CSP-DSW technologies and designing an integrated system. Clearly the state of the former affects the optimality of the latter.

The Cyprus Institute and its collaborators will continue with research and testing of the various technologies presented herein to further enhance their designs and operation beyond the scope of this study. These results will be made available to the general public and to Government authorities for their consideration.

Chapter 2. The CSP-DSW Project

This Document comprises the final report as prescribed in the terms of the contract agreement signed between the Directorate of Control of the Ministry of Communications and Works and the Cyprus Institute for the techno-economic assessment of the current status of technology in the co-production of electricity and desalinated water (Desalination of Sea Water - DSW) using Concentrated Solar Power (CSP).

The study has been a collaborative effort between leading experts in the various fields of desalination, solar power and modelling and relevant authorities in Cyprus and abroad. A more detailed description of the partners and their role can be found in a following section.

The study has been broken down into seven work themes (referred to as work-packages – WP and described in a later section) in order to better examine and investigate the various aspects of the project, and a collaborator has been assigned to lead the research under each theme.

Since the beginning of the Study, the Cyprus Institute with its partners have met 6 times, twice in Boston, USA and four times in Nicosia, Cyprus, and have held a series of teleconference meetings. The work of the individual work-themes, after originally been defined, has continued in parallel, with all the necessary interactions between the various themes.

At the conclusion of the project a number of crucial milestones have been achieved. A review of existing CSP and Desalination Technologies has been conducted. The current and future demand of electricity and water in Cyprus has been explored. Taking into account Cyprus' needs and specific conditions, the most appropriate technologies for a co-generation unit have been selected and a conceptual and an implementation design for a CSP-DSW plant has been decided. Configuration and operational data have been modelled and analysed to a certain degree and will continue to be analysed in research that the Institute will carry out in collaboration with MIT and the UIUC in subjects beyond the scope of this study. Finally, the long-period optimization process of the proposed pilot plant's operation will continue and the conclusions will be published in due time.

An International Workshop was organised on June 23rd 2010, in Nicosia Cyprus in which the findings of the study were presented. Prominent scientists, stakeholders and policy makers participated from Cyprus and the region. The aim of the Workshop was to present and debate the conclusions of the study, engage local and regional participants to a critical discussion on the suggested technological solution, and to establish a discussion platform on technological, economic and policy issues for renewables. From the discussion which followed the presentations of the CSP-DSW project collaborators, the following key points were emphasised:

- Solar Technologies and specific CSP Technologies are most appropriate for the Mediterranean and Middle East regions.
- Energy storage is a highly desired characteristic in renewable energy sources in order to mitigate the intermittence of their availability. CSP comprises one of the best technological choices for coupling with an energy storage system.
- The CSP-DSW design was deemed very promising and technologically sound. The creation of a demonstration unit would be extremely useful after some of its components are subjected to further testing in small-scale and in realistic conditions experiments.

The programme of the Workshop can be found in the Appendix E1, while more information and the presentations of the speakers can be found out at the project's website (http://www.cyi.ac.cy/CSP-DSW/workshop).

The comments and recommendations by the participants of the Workshop have been incorporated in this Final Report.

2.1. State of Affairs at the beginning of the Study

Cyprus is facing the severe consequences of climate change; robust model predictions forecast a worsening situation in terms of water precipitation and extreme weather conditions. Precipitation has dropped noticeably in the past few years and continues to decrease at a rate of 1mm of rain per year on average. Rising temperatures, which both will increase demand and make more difficult the storage of water, have been increasing at a rate of 0.01°C per year. A number of works have been carried out to maximize storage capacity, nevertheless in the past years all surface storage (dams) have reached extremely low levels and most of the aquifers have being depleted. At the same time there has been an increasing demand for water. It is generally accepted that the only viable, long-term, solution for covering Cyprus' needs for water, in addition to improved management of its storage and use, lies with desalination which however requires a lot of energy.

Cyprus is almost completely dependent on fossil fuel and in particular exclusively on oil and heavy oil, for energy production at a rate of 98%. Natural gas which is anticipated to arrive to Cyprus in the next five years is also an imported commodity and its price subjected to outside factors. Isolated from continental power grids, all energy production is taking place on the island. Electricity demand has continued to increase in the past few years and although steps have been taken to ensure meeting Cyprus' needs, they also depend on fossil fuel (oil).

Additionally, Cyprus is required to meet the newly introduced EU standards which demand that by 2020, 20% of Cyprus' energy consumption (revised to 13% in 2009) must come from renewable sources and greenhouse gases emissions (CO_2 especially) must be reduced by 20%.

The co-generation of electricity and useful heat has been recognised by the European Parliament and the EU Council as a major contributor towards energy savings and reducing carbon emissions. A special Directive (2004/8/EC) has been adopted to promote the use of co-generation. The Directive was adopted in Cyprus on December 2006 (N 174 - I).

The CSP-DSW project examines a most promising solution for Cyprus: production of water to cover the rising demand and simultaneous production of economically competitive, green energy from solar power. This co-generation scheme is a novel approach which employs both new and tested technologies, bespoken to Cyprus' needs and conditions.

The CSP technology is most suitable for the Mediterranean region. In a comprehensive study carried out by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR)[1], the CSP technology is recognised as the main option for the region for renewable energy. The Solar potential is excellent with small cloud coverage and a high factor of irradiation throughout the year. Especially for Cyprus the average time per day of sunshine is 11.5 hours in the summer and 5.5 hours in the winter. CSP provides a clear advantage over other renewable energy generation technologies (such as Photovoltaics – PV), as it can be combined with energy (thermal) storage in an efficient and economically viable way. The storage option is crucial for solar energy schemes as it can lead to a potential 24-hour, 7 days-a-week operation. All viable CSP technologies such as heliostats, troughs, parabolic dishes and Fresnel lenses, have been examined and evaluated in the framework of this study.

Desalination technologies have evolved significantly over the years. On-going research mainly focuses on refining well-established techniques and on developing new materials to be used as membranes. The two main methods, Reverse Osmosis (RO) and Multi-effect Distillation (MED) present both advantages and disadvantages and are selected according to specific cases. Both methods are explored herein, for the co-generation scheme.

2.2. Themes

In order to better examine and investigate the various aspects of the project, the latter was divided into seven themes. For each theme the CyI has sought leading experts from world-class institutions to participate in this study and a number of people in the relevant Cyprus authorities to ensure a smooth and precise integration in the Cypriot conditions. The overall coordination and management of the project was assumed by the Cyprus Institute. The Principal Investigator of the study is Prof. C.N. Papanicolas who is also the President of the

[1] http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/projects/MED-CSP_Full_report_final.pdf

Institute. Dr. G. Tzamtzis is the Project Coordinator and Project Manager. The seven work-themes (referred to as work-packages - WP) identified and which comprise the project are:

a. WP1: Policy & Techno economic Assessment (Leader: Prof. Papanicolas, CyI)
b. WP2: Light Harvesting (Leader: Prof. Slocum, MIT)
c. WP3: Thermal storage (Leader: Prof. Slocum, MIT)
d. WP4: Electricity Generation (Leader: Dr. Poullikkas, EAC)
e. WP5: Desalination (Leader: Prof. Georgiadis, CyI and UIUC)
f. WP6: Optimization and Integration (Leader: Prof. Mitsos, MIT)
g. WP7: Siting (Leader: Dr. Anastasiou, CyI)

These seven themes represent critical parts of the study for the creation of the proposed pilot plant.

2.2.1. Policy & Techno economic Assessment

This theme examines policy and economic issues related with the appraisal of existing CSP and Desalination technologies, and of the planned pilot plant. Key features of this theme were to:

- Provide a comprehensive review of forecasts on Demand for Electricity and Water in Cyprus until 2020
- Establish a comparison baseline of the feasibility and production costs in Cyprus during the same periods
- Identify, evaluate and discuss the externalities of each production method for DSW and Electricity production
- Identify and estimate costs of externalities that will be taxed (e.g. CO_2 EU Carbon Tax) and externalities that are currently not obviated
- Identify and whenever possible forecast policy targets or commitments: EU Directives (e.g. 20:2020), the Kyoto treaty and its extension, etc.
- Establish a baseline for the cost of producing Electricity and DSW water by the proposed co-generation method of CSP-DSW. Provide benchmarking for the method by offering comparative costs for alternative methods. Analyze the

comparative advantages and disadvantages of this method vis-à-vis externalities, policy directives and goals.

This theme was coordinated by the Cyprus Institute and its principal investigator is Prof. C.N. Papanicolas.

2.2.2. Light Harvesting

The light harvesting theme examined the different methods currently being employed of harvesting solar power using mirrors in different configurations. This included all commercially available variants (heliostats, troughs, Fresnel). In addition to the review of the available technologies research for this theme area concentrated on the following topics:

- Conduct experiments and simulations to further define mirror configurations and storage media
- Derive scaling principles which will be used for different sizes for the proposed plant
- Develop a conceptual design for the light harvesting array for the pilot plant to be built in Cyprus in next phase after the completion of this research.

This theme was coordinated by Prof. A. Slocum from the department of Mechanical Engineering at the Massachusetts Institute of Technology (MIT).

2.2.3. Thermal storage

The Thermal storage theme represents one of the most innovative and technologically demanding parts of the CSP-DSW study. An ultimate design objective was to enable the proposed pilot plant to operate on a 24-hour, 7 days a week base load. An intermediate goal was to achieve adequate storage time so as to match the daily demand curve to the production of the plant. The CSP-DSW study examined thermal storage media at different storage temperatures primarily involving molten salts, a method that is pursued at various laboratories worldwide (including MIT). The Theme had the following main goals:

- To select one or more molten salts for application to the CSP-DSW project on the basis of their light absorption characteristics and chemical compatibility with prospective structural materials.
- Optimization of efficiency by exploring different temperatures and salts for the storage medium

This research was tightly linked to the Light Harvest Theme and is also coordinated by Prof. A Slocum.

2.2.4. Electricity Production

This Theme examined and proposed solutions for an optimized (most efficient) way to produce electricity through steam generators taking into account the very demanding and rather unique thermodynamic cycle of the co-generation scheme. The Theme's main objectives were to:

- Review the existing steam turbine technologies and identify the most appropriate for the CSP-DSW concept
- Select steam turbine size and type for a range of possible applications and plant sizes
- Identify steam turbine interfaces with other cycle components
- Determine power plant input and output conditions and particular inflows and outflows.

The Theme provided essential elements for the linkage between the solar power harvesting and desalination. The Electricity Production theme was being coordinated by Dr. A. Poullikkas who is an Assistant Manager at the Research and Development Section of the Electricity Authority of Cyprus.

2.2.5. Desalination

The Desalination Theme group addressed the technical issues concerning the co-production of desalinated water of the CSP-DSW project. It attempted to identify the most efficient way through modern desalination techniques of implementing them for the co-generation scheme. Reverse Osmosis (RO) and Multiple Effect Distillation (MED) were both investigated to select the most suitable for utilisation, including a possible hybrid solution. The Desalination theme research pursued the following tasks:

- Review the existing and emerging desalination technologies
- Select desalination unit size and type on the basis of energy efficiency, cost, and integration with other plant components
- Provide a conceptual design for a desalination unit that can be integrated to the CSP-DSW pilot plant.

The desalination component of the project was coordinated by Prof. J. Georgiadis a Professor at the Department of Mechanical Engineering at the University of Illinois at Urbana Champaign.

2.2.6. Optimization and Integration

The optimization and Integration theme group pursued the detailed investigation of the optimization of overall efficiency of the CSP-DSW plant. Methods for comparing and selecting the most promising alternatives for the proposed pilot plant have been developed, taking various factors such as scale (i.e. desired power output and mass-flow of water), weather conditions and economic parameters into consideration. Work pursued under this Theme included the following:

- Process Synthesis for selecting an optimal process alternative which is the first step for the system-design given the technology options
- Nominal Process Optimization including design choices, sizing of the storage components, unit operation, specifications of operating temperatures, etc.
- Incorporation of Time-Variation and Uncertainty, which will optimise the operation considering time-dependent demands for electricity and water.

This Theme drew input from all other themes which was used in the modelling process to evaluate and select optimum choices of design and operation. The Theme was coordinated by Prof. Alexandros Mitsos of the Department of Mechanical Engineering at MIT.

2.2.7. Siting

This Theme dealt with the identification of suitable locations on the island which would be optimal for hosting the proposed pilot plant. The Theme's main objectives included the following:

- Develop a methodology and outline the considerations which should drive the choice for potential sites for the CSP-DSW plants
- To identify potential plots in Cyprus where the CSP-DSW plant can be built
- To assess how the morphology and location of each plot can affect the economics of the plant
- To conclude with a list of possible sites presenting advantages and disadvantages.

This theme was coordinated by the CyI and is headed by Dr. T. Anastasiou.

2.3. Partners and Participants

A brief description of the groups that have undertaken critical parts of this study according to the Themes presented above, follows:

Techno-economic, Policy and Siting Assessment Group at CyI

Prof. C. N. Papanicolas (Theme Leader – Principal Investigator) is the President of the Cyprus Institute and CEO of the Cyprus Research and Educational Foundation. A US (MIT) educated Nuclear Physicist has held positions with French Atomic Energy Commission (Saclay, France) and served as Professor of Physics at the University of Illinois. He currently holds professorial appointments with the University of Athens (Greece) and the University of Illinois (adjunct). He has served as Director of the Institute of Accelerating Systems and Applications (Athens GR), Chairman of the Accreditation and Certification Council of Cyprus and Member of the National Advisory Research Council of Greece. He is a fellow of the American Physical Society.

Dr. G. Tzamtzis (Project Coordinator and Manager) holds a B.Sc. in Physics from the University of Patras, Greece and a Ph.D. in Mathematical Physics from the University of Durham, UK. He has worked for the Cyprus Institute from the position of Assistant to the President of the Cyprus Institute for three years and for the past year as a research associate. He is currently responsible for the overall management and coordination of the CSP-DSW project.

Dr. T. Anastasiou (Theme Leader) received his PhD in Physics from the University of Cambridge in 2003. Between 2003 and 2007 he worked for BP Oil International in the UK both in Technical and Project Management roles, focusing on the optimal and safe operation of BP's process plants. Since 2008, Tasos is an associate of the institute working in the fields of Renewable Energy and Energy Policy.

Dr. A. Bonanos has a BSc in Aerospace Engineering, from the University of Virginia, USA, and an MS and PhD in Aerospace Engineering, from the Virginia Tech, USA. He was previously a Post-Doctoral Scholar in Aeronautics at the California Institute of Technology Pasadena,USA.

Dr. I. Mitra holds an M.Sc. from the University of Oldenburg, Germany an MBA in Energy Management from the Indian Institute of Social Welfare and Business Management, India and a Ph.D. in Renewable Energy from the University of Kassel, Germany. He has a strong professional experience in a wide spectrum of fields in energy, environment and sustainable development sector. He has been a visiting scientist at ISET e.V., Germany and prior to that held a research associate position at The Energy and Resources Institute (TERI), New Delhi, India. Dr. Mitra joined CyI's EEWRC in 2009 assisting primarily with the Techno-economic and policy assessment Theme of the CSP-DSW project.

Light Harvesting and Head Storage Group at MIT

Prof. Alex Slocum (Theme Leader) of the Department of Mechanical Engineering leads the CSP-DSW group at MIT which seeks to understand the basic science of liquid salt light absorption and use this new knowledge to design a direct absorption concentrated solar power system. Prof. Slocum has been designing precision machines for two decades and is now focused on renewable energy systems. His contribution to the project will be that of overall coordinator and to lead the research on the structural and servomechanism components including error budgeting to predict system thermodynamic efficiency.

Prof. Jacopo Buongiorno is the principal investigator of the MIT nanofluid heat-transfer program which seeks to understand key energy transport phenomena in colloidal dispersions of nanoparticles, and to explore their applicability to energy-intense systems such as nuclear reactors. His lab is equipped with state-of-the-art instrumentation to measure the thermophysical properties of nanofluids. In this project Prof. Buongiorno will lead the effort to characterize the heat transfer properties of molten-salt-based nanofluids.

Dr. Charles Forsberg recently joined MIT after leaving Oak Ridge National Laboratory as a Corporate Fellow. At ORNL he led a partnership to develop salt-cooled high-temperature nuclear reactors. In addition, he examined the use of fluoride and chloride salts as heat transfer systems in (1) solar power towers that would operate at peak temperatures up to ~700°C and (2) heat transfer systems to move heat from high-temperature reactors to chemical plants. He currently serves on an International Atomic Energy Agency technical panel as the U.S. expert on liquid salts for nuclear systems. In this project *Dr. Forsberg* will lead the efforts to develop and integrate salt technologies into the CSP-DSW system.

Prof. Ahmed F. Ghoniem is head of Energy Science and Engineering in Mechanical Engineering. His research focuses on multi-scale simulations of multi-physics problems in reactive flows, active control applications to power and propulsion systems, and energy systems analysis. His Lab is equipped with modern computational clusters, and optical diagnostics for flow, transport and reactive species. Prof. *Ghoniem*'s contribution to this project builds on his experience with computational methods for turbulence, buoyant and reactive flows, and integrating descriptions of complex phenomena with control strategies.

Prof. T. Alan Hatton leads a program on the synthesis, functionalization and stabilization of magnetic nanoparticles in aqueous and organic media, with an interest both in the fundamental characterization of the properties of these systems, and in their use in a number of applications in the biological, chemical and environmental processing areas. Prof. Hatton's contributions to this project will be to develop and characterize stable nanoparticle dispersions in molten salts over a wide range of temperatures.

Dr. Tom McKrell is a Research Scientist at the Center of Advanced Nuclear Energy Systems (CANES), at MIT where he directs out-of-core experimental activities for the Center. He has directed many system designs, failure analyses, condition assessments, and life prediction projects in the nuclear power industry. He also has over fifteen years of experience with instrumentation and the design and fabrication of various types of custom testing systems. For this project, Dr. McKrell will be in charge of the experimental systems.

Principal students working on CSP-DSW include:

Mr. Danny Codd (Ph.D. student) is working on the secondary beam-down mirror that will receive the light from the heliostats and direct it into the pond of salt, and the container for the pond of salt.

Mr. Nevan Hanumara (Ph.D. student) is working on precision spherical mechanisms, to make them low cost should we need new heliostat technology.

Mr. Stefano Passerini (Ph.D. student) is working on the optical characterization of the salt, which includes design and building of the test furnace, and the thermal model of energy absorption as a function of depth.

Mr. Folkers Rojas (S.B. student whose work on CSP-DSW will continue into his masters thesis research) is working on the thermal model of the container and the salt-to-steam generator heat exchanger.

Mr. Vaibhav Somani (Ph.D. student) is working on the selection/design/stability and behavior of nanoparticles that likely will be needed to tune the optical properties of the salt.

Electricity Production at EAC

Dr. Andreas Poullikkas (Theme Leader) is leading the Electricity Production group. He holds a B.Eng. degree in mechanical engineering, an M.Phil. degree in nuclear safety and turbo-machinery, and a Ph.D.degree in numerical analysis from Loughborough University of Technology, U.K. He is a Chartered Scientist (CSci), Chartered Physicist (CPhys) and Member of The Institute of Physics (MInstP). His present employment is with the Electricity Authority of Cyprus where he holds the post of Assistant Manager (RTD); he is also, a Visiting Fellow at the Harvard School of Public Health, USA, and at the University of Cyprus. In his professional career he has worked for academic institutions, before joining the Electricity Authority of

Cyprus. He has over 15 years experience on research and development projects related to the numerical solution of partial differential equations, the mathematical analysis of fluid flows, the hydraulic design of turbo-machines, the nuclear power safety, the electric load forecasting and the power economics. He is the author of various peer reviewed publications in scientific journals and conference proceedings. He is, also, a referee for various international journals, serves as a reviewer for the evaluation of research proposals related to the field of energy and a coordinator of various funded research projects.

Dr. Constantinos Rouvas received his B.Sc. and M.Sc. degrees in Mechanical Engineering from Case Western Reserve University in Cleveland, Ohio and his Ph.D. degree from the Turbomachinery Laboratory of Texas A&M University in College Station, Texas. He has worked as a Lecturer at Frederick Institute of Technology, and the University of Cyprus. He is currently an Assistant Station Manager at the Electricity Authority of Cyprus. He has extensive experience in power station operation, and has been involved in a number of projects relating to renewable energy project development and energy efficiency.

Mr. Ioannis Hadjipaschalis holds a B.Eng. (Electrical Engineering), from the University of Sheffield, an M.Sc. from the London School of Economics and an MBA. During 1996-2000 he worked at the Electricity Authority of Cyprus as Electrical Engineer, while during the period 2001-2005 he worked at ACNielsen Market Research. He joined EAC Research and Technological Development team in 2006, where he has been working on European funded research involving RES, Distributed Generation (DG), Electricity distribution networks, Hydrogen and CO2 capture and storage (CCS) technologies.

Mr. George Kourtis holds a Diploma in Electrical Engineering from the Polytechnic School of Aristoteleio University of Thessaloniki (AUTH). During 2007 he has worked as a technician for LOGICOM LTD, where he was responsible for the maintenance of 3G Mobile stations. The last year he is a postgraduate student at the University of Cyprus where he is doing his Master Degree on Electrical Engineering. He joined Electricity Authority of Cyprus (EAC) in 2008, where he works on research programs as a scientific collaborator.

Desalination Group at UIUC

Prof. John Georgiadis (Theme Leader) who leads the Desalination group, holds a Dipl. Eng. degree in Mechanical Engineering from the National Technical University of Athens, and an M.Sc. and PhD from the University of California at Los Angeles. He is currently the R. Kritzer Professor of Mechanical Engineering in the Dept. of Mechanical Science & Engineering at the University of Illinois at Urbana-Champaign and also holds a joint appointment as a visiting Professor at the Cyprus Institute. He is a group leader of the Desalination and Water Reuse effort in the Center of Advanced Materials for the Purification of Water with Systems (WaterCAMPWS), which is a Science & Technology center supported by the USA National Science Foundation. His research group efforts focus on the use of non-invasive imaging methods in the study of fluid mechanics and heat & mass transport phenomena towards developing novel and more economic water purification materials and processes.

Mrs. Andrea Vozar holds a B.Eng. degree in Mechanical Engineering from Bradley University. Since January 2009, she is a graduate student in the Dept. of Mechanical Science & Engineering at the University of Illinois at Urbana-Champaign, and a member of the research group of Dr. Georgiadis which is affiliated with the WaterCAMPWS. After her undergraduate degree, Andrea worked as a test engineer at Stirling Technology Co. and as a design engineer at Caterpillar, Inc.

Dr. Myunghoon Seong is a post-doctoral associate at the Mechanical Science & Engineering Dept. of the University of Illinois (UIUC) focusing on the data acquisition system aspects of the UIUC 10 kW (thermal) Multiple Effect Distillation demo unit, and the modelling of the 4 MW (electrical) dual purpose plant. His educational background includes a BS from Seoul National University (1999), a MS from Stanford University (2001), and a PhD from the University of California at Los Angeles (2009).

Mr. Joao Pedro Bianco Bekenn is an undergraduate research assistant from Pontifica Universidade Catolica-Rio Janeiro, currently enrolled in the study abroad program at University of Illinois (UIUC) and focusing on the UIUC 10 kW (thermal) Multiple Effect Distillation demo unit.

Mr. Marios Georgiou is a PhD student at the Mechanical Science & Engineering Dept. of the University of Illinois (UIUC) and is focusing on the thermal design of the 10 kW (thermal)

Multiple Effect Distillation demo unit. He obtained his BSc in Physics from the National & Kapodistrian University of Athens in 2009, and he is currently a Cyprus Institute Fellow.

Optimization and Integration Group at MIT

Prof. Alexander Mitsos (Theme Leader) leads the system integration & optimization task. He is an Assistant Professor at the Department of Mechanical Engineering at MIT, with a research focus on optimization of energy systems. He brings expertise in system-wide modelling and optimization and mathematical programming.

Dr. Amin Ghobeity is a NSERC Postdoctoral Fellow and a Postdoctoral Associate at the Department of Mechanical Engineering at MIT. His research focus will be the optimal design and operation of the plant. Ghobeity has previous research experience and publications in experimental process mechanics, and also computational heat transfer. Moreover he brings significant industrial experience in commercial R&D settings.

Mr. Corey J. Noone, a graduate student at the Department of Mechanical Engineering since September 2009 and a research assistant supported by the CSP-DSW project. Noone develops tools for site selection and optimal heliostat placement.

Mr. Christopher M. Williams, a graduate student at the Department of Mechanical Engineering since September 2009 and a research assistant supported by the CSP-DSW project. Williams develops models for the power requirement of MED and will focus on comparing different alternative technologies.

Ms. Latifah H. Hamzah, an undergraduate student at the Department of Mechanical Engineering. Hamzah is doing an undergraduate research project without compensation. She assists Dr. Ghobeity in developing and comparing component models.

Mr. Alex Pak, an undergraduate student at the Department of Chemical Engineering. Pak is doing an undergraduate research project without compensation. He assists Dr. Ghobeity in developing costing estimates.

Other Participants

The Cyprus Institute in its effort to better integrate the project in Cyprus's conditions and needs has asked the participation of the relevant competent authorities. These authorities have contributed significantly in a number of themes, especially in the Techno-Economic Assessment theme, by providing valuable information and data concerning the use of energy and water, infrastructure (both existing and planned), policy and directives pertained to usage, etc. A brief review of the participants follows:

The Cyprus Regulatory Authority is the competent authority of the Republic of Cyprus for regulating the Energy Industry. It is charged with a number of duties concerning the energy sector. Amongst them are the following:

a. grant, monitor, enforce, modify or revoke authorisations, including where necessary invite the submission of applications for authorisations issued under this Law;
b. advise the government on all matters concerning electricity;
c. ensure that the Trading and Settlement Rules and Trading Rules are prepared and approved;
d. secure that all reasonable needs and demands for electricity are satisfied;
e. regulate tariffs, charges and other terms and conditions applied by licensees for any services provided under the terms of their authorisations;
f. set out, publish and enforce quality standards to be complied with by authorisation holders;
g. determine rules or procedures under which complaints concerning the services provided by licensees will be dealt with, including where it considers it appropriate, investigation and resolution of such complaints;
h. investigate and resolve disputes arising between authorisation holders in accordance with the Arbitration Law;
i. to act in accordance with the instructions of the Council of Ministers in an event involving national security or the defence of the Republic;
j. issue Regulations in accordance with this Law; and
k. take decisions and regulatory decisions as provided by this Law and the Regulations issued under it.

Marilena Delenta and ***Costas Ioannou*** are the CSP-DSW contacts at CERA.

The Water Development Department is the competent authority of the Republic of Cyprus responsible for implementing the water policy of the Ministry of Agriculture, Natural

Resources and Environment. Main objective of this policy is the rational development and management of the water resources of Cyprus. In this context, the responsibilities of the department cover a wide and diverse spectrum, which includes:

a. the collection, processing and classification of hydrological, hydrogeological, geotechnical and other data necessary for the study, maintenance and safety of the water development works,
b. the study, design, construction, operation and maintenance of works, such as dams, ponds, irrigation, domestic water supply and sewerage schemes, water treatment works, sewage treatment and desalination plants, and
c. the protection of the water resources from pollution.

Spyros Stefanou and ***Andreas Manolis*** were the contact persons at the WDD.

The Cyprus Meteorological Service (CMS) of the Ministry of Agriculture, Natural Resources and Environment is mainly responsible for matters related to the weather and climate of Cyprus. The Meteorological Service is providing services and information relevant to the weather and climate aiming the wellbeing of the people of Cyprus and the protection of their life and property.
For the achievement of the above objectives, the Meteorological Service collects and uses the meteorological information over the Cyprus domain effectively and properly and shares this information with other National Meteorological Services and the World Meteorological Organization (WMO).

Dr. Silas Michaelides and ***Dr. Stelios Pashiardes*** were the contact persons in the CMS.

2.4. Structure of the Final Report

The remaining portion of the Final Report is organized as follows:

In Chapters 3, the current state of CSP Technologies is presented. The various Solar Harvesting options are examined and compared. In Chapter 4 the two prime Desalination technologies are analysed with an emphasis on the particular conditions of Cyprus. In

Chapter 5, the most suitable Steam turbines for electricity production within the CSP-DSW concept are listed. An assessment of Energy and Water production and demand in Cyprus follows in Chapters 6 and 7 respectively.

The Report continues with the formulation of the proposal for a pilot CSP-DSW plant. In Chapter 8 the conceptual design of the plant and the basic parameters of its operation are presented, and integration and Optimisation issues are discussed. In Chapter 9, the innovative CSPonD concept developed by MIT is presented and operating and technological issues are addressed. The Heliostat system that could be used for the CSP-DSW pilot plant and the issues regarding its placement on a hillside are discussed in Chapter 10. An innovative MED design for the CSP-DSW system appears in Chapter 11, while on Chapter 12 a financial analysis of the CSP-DSW solution is performed. In Chapter 13, issues about the placement of the CSP-DSW plant in Cyprus are discussed and a number of candidate sites are given.

The Report concludes with Chapter 14 with the main conclusions of the CSP-DSW Study, and with the Principal Investigator’s recommendations to the Government.

Chapter 3. Concentrated Solar Power Technologies

This is an overview of the CSP technologies and their features that are commercially available today. It summarizes salient features of various CSP plant types and discusses the role of a few major factors which influence the performance of CSP plants. A short survey was conducted to explore the CSP technology and practices and presented in this report in concise manner.

3.1. Introduction

Concentrating Solar Power (CSP) plants utilise Solar Energy by focusing direct beam sunlight at a specific target in order to produce high temperature heat which can then be used for electrical power generation. Most CSP plants comprise of two components: the Light Harvesting section involves the collection of solar energy in a concentrated form and its conversion to heat, and the Heat Utilisation which involves the conversion of heat into useful work (i.e. by generating electrical power or operate various other thermal processes). CSP plants, as with solar energy systems, depend on an intermittent source therefore cannot offer a dependable, autonomous and continuous power generation solution. Nevertheless this problem may be overcome by either using a hybrid solution which uses fossil fuel to compensate for unavailability of solar energy or may be combined with various thermal energy storage solutions.

In this report an overview of the CSP concept is presented, salient features of commercially available CSP technologies are reviewed and the influencing key factors to the CSP plant's performance is discussed. The four primary types of CSP technology, Parabolic Troughs, Fresnel Systems, Central Towers (power towers) and Parabolic Dishes are also presented and discussed.

A literature survey has been conducted with emphasis on the realistic issues of existing CSP initiatives. Despite the existence of a wide spectrum of technology components related to CSP plants, central receiver type systems appear to be most suitable for rough land terrain, high temperature applications, high efficiency and better thermal storage potential.

3.2. The need for concentration

The Carnot efficiency defines the physical limit for the conversion of heat into mechanical work:

$$\eta_{Carnot} = \frac{W}{Q_{in}} = 1 - \frac{T_{out}}{T_{in}},$$

where W is the work done by the system, Q_{in} is the heat input, and T_{in} and T_{out} the temperatures of the cold and hot reservoirs respectively between which the engine operates. It is clear that the greater the difference in operating temperature, the greater the efficiency. By decreasing the area from which heat losses occur, greater delivery temperatures can be achieved. The way this is realised is by interposing an optical device between the source of the radiation and the energy-absorbing surface. Concentrating collectors reduce the receiving area by reflecting (or refracting) the incident light onto an absorber of small area. Solar energy concentration minimizes thermal loss while at the same time increases the temperature of the absorber (which is close to T_{in} so that higher Carnot efficiencies can be achieved.

3.3. Salient features of CSP units as power generating systems

Solar plants share some functional similarities with conventional electricity production power plants (e.g. oil, gas, coal or nuclear) in the sense that their output is thermal energy which is used to generate steam and produce electricity through a steam turbine. In contrast however with conventional power sources, solar radiation, the primary energy input into a CSP system has no material form, is dilute and is terrestrially accessible only during daylight hours. Its availability depends on location, season, time of day, ground morphology and momentary meteorological conditions. The main limiting feature of solar radiation is that it cannot be stored directly for later usage. On the other hand, solar radiation is free, indigenous, renewable and environmentally friendly.

The following constitute some of the most salient characteristics of the CSP Power plants:

1. **Land Requirements**

   CSP plants require substantially more on-site land area than conventional power plants due to the extended solar harvesting field. On the other hand, in a global sense, no off-site land area is needed for raw material mining, processing, handling and transport, or for the disposal of power production residues.

2. **Separate Elements**

   In CSP plants there is a physical separation between energy concentration elements (the "fuel" is collected via reflective surfaces aiming at a single or multiple targets) and energy conversion elements (solar radiation is converted to heat in receivers or absorber tubes)

3. **Design Points**

   A base load conventional thermal power plant is rated as its nominal (nameplate) output conditions within which the plant is expected to operate for a long time period. CSP plants have **'Design Points'** because of the periodic and fluctuating solar energy input. These points are fixed by assuming a specific irradiance at a specific time during a particular day of the year. For example, a design point for Cyprus could be a solar irradiation of 900 W/m^2 at noon at equinox. CSP plants are usually rated by design point operating conditions along with a specification of the output power capacity. One must be careful while comparing different CSP plants on the basis of nominal performance because design points may vary between different sites [1].

4. **Solar Input Variability.**

Solar insolation, the energy input source for CSP plants, has a high degree of temporal and spatial variability. No control is possible over availability, quality and quantity at a given site at a specific moment. Thus the role of local meteorological data as well as forecast capability becomes important to estimate the solar energy availability for a specific CSP plant.

5. **Hybridization and Thermal Storage.**

Utilisation of CSP plants for electricity production on a continuous (24 h) basis vis a vis solar energy availability requires solutions that circumvent the problem. The two most common solutions considered are:

- Utilization of a back-up energy source. This is realised in hybrid plants which often use a fossil fuel auxiliary power generation unit that is coupled in hybrid mode with the CSP plant and which contributes in either augmenting the plant's output or for temporarily substituting solar energy [1].

- Thermal storage is more cost-effective than storing the produced electrical power for later distribution. However, thermal storage of significant amounts of energy requires a very large mass with significant thermal capacity. Energy storage is an area of intense research pursued by many institutions and companies throughout the globe. It is one of the driving forces behind the Hydrogen economy as it provides an on-demand solution for electricity production through hydrogen storage. At the moment the level of maturity of energy storage technology is still low: technical capability is far from being supported by economic viability. A significant portion of this research is focused on thermal storage systems which couple naturally with CSP systems due to their ability to deliver easily high temperatures. These thermal storage systems can then cater to both electricity production as well as separate thermal processes (e.g. a CSP project for electricity and thermal desalination).

6. Electricity production and CSP

With regard to electricity production, a number of thermodynamic cycles exist which can be coupled to the thermal production of a CSP plant. The most common are the following:

- For large capacity power systems with Rankine cycle where water/steam are used as the phase change medium in a closed loop and the Brayton cycle with air/gas as working medium in an open loop have reached maturity by being utilized at conventional power systems. Nevertheless the employment of such systems does not translate directly in CSP plants since they might operate under non-steady state, frequently-variable input conditions. This is the main reason why the role of appropriate thermal energy storage capability becomes imperative for CSP plants: in addition to storage it provides a regulatory role for steady thermal flow.
- Stirling cycle engines which employ air or hydrogen as a working fluid are most attractive solutions for heat input from solar radiation. Assuming equal lower temperatures for all cycles, the longer span between upper (about 900 deg. C) and lower operating temperatures is a major advantage for superior conversion efficiency. However, at present the availability of proven robust long-life low-maintenance commercial Stirling systems is non-existent. In the MW range capacity there appears to be no availability of Stirling units at this moment. Several companies claim to be at the verge of commercial launching of Stirling units, typically below the 25 kWe range which will have many an applications with renewable systems. Therefore it seems Stirling systems will be suitable in the future for multiple parabolic dish type energy farming applications.
- Organic Rankine cycle (ORC) systems are available below the 30 MW range which use inorganic or organic phase change liquids such as CFC or HCFC in a closed loop. The typical net electrical efficiency of such systems lies below 18%.

7. Co-generation Schemes

CSP and desalination has been combined before but this combination is realised in a serial way, i.e. by producing electricity which is then used to drive a Reverse Osmosis desalination process. This offers significant advantages in its own and our considerations trivially reduce to this “minimal integration”. Nevertheless the combination of CSP and desalination technologies is also possible by utilising the heat from the CSP plant for thermal desalination in parallel with the electricity production. This method can overall provide a more efficient co-generation scheme by utilising heat losses and electricity production thermal emissions for desalination. In this case, the extraction or back pressure type of steam turbines is most suitable. A detailed study on appropriate steam turbine system has been performed under this project. In general, the turbine system efficiency improves with the increase in capacity of the plant corresponding to a decrease in cost. It can be seen from Figure 3-1 below that the cost of a turbine reaches attractive values beyond 10 MW level. The typical efficiency of a turbine relative to its capacity is shown below in the Figure 3-2.

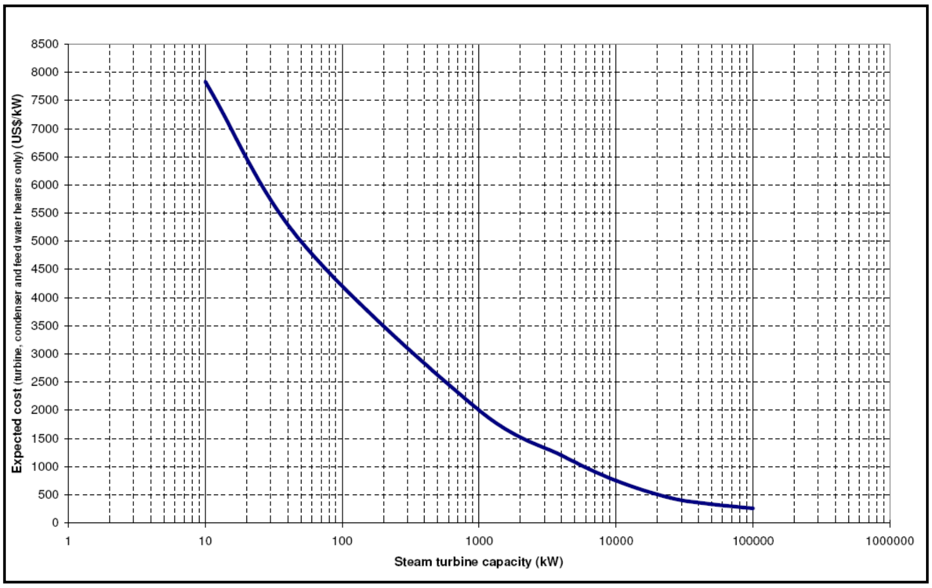

Figure 3-1: Steam turbine capacity vs. Cost [2]

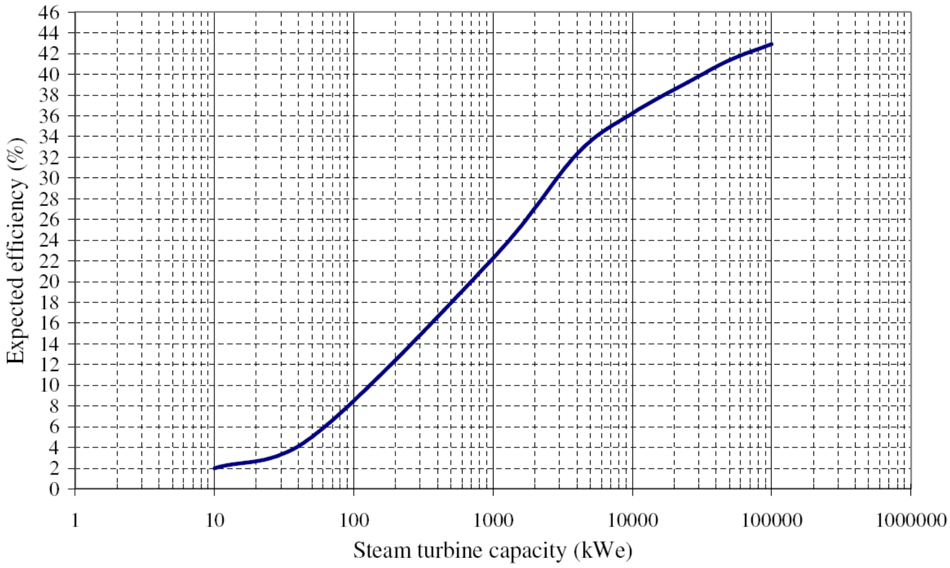

Figure 3-2: Expected turbine efficiency related to its capacity [2]

Normally, the normalized cost of electricity decreases with the increase of the plant capacity not only because of the efficiency gain and cost reduction in the power block but also because the cost of solar collectors follow the economies of scale; plant building as well as operation & maintenance costs increase disproportionally with the increase in the plant size [3]. However in certain CSP systems (i.e. Central Receiver), optical efficiency drops as the field size grows, indicating a smaller rather than a larger size is preferable.

3.4. The Four Major Types of CSP technology

CSP technologies can be classified into two categories with respect to their solar harvesting system:

- Line concentrating systems. In such systems the collectors concentrate the radiation on a long absorber surface
- Point concentrating systems. In such systems the collectors concentrate the direct radiation on an absorber (a receiver) of relatively compact volume.

There are four major types of CSP technology which are based on the above solar harvesting systems. The concept of *'solar chimney'* where the air flow created with the help of collected solar energy is used to operate a wind turbine for electricity production is not generally considered a CSP technology.

3.4.1. Parabolic trough

Technology Description

The parabolic trough is a line concentrating system where a long trough-shaped reflector with a parabolic cross section is utilized for harvesting solar power. A long absorber tube is placed in the focal plane of the trough which acts as the energy receiver. A single axis tracking system ensures that at all times the reflected solar energy focuses on the receiver length. The solar collection field consists of several such parabolic troughs connected in rows and columns and oriented in the north–south horizontal axis forming an array. The heat transfer fluid, which is circulated through the receiver tubes, absorbs the heat energy input reaching temperatures of 390-550^{o} C. The heated fluid is pumped into a central power block area, where it passes through a heat exchanger in which the heat is transmitted to the power process. The array of parabolic trough thus supplies heat to the steam generator of a Rankine cycle system by taking over the role of a fossil fuel powered steam boiler. A basic layout of a Parabolic Trough system is shown in Figure 3-3.

There can be many design variations of the parabolic trough-based CSP plants. The latest concept which is called Integrated Solar Combined Cycle System (ISCCS), involves a combined cycle (CC) which consists of a Gas Turbine (GT), a Heat Recovery Steam Generator (HRSG) and a Steam Turbine (ST). The HRSG produces steam from the remaining heat of the exhaust gases of the Gas Turbine, which is used in the Steam Turbine's bottoming cycle. Hence, the energy in the gas or other fossil fuel, is used in a much more efficient way than in the GT alone. In this design, solar energy is useful as supplementary to the waste heat from GT in order to augment power generation in the steam Rankine bottoming cycle.

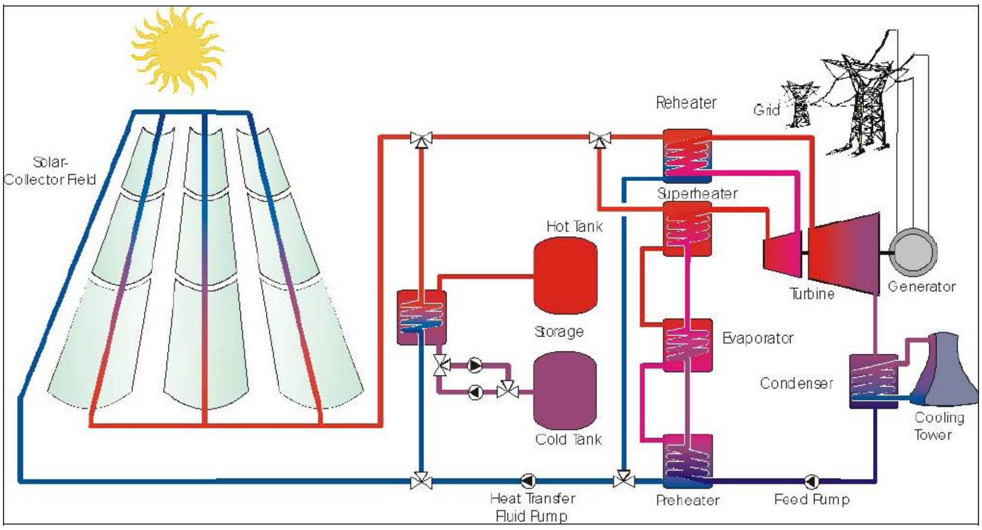

Figure 3-3: Parabolic trough type CSP plant concept [4]

Characteristic projects

Parabolic trough is the most mature CSP technology used at the moment. The first commercial plant started operation in California in 1985. The Solar Electric Generating System (SEGS) is the biggest solar power generation facility of the world so far with a 354 MW total installed capacity, consisting of nine plants, located in the Mohave Desert in California, USA. The details of the nine plants are given below in Table 3-1. It should be noted that the plants are actually hybrid type, with a backup fossil fuel fired (natural gas) capability that can be used to supplement the solar output during low solar radiation.

SEGS Plant	1st Year of Operation	Net Output (MW_e)	Solar Field Outlet Temp. (°C/°F)	Solar Field Area (m^2)	Solar Turbine Eff. (%)	Fossil Turbine Eff. (%)	Annual Output (MWh)
I	1985	13.8	307/585	82,960	31.5	-	30,100
II	1986	30	316/601	190,338	29.4	37.3	80,500
III & IV	1987	30	349/660	230,300	30.6	37.4	92,780
V	1988	30	349/660	250,500	30.6	37.4	91,820
VI	1989	30	390/734	188,000	37.5	39.5	90,850
VII	1989	30	390/734	194,280	37.5	39.5	92,646
VIII	1990	80	390/734	464,340	37.6	37.6	252,750
IX	1991	80	390/734	483,960	37.6	37.6	256,125

Table 3-1: SEGS Plant details [3]

Nevada Solar One is another parabolic trough type plant which is located in the El Dorado valley in Nevada, USA. It has a nominal generating capacity of 64 MW. As with the case of SEGS, it has a supplementary gas firing system.

Andasol Solar Power station is Europe's first commercial parabolic trough type CSP plant, located near Guadix in the province of Granada, Spain. It follows a staged deployment with the first stage becoming operational in November 2008. Each stage has 49.9 MW nominal turbine capacity. This plant uses a two tank molten salt storage system where 28500 ton nitrate salt is being used to provide a 7.5 hours of full load capacity. While charging the storage system heat is transferred to the molten salt tank which collects the heat and the molten salt moves from the cold tank to the hot tank. At the time of discharging the salt cools down and moves to the cold tank. The estimated peak efficiency of the plant is about 28% while annual average is about 15%. A basic schematic of Andasol plant is shown in Figure 3-4.

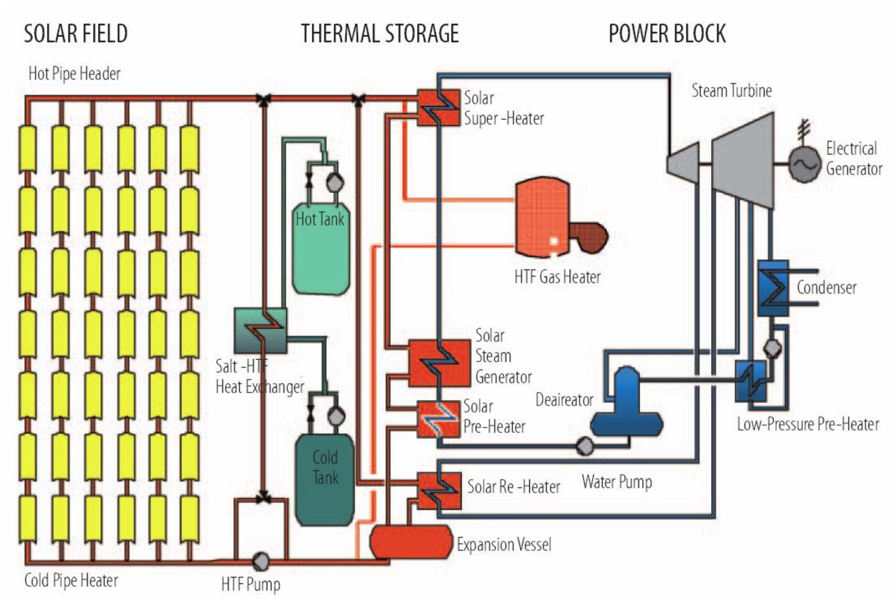

Figure 3-4: Andasol plant schematic [5]

3.4.2. Linear Fresnel

Technology Description

Linear Fresnel is a CSP line concentrating system and has many similarities with the parabolic trough type systems. Linear Fresnel systems have recently been developed by several companies aiming to achieve through a simpler design, lower capital cost than that of the parabolic trough. Linear Fresnel CSP technology derives its name from the type of optical system used which employs a multiplicity of small flat optical faces, which was invented by the French engineer Augustin-Jean Fresnel. These flat or slightly curved optical surfaces are arranged in long parallel lines, and are positioned to reflect direct sunlight into a long target, or receiver, with one surface having a Linear Fresnel concentrator. In a Fresnel system, the parabolic shape of the trough is split into several smaller, relatively flat segments. These are put on a horizontal rag and are connected at different angles to a bar that moves them simultaneously in order to track the sun during the day. Due to this arrangement, the absorber tube can be fixed above the mirrors in the centre of the solar field, and does not have to be moved along with the mirrors during the sun-tracking process. A photograph of Fresnel mirrors is shown in Figure 3-5. Linear Fresnel CSP plants use power blocks which are quite similar to the parabolic trough type systems. The direct steam generation option is also possible. This type of CSP Technology has many appealing features. The Fresnel mirrors are light weight and easy to manufacture. The associated capital costs for such a plant are low when compared to others CSP technologies, while land requirements are not as great. Finally the Fresnel system when compared to the parabolic trough system has a better solar energy yield per square meter of land by a factor of 2 roughly, even though it is less optically efficient than the parabolic trough technology [4].

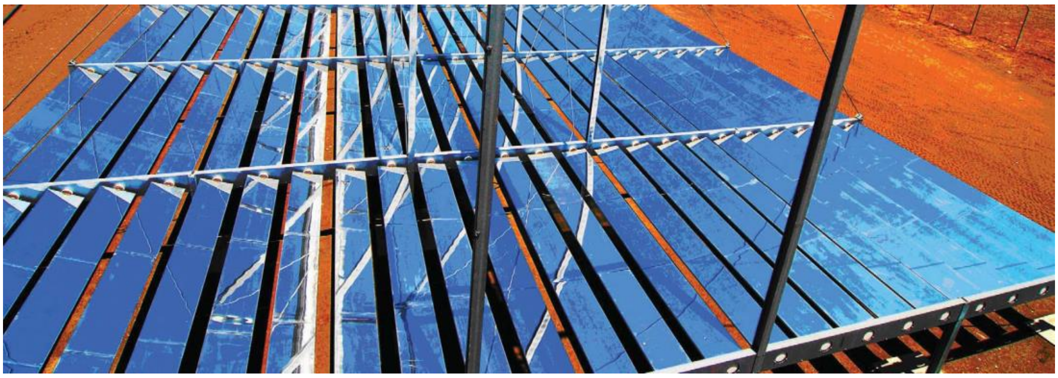

Figure 3-5: Linear Fresnel mirrors [6]

Characteristic projects

The Fresnel type of CSP technology is still at the stage of research and demonstration. Due to the limited experience with this technology, reliability issues are relatively unknown at this moment. Under the joint project FresDemo, the technology supplier Solar Power Group (SPG), the general contractor MAN Ferrostaal, the German Aerospace Agency (DLR) and the

Fraunhofer Institute commissioned a prototype in Almeria, Spain, in 2006, in order to test the capabilities of the Fresnel technology in actual operation. Its configuration involves a steel construction made of standard components which supports several rows of planar primary mirrors. A “receiver unit” has been placed about ten metres above the primary mirrors and consists of a secondary mirror and an absorber tube. The primary mirrors reflect the sunlight onto absorber tubes of the receiver unit, and heat the medium directly. Since part of the reflected sunlight does not meet the absorber tube on first instance, a secondary mirror captures and refocuses most of the dispersed light. With the use of the secondary mirror, it is possible to heat the medium to temperatures of over 420 °C.

In the FresDemo, water is used as the heat transfer medium which allows for direct steam generation, thus circumventing the heat exchanger in the heat transfer fluid loop. In the absorber tube, the concentrated sunlight is converting water to superheated steam (at temperatures up to 450°C) which drives a steam turbine to produce electricity.

In May 2008, the German Solar Power Group GmbH and the Spanish Laer S.L. agreed to jointly construct a solar thermal power plant in central Spain and specifically in Gotarrendura, a small village, about 100 km northwest of Madrid. When completed, it will be the first commercial solar thermal power plant in Spain based on the Fresnel collector technology of the Solar Power Group. The planned size of the plant will be 10 MWe and it will combine a solar thermal collector field with a fossil fuel co-firing unit as a backup system.

3.4.3. Parabolic Dish

Technology Description

The Parabolic Dish CSP technology falls under the point concentrating category. The system consists of a parabolic concentrator which focuses the sunlight onto a point-receiver and a power generation system. The concave surface of the parabolic concentrator is covered either by glass-surface mirrors or by front-surface-silvered or aluminized reflective films. In order to track the sun the collectors are equipped with a two-axis tracking system. The receiver absorbs energy reflected by the concentrator which is then transferred to the engine’s working fluid. The absorbing surface is usually placed behind the focus of the concentrator to reduce the incoming flux intensity. An aperture is placed at the focus point to reduce radiation and convection heat losses.

A number of thermodynamic cycles and working fluids have been considered for the Dish-Engine systems. These include Rankine cycles which use water or an organic working fluid, both open and closed Brayton cycles, and Stirling cycles. The heat engines that are generally favoured are those with the Stirling and open Brayton (gas turbine) cycles. A supplementary gas burner is usually present to allow operation during cloudy weather and during the night. Electrical output in the current prototypes is about 25 kWe for Stirling system and about 30 kW for the Brayton systems. Smaller 5 to 10 kWe Stirling systems have also are being developed.

Parabolic dishes can be arranged either individually or in a distributed field arrangement:

- **Individual systems.**

  Each individual system is equipped with a power conversion unit so that each dish delivers electricity. Due to its high concentration ratio it achieves high temperature heat which can be transformed through high efficient power converters such as a Stirling engine. They can be combined to form a CSP plant. Such a plant is shown in Figure 3-6.

- **Distributed field systems.**

  Distributed systems comprise of several dishes with a common central conversion unit which transforms heat into electricity. This arrangement offers two basic advantages over the individual systems, namely the lower investment cost for a single central conversion unit, and the ability to incorporate a bulk thermal storage unit. However the heat losses due to heat transfer fluid transportation over long distances becomes a major drawback.

The Parabolic dish is a very versatile technology with several applications. It has inherent modularity and capability to accommodate hybridisation with fossil fuelled firing systems. It can be deployed as a standalone power generator for specific applications in remote locations, as a cluster forming a mini-grid, and even as a utility-level grid.

Figure 3-6: Solar Dish power plant, Almeria, Spain

Characteristic projects

The technology is at the engineering development stage and some technical challenges still remain concerning the solar collection components and the commercial availability of suitable engines which could be coupled to the system.

Solar Power Plant	***First Year of Operation***	***Net Output [MWel]***	***HTF/ Power Conversion Unit***	***Additional Features***
Distributed Arrangement				
Sulaibyah, Kuwait	*1981*	*0.4*	*Thermal Oil, water/steam*	*MBB dishes*
Shenandoa, USA	*1982*	*0.4*	*Thermal Oil, water/steam*	*GE dishes*
Warner Springs, USA	*1983*	*4.9*	*Water/Steam*	*LaJet dishes*
White Cliffs, Australia	*1985*	*0.025*	*-*	*ANU*
Australia	*1992*		*Water/Steam*	*ANU*
Individual Units				
Rancho Mirage, USA	*1983*	*0.025*	*Stirling Motor*	*Individual-facet Vanguard*

Los Angeles, USA	*1984*	*0.025*		*Individual-facet, MDAC-25*
Warner Springs, USA	*1987*			*Individual stretched membrane facets*
Osage City, USA	*1987*			
Saudi Arabia	*1984*	*0.05*	*Stirling Motor*	*SBP, stretched membrane*
Freiburg, Germany	*1990*			*Fixed focus, Bomin Solar*
Lampoltshausen, Germany	*1990*		*Stirling Motor*	*SBP, stretched membrane, 2nd generation*
Almeria, Spain	*1990-1995*		*Stirling Motor*	*SBP, stretched membrane*

Table 3-2: A few dish type CSP initiatives

In March 2008, Stirling Energy Systems, in conjunction with Sandia National Laboratories, achieved a new world record of solar-to-grid system conversion efficiency of 31.25%, significantly beating the previous record of 29.4% set in 1984.

In California, the Arizona-based Stirling Energy Systems Inc. plans to install 20,000, 11.5-metre diameter solar dishes with a total capacity of 500 MW, in the Imperial Valley east of San Diego. In the subsequent phases, Stirling could expand the project up to a capacity of 1,750 MW which would involve 70,000, 90 m^2 solar dishes. Various projects using this technology are described in Table 3-2.

3.4.4. Central Receiver (Power Tower)

Technology Description

The Central Receiver falls under the point concentrating type of CSP technologies. The usual realisation of this CSP technology is the Solar Tower system which has a single receiver placed on top of a tower surrounded by a large number of mirrors (heliostats) which follow the motion of the sun in the sky and which re-direct and focus the sunlight onto the receiver. The key elements of a solar tower system are the heliostats coupled to a two-axis tracking system, the receiver, the steam generation system and the storage system. The number of heliostats will vary according to the particular receiver's thermal cycle and the heliostat design. Radiation is concentrated at the central receiver. The energy is then transported via a heat transfer fluid to a Rankine or less often a Brayton Cycle. The central receiver is designed to receive very high concentrations of solar irradiation and subsequently operates at high temperatures in the receiver coolant. As the central receiver is designed to collect solar energy by optical rather than by thermal means, it avoids heat losses from insulated piping that is needed to connect the concentrators in the distributed collectors of a parabolic trough system (although it suffers from various other optical losses, such as cosine, blocking shading, spillage, etc.). The heat loss from the piping and from large absorber surfaces in the distributed design leads to a lower operating temperature for the thermal conversion cycle.

Different Heat transfer fluids can be used in the central receiver. The most common are the following:

- Water/Steam
- Molten salts
- Air at atmospheric pressure
- Liquid metals (sodium)
- Pressurized air

Accordingly, there are a few design variations like molten salt receiver, saturated steam receiver, atmospheric air receiver, pressurized air receiver etc.

- In the case of a Brayton cycle, which can achieve temperatures over 1,400°C, pressurized air is used and has to be heated in the receiver.
- In the case of Rankine cycles, the heat of the absorber coolant is transferred to the water/steam cycle. The temperature is limited to 565°C due to material restrictions.
- In a molten-salt solar tower, liquid salt at 290^{o} C is pumped from a 'cold' storage tank through the receiver where it is heated to 565^{o} C and then on to a 'hot' tank for storage. When power is needed, hot salt is pumped to a

steam generating system that produces superheated steam for a conventional Rankine cycle utilising a turbine for power generation. From the steam generator, the salt is returned to the cold tank where it is stored and eventually reheated in the receiver.

Characteristic projects

There have been several attempts to build central receiver type CSP plants. Some of those are listed in the Table 3-3.

Solar Power Plant	*First Year of Operation*	*Net Output [MWel]*	*HTF*	*Thermal Energy Storage*	*Status*
Adrano, Italy	*1981*	*1*	*Water/steam*	*Eutectic salt*	*Demonstration*
Nio, Japan	*1981*	*1*	*Water/saturated steam*	*Steam*	*Demonstration*
IEA-SSPS, Almeria, Spain	*1981*	*0.5*	*Sodium*	*Sodium*	*Demonstration*
Targasonne, France	*1982*	*2.3*	*Salt*	*Salt*	*Demonstration*
Solar 1, Barstow, USA	*1982*	*10*	*Water/steam*	*Oil*	*Pilot*
CESA 1, Alemeria, Spain	*1983*	*1*	*Water/steam*	*Salt*	*Demonstration*
Crimea; USSR	*1988*	*5*	*Water/saturated steam*	*-*	*Demonstration*
Solar II, Barstow, USA	*1995*	*10*	*Salt*	*Salt*	*Pilot*
TSA, Almeria, Spain	*1995*	*2.5 MWt*	*Air, Water/steam*	*Salt*	*Demonstration*
PS-10, Near Sevilla, Spain	*2006*	*10*	*Water/Steam*	*Steam storage*	*Demonstration*
GAST-20 study, Spain	*-*	*-*	*Air*	*Salt*	*Concept*
PHOEBUS, Jordan	*-*	*-*	*Air, water steam*	*Salt*	*Concept*
COLON SOLAR, Spain	*-*	*10*	*Water/Steam*	*-*	*Concept*
Solar Tres, Spanien	*-*	*15*	*Water/steam*	*Salt*	*Concept*

Table 3-3: A few central receiver type CSP plants

The PS 10 plant which started its operation in 2007 in Sanlucar de Mayor in Sevilla, Spain, is the world's first commercial solar tower CSP plant. The plant's schematic is shown in Figure 3-7. It has a nominal power output of 11 MW with an annual capacity factor of 25%. The heliostat field consists of 624 units of 120 m^2 each. This plant uses a water/steam storage system with a thermal storage capacity of 20 MWh which corresponds roughly to 50 minutes supply at a 50% rate. It has also an option for natural gas combustion. The total efficiency of the plant is about 17%.

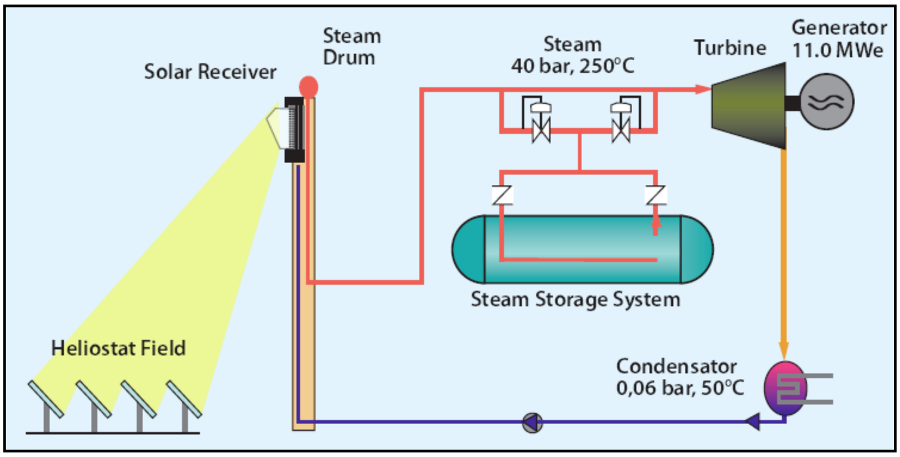

Figure 3-7: PS 10 plant schematic [5]

The solar thermal energy plant Planta Solar 20 (or PS20) is located in Sanlucar la Mayor in Spain near Seville and has started its operation in April 2009. It is based on the general PS10 concept with a power tower of 165m height and has an output of 20MW. It is considered the most powerful central receiver plant in the world at the moment employing 1,255 heliostats, each with a 120m² mirror surface. The PS20 tower boasts important improvements in almost all of its components from the receiver to the storage system compared to its predecessor.

Solar Two (before its decommissioning in 1999) was a 10 MW Power Tower facility in the Mojave Desert in the USA. It was built as an expansion of the previous Solar One facility and became operational in 1995. It consisted of 1926 heliostats with a total mirror surface area of over 82,000 m^2. Solar Two also employed a thermal storage solution for continuing operation during night-time and overcast. As storage medium, molten nitrate salts were used in a two-tank configuration.

SOLAR TRES is another Solar Tower plant which is under construction at the moment in Ecija, close to Seville in Spain. The name of the plant has been changed to Gemasolar. The nominal output power is expected to be 17 MW and it incorporates the two tank molten salt storage solution. It will use 6250 tonnes of salt that could provide power for 17 hours. The 2480 heliostats will amount to a reflecting surface of 285200 m^2 area with land coverage of 142 hectares. The estimated annual electricity generation will be at the 96.4 GWh range with an overall plant efficiency of 14%. It is expected that the plant will have 24 hours operation during summer and will reach annual capacity factor of 65%. The schematic of this plant is depicted in Figure 3-8.

In the summer of 2009, Sierra Sun Tower plant was commissioned. This is so far the only CSP power tower type plant which is operational in North America. It has 5 MW generation capacity with 20 acres of land, 2 towers and 24,000 heliostats.

The DESERTEC project is an ambitious endeavour to set-up a large-scale complex of power production plants in the Sahara desert using CSP technologies. Electricity produced will be transmitted to European and Middle East and North Africa (MENA) countries through a super grid of High Voltage Direct Current (HVDC) lines. The initiative is led by a group of European and African companies (DESERTEC Industrial Initiative – DII) in collaboration with the DESERTEC Foundation. It is expected that by 2012 the analysis and the establishment of a framework for investments for electricity from renewables will be completed.

The long-term goal is by 2050 through the DESERTEC project, 15% of Europe's electricity demand and most of the MENA's countries will be accomplished [7]. The proposed network map of DESERTEC initiative is shown in Figure 3-9.

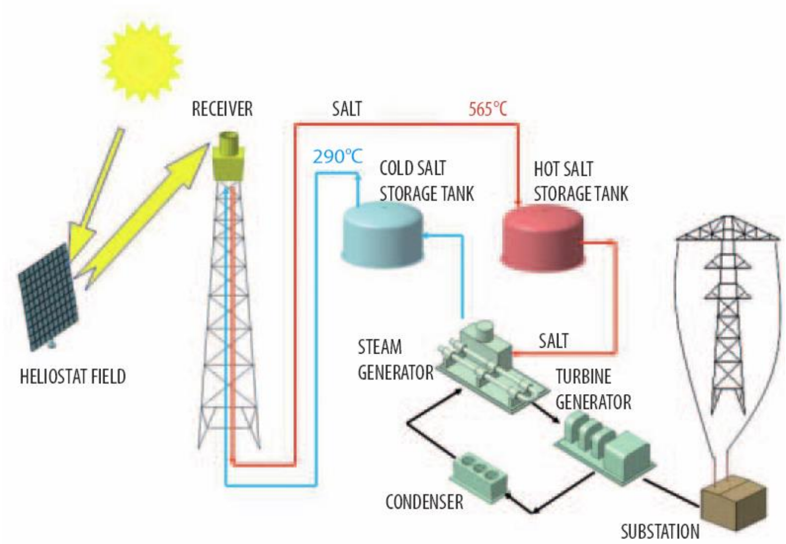

Figure 3-8: SOLAR TRES plant schematic [5]

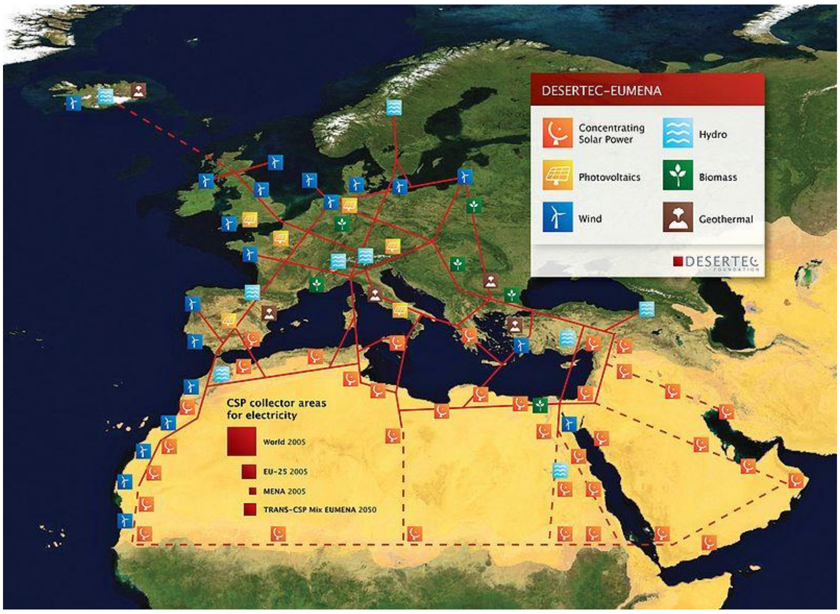

Figure 3-9: DESERTEC map [7]

3.5. A few important aspects of CSP

3.5.1. Storage

A critical advantage of CSP plants is the ability to store thermal energy. The existence of a thermal storage subsystem, almost definitely implies an oversized collector subsystem relative to the one need for rated design point output in order to enable plant output and thermal storage simultaneously. The ratio of the collector subsystem's output power at the design point to that needed by the power conversion units for generating nominal output is called 'Solar Multiple' (SM). It is possible to charge the thermal storage by the excess energy collected with SM greater than 1. A CSP system without storage only operates at its design point for a few hours within a year with solar multiple of one, while over-sizing the system allows it to operate closer to the design point for more hours per year. The system with the oversized solar field produces more electricity, thereby reducing the system's levelized cost of energy. However, there is a trade-off between the increased installation cost of the larger system and the increased electric energy output. As the solar field size increases beyond a certain point, the higher cost outweighs the benefit of the higher output. Adding storage to the system introduces an additional level of complexity. Systems with storage can increase output by storing energy from an even larger solar field for use during times when the solar field output is below the design point, but the thermal energy storage system's cost and thermal losses have a negative effect on the levelized cost of energy.

The thermal storage system can act as an internal plant buffer which smoothes the effect of fluctuations in insolation and helps normalise plant operation. It most crucially allows operation during the night or unfavourable weather. Usually heat capacity is given in kWh per cubic meter. Some of the existing storage systems are shown in Table 3-4.

The storage media can be classified mainly in the following ways:

- **Sensible thermal storage.**

  Heat stored in substances that experience a change in internal energy due to temperature change. Heat can be stored by means of solid or liquid media. The solid medium, preferably with good heat capacity, is arranged in packed beds exchanging heat with a fluid. Solid media such as reinforced concrete, NaCl (solid), cast iron, cast steel, silica fire bricks, and magnesia fire bricks are the most commonly used substances. The liquid media are able to maintain natural thermal stratification as a result of thermal differences between the hot and cold fluid. Technical considerations regarding mixing must also be taken into account. Typical liquid storage media are synthetic oil, silicone oil, nitrite salts, nitrate salts, carbonate salts and liquid sodium. The utilization of their heat capacities is constrained by the upper operation temperature of the CSP plant.

- **Latent heat storage**.

  Isothermal storage of thermal energy from the latent heat of the phase change of specific substances. The substances are called phase change materials (PCM) and they offer the advantage of reduced size in comparison with the Sensible thermal storage. The main disadvantage is that PCMs degrade after a number of cycles. Typical PCMs used in storage systems are $NaNO_3$, KNO_3 and KOH.

- **Chemical storage**

  Thermal energy storage by means of chemical reactions which need to be reversible. Usually catalysts are needed to release the heat, but have the additional advantage, that the reaction can be controlled by the catalyst. Although reversible thermo-chemical reactions have several advantages, uncertainties regarding their thermodynamic properties over a wide range of operating conditions, make them not viable currently.

According to the International Energy Agency (IEA), the Levelized Energy Cost (LEC) is reduced by adding more storage up to a limit of about 13 hours (~65% capacity factor) [8]. While it is true that storage increases the cost of the plant, it is also true that plants with higher capacity factors have better economic utilization of plant equipment such as the turbine. Since salt storage is inexpensive, reductions in LEC due to increased utilization of the turbine more than compensates for the increased cost due to the addition of storage.

Project	*Type*	*Storage Medium*	*Cooling Loop*	*Nominal Temperature Cold /Hot °C*		*Storage Concept*	*Tank Volume m³*	*Thermal Capacity MWh$_t$*
Irrigation Pump Coolidge, AZ	*Central receiver*	*Oil*	*Oil*	*200*	*228*	*1 Tank Thermo-cline*	*114*	*3*
IEA-SSPS Almería, SP	*Parabolic trough*	*Oil*	*Oil*	*225*	*295*	*1 Tank Thermo-cline*	*200*	*5*
SEGS I Dagget, CA	*Parabolic trough*	*Oil*	*Oil*	*240*	*307*	*Cold-Tank Hot-Tank*	*4160 4540*	*120*
IEA-SSPS Almería, SP	*Parabolic trough*	*Oil/Cast Iron*	*Oil*	*225*	*295*	*1 Dual Medium Tank*	*100*	*4*
Solar One Barstow, CA	*Central receiver*	*Oil/sand/ rock*	*Steam*	*224*	*304*	*1 Dual Medium Tank*	*3460*	*182*
CESA-1 Almería, SP	*Central receiver*	*Liquid salt*	*Steam*	*220*	*340*	*Cold-Tank Hot-tank*	*200 200*	*12*
THEMIS Targassone, FR	*Central receiver*	*Liquid salt*	*Liquid salt*	*250*	*450*	*Cold-Tank Hot-Tank*	*310 310*	*40*
Solar Two Barstow, CA	*Central receiver*	*Liquid salt*	*Liquid salt*	*275*	*565*	*Cold-Tank Hot-Tank*	*875 875*	*110*

Table 3-4: Some of the existing storage systems with CSP projects

IEA has published the following Table 3-5 where it can be seen that molten salt storage system with power tower is the most attractive option among three options considered.

	Installed cost of energy storage for a 200 MW plant ($/kWhr$_e$)	Lifetime of storage system (years)	Round-trip storage efficiency (%)	Maximum operating temperature (°C/°F)
Molten-Salt Power Tower	30	30	99	567/1,053
Synthetic-Oil Parabolic Trough	200	30	95	390/734
Battery Storage Grid Connected	500 to 800	5 to 10	76	N/A

Table 3-5: Comparison of storage systems for a hypothetical 200 MW plant [8]

Today's commercial CSP plants use either two tank molten salt or steam accumulator systems.

Molten salt systems with two tanks

A liquid storage medium is pumped between two storage tanks. During the storage process, the cold storage medium is extracted from the first tank, heated by solar energy and stored in the second tank. During discharge, the hot storage medium flows from the second tank to the power cycle, provides energy and is then pumped to the cold tank. If the storage medium is not used as a heat transfer medium in the solar absorber units, a separate working fluid can transfer the energy in a heat exchanger to the storage medium during the charging process. Usually, the storage medium is at atmospheric pressure. A mixture of $NaNO_3$ and KNO_3 is usually applied. This has a freezing point of approximately 230 °C.

This concept was demonstrated within the Solar Two project (110 MWh capacity, 1.400 t of molten salt, 290 °C / 565 °C) and is also used for the Andasol power plants (1.010 MWh capacity, 28.500 t of molten salt, 292 °C / 386 °C).

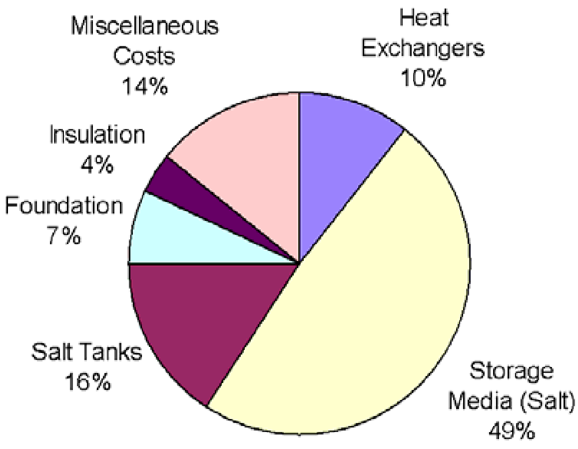

Figure 3-10: Typical capital cost structure of two tank molten salt system [9]

Steam accumulator systems

Steam accumulators use pressurized water for the storage of sensible heat. During the charging process, steam is fed into a pressurized vessel filled for the most part with saturated liquid water. The liquid water volume is heated by the inflowing steam. During discharging, steam accumulators provide saturated steam at a declining pressure.

Concept	***Strengths***	***Weaknesses***
Two tank molten salt	*Provides heat at constant temperature during discharge* *Good behavior during partial charge* *Using storage medium as the working fluid in the solar field can be possible*	*Risk of irreversible freezing* *Complex initial feeling procedure* *Total cost of the storage system strongly dependent on the cost of the storage medium (salt)*
Steam accumulator	*Low response time* *High volume-specific power* *Well established operating experience in process industries*	*-Temperature not constant during discharge* *-Storage capacity limited* *- Large pressure vessel required* *- Cost attractive only for small pressures*

Table 3-6: Strength and weaknesses of the two common CSP storage systems

Due to the non-linear correlation between saturation pressure and saturation temperature, steam accumulators are preferred for low pressure applications. The PS10 central receiver power plant uses steam accumulators with a total storage capacity of 20 MWh, providing saturated steam at 20 bar. The Table 3-6 lists the main strengths and weaknesses of these two concepts.

The following three kinds of thermal energy storage are at the research and development phase at present and possess future potential for real life applications:

Thermocline with filler material

The capital costs for the two-tank concept depend strongly on the costs of the storage material. One option for reducing costs is the partial replacement of the molten salt by a low cost filler material. Instead of two tanks, only a single tank is used in this scheme. During the charging process, hot molten salt enters the top of the storage vessel while colder molten salt exits the bottom. For the Thermocline concept compatibility of the filler material and the molten salt is of particular importance.

Packed bed with air as heat transfer fluid

In this system, hot air, heated within power plants or various industrial processes, flows through an atmospheric regenerative heat exchanger storage system. In principle, pressurized operation is also possible. The heat can be stored in various materials such as low-cost natural stone, ceramics arranged as packed beds or honeycombs and regularly shaped refractory brickwork in applications up to 1000° C, and more. Since the air passes directly over the storage material to charge or discharge the storage, no additional heat exchanger is needed.

Concrete storage with embedded heat exchanger

Concrete is one of the lower-cost materials used for thermal storage. A heat exchanger is integrated into the storage volume to transfer energy from the working fluid to the storage medium. Since low cost storage materials usually show low thermal conductivities, a large heat transfer area is required. As a result, the costs for the heat exchanger are the dominant, in the costing of the whole system. This concept has been demonstrated using a 400 kWh concrete storage module operated between 300 °C and 400 °C. This technology is applicable up to 400 °C.

3.5.2. Capacity factor

Practically no power plant based on fossil, nuclear or renewable energy sources, operates at the nominal output capacity for the entire year. Specifically, a CSP plant cannot maintain continuous output for extended periods with a finite storage capacity and solar energy as the only input. Although there is a difference between base-load and peak type plants with respect to their capacity factor and the value of energy supply, as a general rule, the higher the capacity factor, the better the utilization of the plant. Assuming an equal level of operational reliability, CSP plants without storage will have the lowest capacity factor. One of the performance indicators regarding the maturity of the plant is related to the comparison of the observed capacity factor with the calculated/predicted value.

3.5.3. Major factors influencing performance

a. Irradiation conditions

CSP plants utilise the direct solar radiation. The sun tracking mechanism enables a plant to maximise energy harvest to use as effective input. Thus Direct Normal Irradiance (DNI) values for a specific location are of the utmost importance to any CSP project. Insolation is usually given in the annual distribution of hourly averages of DNI values in kW/ m2 or in terms of annual distribution of daily averages (kWh/m2 per day). Some criteria for minimal irradiation conditions have been reported by Winter et al. [1]. For normal operation of CSP plants with SM = 1 and without auxiliary input, the minimum need is 300 W (DNI) / m2 daily average irradiation and at least 3 hours above 600 W (DNI) / m2 for net output. In the same report, it is also mentioned that from experimental CSP plants the following energy input thresholds ranges were suggested for SM=1:

- parabolic dish: 1.0 - 1.5 kWh (DNI) / m^2 d

- parabolic trough: 2.0 - 3.0 kWh (DNI) / m^2 d
- central receiver: 3.0 – 4.0 kWh (DNI) / m^2 d

It is expected that advanced CSP plants will have smaller thresholds.

DNI is very much location-specific due to geographic characteristics, local weather and air quality (like aerosols, dust, haze etc.) conditions. Thus high quality, locally obtained, solar radiation data from an extended time period are very important for site selection, design and performance predictions of a CSP plant.

b. Energy storage size

It is technically possible to achieve 24 hours of output power generation by using a large enough thermal storage unit coupled with a CSP plant. However this has not yet been implemented in any of the existing CSP facilities mainly due to the high cost involved and the storage at relatively low temperatures. The size of a storage subsystem has to be matched and optimised with the collector subsystem. Effective deployment of a storage capability will increase operating hours and, correspondingly, the capacity factor of a CSP plant.

c. Energy inventory, flexibility and threshold

Winter et al. have stated the importance of thermal inventory (commonly known as thermal mass), in addition to energy stored in a dedicated storage system, which can be helpful to operationally bridge short interruptions in solar energy input caused by passing clouds [1]. This is linked to the inability of fast adjustments to sudden changes in input conditions. The smaller the thermal inertia, the higher the probability of a net output generation under non-steady-state operating conditions.

A CSP plant needs energy to maintain its own operation and even during operational stand-by condition it consumes certain amount of energy. A small auxiliary power consumption (parasitic power) of a CSP plant and low operating thresholds are important design objectives.

d. Water availability

A major limiting factor for CSP plants is the availability of water to be used in the Rankine Cycle system. CSP plants function best in areas with little rain and, therefore in regions where water is naturally less available. They require massive amounts of water to operate, and for every MWh of electricity produced about 4500 to 5500 litres of water is required [10]. Although in principle, it is possible to substitute water-based cooling by dry-cooling systems, it would reduce the annual efficiency of up to 10% [3].

CSP plants in islands like Cyprus have a clear advantage because of this water dependency. Moreover, a co-generation of electricity and desalination from sea water would bring down even further the net water requirement in the system by completely or partially replacing the cooling water loop by MED type thermal desalination plant.

e. Cleanliness

The optical performance of the solar collector field deteriorates by dust, soil and other tiny particles over the reflecting surfaces. Thus it is very important to have a regular and effective cleaning schedule.

f. Maturity and reliability

Of extreme importance is the degree of maturity and reliability of all components of the CSP plant. High operational efficiency is directly linked to technical reliability of subsystems which in turn is connected to the technical maturity of the technology. There are several research, demonstration and pilot type efforts worldwide on these issues for specific elements (e.g. heliostats, receivers, collectors etc.). However, there is a lack of consistent, multi–year performance data from the existing CSP plants as a whole. This is an information deficit of high importance.

3.6. Discussion

The German Aerospace Agency (DLR) undertook the ECOSTAR (European Concentrated Solar Thermal Road Mapping) study during 2003-2005 under the European Sixth Framework Programme where several different CSP designs were analysed and compared under certain assumptions [11]. According to this study, the molten salt type central receiver system had the high solar capacity factor of 33% followed by parabolic trough (29%) and parabolic dish (22%). The Levelized Energy Costs for a solar – only power facility consisting of several reference CSP systems with a total capacity of 50 MW were also estimated in ECOSTAR. Molten salt central receiver system have the lowest energy cost of 0.155 Euros/ kWhe followed by the parabolic trough (0.172 Euros/kWhe) and the parabolic dish (0.193 Euros/ kWhe) [11].

	Capacity Unit MW	Concen-tration	Peak Solar Efficiency	Annual Solar Efficiency	Thermal Cycle Efficiency	Capacity Factor (solar)	Land Use m²/MWh/y
Trough	10 – 200	70 - 80	21% (d)	10 – 15% (d)	30 – 40 % ST	24% (d)	6 - 8
				17 – 18% (p)		25 – 90% (p)	
Fresnel	10 - 200	25 - 100	20% (p)	9 - 11% (p)	30 - 40 % ST	25 - 90% (p)	4 - 6
Power Tower	10 – 150	300 – 1000	20% (d)	8 – 10 % (d)	30 – 40 % ST	25 – 90% (p)	8 - 12
			35 % (p)	15 – 25% (p)	45 – 55 % CC		
Dish-Stirling	0.01 – 0.4	1000 – 3000	29% (d)	16 – 18 % (d)	30 – 40 % Stirl.	25% (p)	8 - 12
				18 – 23% (p)	20 – 30 % GT		

d=demonstrated; p=projected; ST=steam turbine; CC=combined cycle;

Table 3-7: performance data for various CSP technologies [4]

With regards to the solar energy efficiency of the system, the Central Receiver type has the best theoretical values. Although the parabolic dish type system has actually demonstrated the highest annual solar efficiency of 16-18%, the projected annual solar efficiency of a central receiver can reach up to 25% [4]. In the year 2007 the German Aerospace Agency conducted another study called Aqua–CSP (Concentrating solar power for sea water desalination) where performance data for various CSP technologies were estimated. Tables 4-7 and 4-8 have been taken from this study.

It is to be noted here that despite having the advantage with high temperature and efficiency parameters, a central receiver type CSP plant requires large amount of land. Nevertheless, parabolic trough plants need horizontal flat surface, while only the Central type plant can be built utilising uneven land terrain and in steep hilly slopes. Linear Fresnel plants can be built on little slopes or mild uneven surfaces.

Concentration Method	line concentrating system		point concentrating system	
Solar Field Type	**Parabolic Trough**	**Linear Fresnel**	**Central Receiver**	**Parabolic Dish**
State of the Art	commercial	pre-commercial	demonstrated	demonstrated
Cost of Solar Field (€/m²)	200 - 250	150 - 200	250 - 300	> 350
Typical Unit Size (MW)	5 - 200	1 - 200	10 - 100	0.010
Construction Requirements	demanding	simple	demanding	moderate
Operating Temperature	390 - 550	270 - 550	550 - 1000	800 - 900
Heat Transfer Fluid	synthetic oil, water/steam	synthetic oil, water/steam	air, molten salt, water/steam	air
Thermodynamic Power Cycle	Rankine	Rankine	Brayton, Rankine	Stirling, Brayton
Power Unit	steam turbine	steam turbine	gas turbine, steam turbine	Stirling engine
Experience	high	low	moderate	moderate
Reliability	high	unknown	moderate	high
Thermal Storage Media	molten salt, concrete, PCM	molten salt, concrete, PCM	molten salt, ceramics, PCM	molten salt, ceramics, PCM
Combination with Desalination	simple	simple	simple	Simple
Integration to the Environment	difficult	simple	moderate	Moderate
Operation requirements	demanding	simple	demanding	Simple
Land Requirement	high	low	high	Moderate

Table 3-8: Comparative summary of different CSP technologies [4]

Parabolic trough plants are most matured, proven and reliable systems among all types of CSP technologies today, however, they have a low temperature yield. On the other hand, central receiver type plants seem to be more suitable for high temperature applications, higher efficiency along with extended thermal storage possibilities despite the weakness that there still exist a lack of operational experience and degree of maturity in this direction.

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Chapter 4. Desalination of Seawater: Technology & State-of-the-Art (with emphasis on Cyprus)

4.1. Motivation & Background: Desalination with Solar Energy

Facing increasing demand for new sources of fresh water, many coastal communities (for example, in the Eastern Mediterranean region) are considering building desalination of seawater (DSW) plants driven by renewable energy sources. Recent studies (DLR AQUA-CSP 2007 [1]) indicate that the coupling between a closed power cycle (driven by concentrated solar power, or CSP) and water desalination (Figure 4-1 (a)) is both technically feasible and economically viable. A well-integrated power plant and desalination system has much higher energy utilization (close to 100%) than when generating electricity and desalinating water separately (close to 30%). CSP-DSW dual-purpose plants do not yet exist. Since CSP typically drives a thermal engine (Rankine cycle), it is imperative to optimize the dual plant to maximize economic profit, and this requires significant investment and careful engineering design of all subsystems.

(a)

(b)

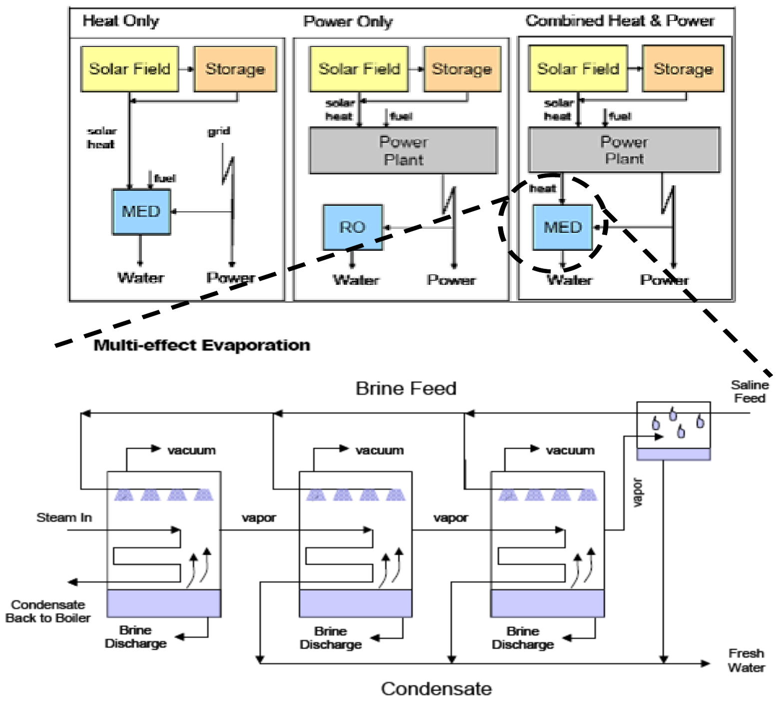

Figure 4-1: (a) Basic CSP-DSW concept, from the DLR AQUA-CSP Study Report, 2007; (b) MED desalination (schematic from Miller, 2003).

The first aim of this review is to survey the most promising technologies available for the integration of the power and desalination cycle under the CSP-DSW concept. Although a plethora of methods have been proposed for desalination using renewable resources [2,3,4], two classes of desalination methods appear to be the most promising, in the sense that they are industrially tested and proven to be efficient: membrane-based methods, such as Reverse Osmosis (RO), and thermal desalination methods, such as Multiple Effect Distillation (MED), Figure 4-1(b).

There seems to be a considerable confusion in the literature about the energetic cost of desalinating water with these methods. This stems partly from inaccurate reporting of the operating conditions employed, and failure to normalize the energy estimates before attempting to compare performances and discuss the relative merits of the various schemes. In some cases, the estimates are plainly wrong. It is the second aim of this review to reduce this confusion by deriving independent estimates of the energetics of RO and MED from thermodynamic, heat transfer, fluid mechanics, and best practice considerations. For definitiveness, we will frame the discussion in the context of a dual-purpose plant in the coastal area of the island of Cyprus, as abstracted in Appendix A.1 designed to produce electricity for the grid and potable water containing less than 500 ppm TDS. Information regarding the elemental composition of Cyprus seawater can be found in Appendix A.2, while oceanographic data regarding temperature and salinity distribution are given by Painter and Tsimplis [5].

Driven by rising energy costs and water scarcity, the drive towards the design, construction, and operation of a dual-purpose CSP-DSW plant is relentless. Innovative solutions to the problem of thermal energy storage, which will decouple CSP from fossil or nuclear fuel sources, will make the concept of an independent utility-scale CSP-DSW plant a reality. *It is the third aim of this review to point in the direction of an optimum integration of RO/MED with a CSP-driven power plant.* By reviewing existing dual purpose and hybrid plants, we will discuss the available technological solutions and selection criteria for a small (4-10 MWe) plant on Cyprus.

Acronyms and Symbols

CSP-DSW	Concentrated solar power - desalination of seawater
GOR	Gained Output Ratio
MED	Multi-Effect Distillation
MSF	Multistage Flash Distillation
kWe, MWe	Power units in terms of electrical equivalent
PR	Performance Ratio (MED)
Q_P	Process Thermal Power
Q_X	Harvested Thermal Power
RO	Reverse Osmosis
TDS	Total Dissolved Salts
TVC	Thermal Vapour Compression

4.2. Reverse Osmosis (RO)

4.2.1. RO Technology

A typical Reverse Osmosis (RO) process has three stages: pre-treatment, RO filtration, and post-treatment (Figure 4-2). The first stage includes chlorine disinfection, adjustment of pH, and coagulation and flocculation before the filtration unit, followed by the addition of chemicals to reduce scaling and fouling, and the removal of chlorine after the filtration unit. The pre-treatment stage removes silt, colloids, and some organics from the seawater, and it creates RO feed water with a silt density index, SDI[2], less than 1, greatly reducing the need for complex cleaning of the RO membrane itself. Measurements in the Larnaca (Cyprus) seawater RO desalination plant (one of the largest in Europe) indicate that seawater feed has 1.5<SDI <3.5 [6]. These conditions require pre-treatment which involves backwashing and an additional energy for cleaning. Backwashing adds to the energy requirements for RO, but the details are rarely reported.

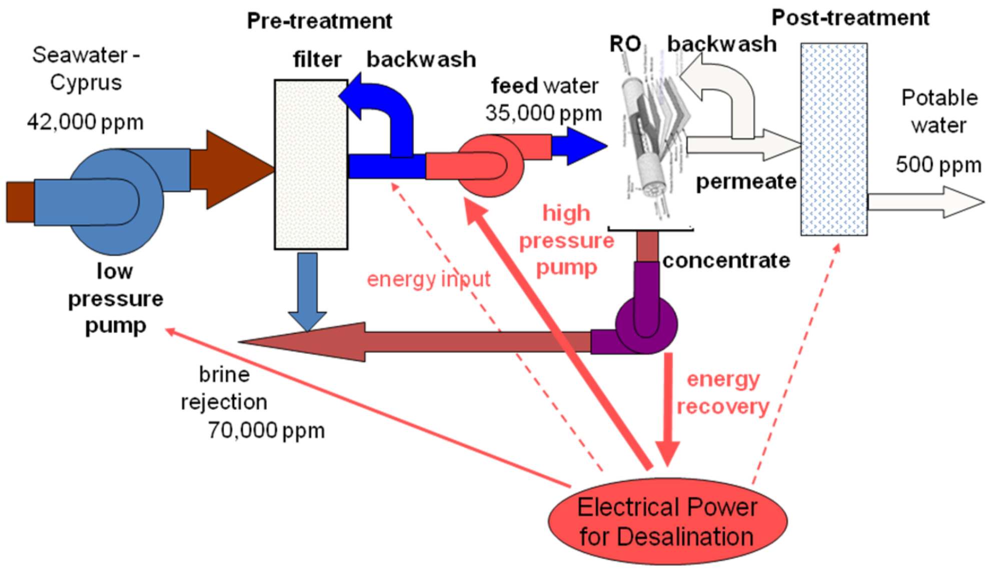

Figure 4-2: Reverse Osmosis (RO) process flow. The water (brown, blue, white) and energy (red) fluxes are represented by arrows.

[2] The SDI = $\%P_{30}/t_T$ with $\%P_{30} = 100(1- t_i/t_f)$, is defined for the initial time, t_i, over the final time, t_f, it takes to initially filter 500 ml of water containing foulants at 30 psi through a 47 mm diameter microfiltration membrane with 0.45 μm pores, between a set total measurement time, t_T. (Prof. M. Shannon, private communication, Urbana-Champaign, USA).

The RO filtration stage removes the remaining organics, and salts. Owing to the physics of mass transport through a perm-selective membrane, only a fraction X (the ratio of desalinated water output-seawater input volume) of the feed water passes through the membrane as permeate. In order to further reduce energy use, one employs high-pressure pumps with energy recovery devices (labelled Pressure Exchangers in Appendix A.1) in order to recover the pressure-volume work from the rejected water. The post-treatment stage involves disinfection with a weak chlorine solution (0.5 ppm), pH adjustment, and re-mineralization to create potable water. This review does not deal with water chemistry per se. Nevertheless, the experience of IDE Technologies Ltd (which manages the Larnaca seawater desalination plant) in decreasing the high boron content of Cyprus seawater (Appendix A.2) to below 1 ppm, has to be noted [6]. The next two sections discuss the factors determining the energetics of RO and how we arrived at our “best” estimate of the energy requirements for seawater RO desalination in Cyprus.

4.2.2. RO Energy Requirements[3]

The minimum possible energy from thermodynamics for separation of salts from 35,000 ppm feed water to 500 ppm distillate is 0.85 kWh/m^3 at a flux of 284 kg/hr×m^2. This estimate assumes complete energy recovery, minimal polarization impedance, no membrane viscous and fouling losses, and no energy losses for membrane cleaning. The Affordable Desalination Coalition has reported 1.58 kWh/m^3 with a flux much less than 38 liters/hr×m^2. The state-of-the-art RO system in use today in Ashkelon, Israel, requires 2.19 kWh/m^3 of electrical energy to desalinate seawater (~ 30,000 ppm), with a flux of ~ 170 liters/hr.m^2 of membrane, after extensive pretreatment to remove foulants, shifting the pH lower and adding anti-scalants. The above comparison demonstrates that the energy needed for RO desalination is tightly coupled to the size of the system and the pressure, *P*, of the feed water. In order to see why this is so, let us revisit the energy requirements for RO.

The minimum possible osmotic pressure of seawater with 35,000 ppm is 21.7 bar, but a practical value is close to ~28 bar. RO Desalination plants, depending on seawater salinity

[3] Contains fundamental from M. Shannon’s course, CEE 598 - Materials for Water Treatment Systems, University of Illinois.

and the amount of pre-treatment conducted, typically run at more than 55 bar, with over-pressures on the same order as the osmotic pressure. The work energy, W_{RO}, needed per amount of product water, V_{Prod}, can be expressed as

$$\frac{W_{RO}}{V_{Prod}} = \frac{1}{V_{Prod}} \int_{Q} \Delta P \, dV \cong \frac{1}{V_{Prod}} \int_{\tau} k \dot{Q}^2(t) \, dt$$

where Q is the volume of water that passes through the system, $\dot{Q}$ is the volumetric flow rate, τ the time period measured, and k is the hydraulic resistance coefficient, defined by the expression $k\dot{Q} = \Delta P$. With $V_{Prod} \propto \dot{Q}\tau$, one can see that the work per product water tends to increase with increasing volumetric flow rates. However, W_{RO}/V_{Prod} is not directly proportional to $\dot{Q}$, since there are many different factors that determine the pressure drop needed to drive the system and produce the product water. If we decompose the ΔP into

$$\Delta P = \underset{(1)}{\Pi_{Osmotic|\infty}} + \underset{(2)}{\Pi_{Osmotic|X}} + \underset{(3)}{\Delta P_{Reject}} + \underset{(4)}{\Delta P_{Foul}} + \underset{(5)}{\Delta P_{Polar}} + \underset{(6)}{\Delta P_{Membrane}} + \underset{(7)}{\Delta P_{Module}}$$

we can address the energy associated with each factor. Term (1) is determined by the initial and final concentration, and cannot be improved. The goal is to reduce every term from (2) to (7), so as to approach the minimum possible for a given product to rejected water ratio that can meet or exceed the specifications.

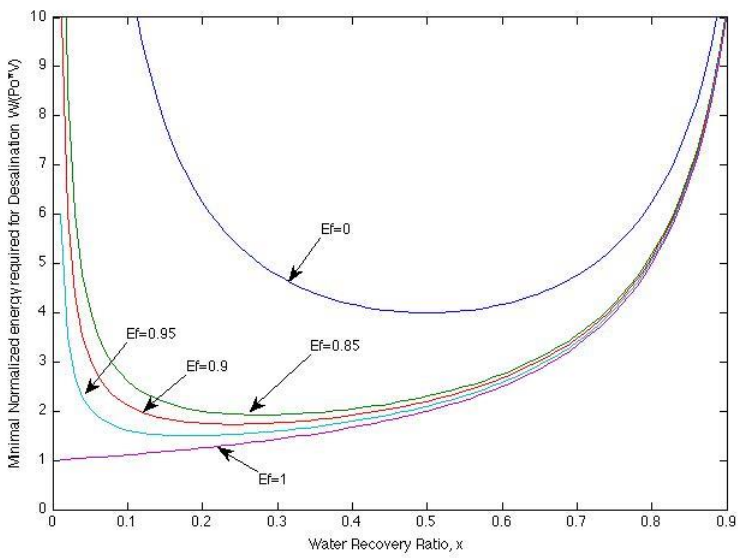

Figure 4-3: Energy requirements of RO as a function of X and efficiency of power recovery. Only factors (1-3) are considered. Feed water at 45,000 ppm salinity is assumed.

Term (2) is primarily determined by the product to water recovery ratio, X, which impacts the size of the system per product water output. The higher X is, the higher the salinity of the rejected water (brine) is and thus the higher the additional pressure is needed to drive the water across the RO membrane. A higher X leads to less water needing pretreatment and smaller pump flows. Going up in X also reduces the volume of rejected water needed to recover energy from. Since energy recovery is not perfect (highest claimed is 90%), minimizing rejected volume minimizes energy loss. To reduce the pressure loss, ΔP_{Reject}, in term (3) the energy from the rejected pressurized stream needs to be recovered. Figure 4-3 shows the variation of energy requirements for RO as a function of X and efficiency of pressure-volume work recovery. Commercial-off-the-shelf pumps have at least 80% energy recovery.

There exist several innovative technologies to reduce pressure drops from factors (4) to (7) to reduce the total overall energy used. These terms in practice are a significant fraction of the overall pressure drop. Desalination plants, depending on seawater salinity that varies at different locations and the amount of pretreatment conducted, operate between a low of 42 bar to a high of 71 bar. (The Larnaca RO plant has a feed pressure of 68 bar, and runs the 5 membrane trains in the range of 70.5-72.6 bar, [6]). Therefore, the over pressures given by terms (3) to (7) are of the same order as the sum (1) + (2). Of all these pressures, ΔP_{Foul}, is often the most significant. With high SDI values (typical of Cyprus seawater intakes), the pressure drop due to fouling can increase one order of magnitude, requiring cleaning. Cleaning itself requires energy to flush or backwash, and no product water is produced during this time, which increases the energy per product water. However, irreversible fouling that results primarily from relatively small molecules and colloidal compounds has a much larger total energy cost. The first two stages remove the particles such that ΔP_{Foul} goes to zero, in particular the irreversible fouling potential.

The loss to the flow of product water at a given input pressure due to polarization impedance in term (5) is affected by the flux: increasing the flux through the membrane, increases the concentration of salt near the membrane. Thus the higher the flux, the higher the pressure required to overcome the polarization impedance. The polarization impedance can be lowered by inducing turbulent flow mixing within the boundary layer, but at the cost of increasing the viscous pressure drop in (7). Term (6) is determined by the resistance to water flow through the membrane, such that $k_M \dot{Q}_M = \Delta P_{Membrane}$. In order to increase $\dot{Q}_M = \dot{Q}_M '' A$, the flux per unit area, $\dot{Q}_M ''$ needs to be increased. In order to minimize the pressure loss induced by the membrane, k_M needs to be reduced. Modern RO membranes (e.g. high-performance FILMTEC™ membranes from Dow) exhibit significantly less resistance than standard asymmetric RO membranes. However, the reduction of $\Delta P_{Membrane}$ brought about by decreasing k_M is partially at the expense of increasing ΔP_{Polar} in (5). Current RO membrane technology development focuses on reducing ΔP_{Polar} while increasing X to reduce $\Delta P_{Viscous}$.

We conclude this section with a comment regarding the practice of heating the feed water in RO plants, as shown in the Appendix A1. Although the membrane resistance increases ($\Delta P_{Membrane}$ decreases), the membrane becomes more permeable to ions (and other impurities as well) and its fouling potential increases, requiring more sophisticated pre- and post-treatment. Thus, in order to maintain the quality of the product water, increasing the temperature of the feed water to improve the performance of seawater RO plants is not enough. During a single pass RO filtration, the boron removal goes from 90% (16 °C) to 80% (28 °C). In the Larnaca plant, for example, the "split-partial design" of the system allows modification of the operation (via a second pass brackish system) during the summer months to meet the boron specification.

4.2.3. RO Energetics (closure)

The specific energy (in terms of electrical energy required to produce a unit of potable water) for RO in a single-purpose plant is in the range 3-6 kWhe/m^3, according to Miller[7] and Semiat [8]. The above amounts need to be divided by the efficiency of the power plant (~35% is a typical value) to estimate the thermal energy required. The large variation in many of the published estimates and comparisons of energy consumption in RO stems from confusion or lack of information regarding thermal efficiencies, feed water salinity, or whether pretreatment or pumping energy was taken into account.

Using the software ROSA 6.1, which is provided by the Dow Chemical Company to predict the performance of FILMTEC™ membranes and typical empirical formulas for energy recovery and the energy of pre-treatment, we arrived at an estimate of 4.1 kWhe/m^3 for seawater at 25°C with composition typical of locations at the south of Cyprus (Appendix A.2). We assumed a feed rate of 500 m^3/hr, a recovery ratio of X=50% (Larnaca uses X=48.5-49.2 % in the various membrane stages) and included estimates of the auxiliary energy requirements but no energy for membrane cleaning. We may note in passing that the website of IDE, the Israeli company that designed and operates the Larnaca 64,000 m^3/day RO plant, quotes a value less than 4.52 kWh/m^3 for the Larnaca plant. The results of Semiat [8], a portion of which is summarized in Appendix A.3, concur that a "good" estimate of specific energy in a modern large-scale RO plant in the eastern Mediterranean is the value of 4 kWhe/m^3. We will use this value in subsequent discussions, by formulating the following reference case:

Case 1: Consider a dual-purpose CSP-DSW plant based on an RO system with performance mimicking that of the Larnaca seawater desalination plant. The power system employs a 4 MWe (nominal) turbine at an operation point selected from the EAC Report by Poullikkas & Rouvas [9], and excerpted in the table given in Appendix A.1. The net electrical output of the turbine is 3.769 MWe. Let us define additionally a reference distilled water output of 209.8 m3/hr. Producing this by RO will require 209.8 m3/hr × 4 kWh/m3 = 0.839 MWe, thus allowing the dual-purpose plant to deliver approximately 2.929 MWe to the power grid. Finally, let us adopt a selling price of 0.26 €/kWh for electricity and 0.92 €/m^3 for water.

4.3. Multi-Effect Distillation (MED)

4.3.1. MED Technology

The MED process consists of several consecutive stages (or effects) maintained at decreasing levels of pressure (and temperature), leading from the first (hot) stage to the last one (cold), as depicted in Figure 4-4. Each effect mainly consists of a multiphase heat exchanger. Seawater is introduced in the evaporator side and heating steam is introduced in the condenser side. As it flows down the evaporator surface, the seawater concentrates and produces brine at the bottom of each effect. The vapour raised by seawater evaporation is at a lower temperature than the vapour in the condenser. However, it can still be used as heating medium for the next effect where the process is repeated. The decreasing pressure from one effect to the next one allows brine and distillate to be drawn to the next effect where they will flash and release additional amounts of vapour at the lower pressure. This additional vapour will condense into distillate inside the next effect. In the last effect, the produced steam condenses on a conventional shell and tubes heat exchanger. This exchanger, called "distillate condenser", is cooled by seawater. At the outlet of this condenser, one part of the warmed sea water is used as make-up water, the other part is rejected to the sea. Brine and distillate are collected from effect to effect, up to the last one from where they are extracted by pumps.

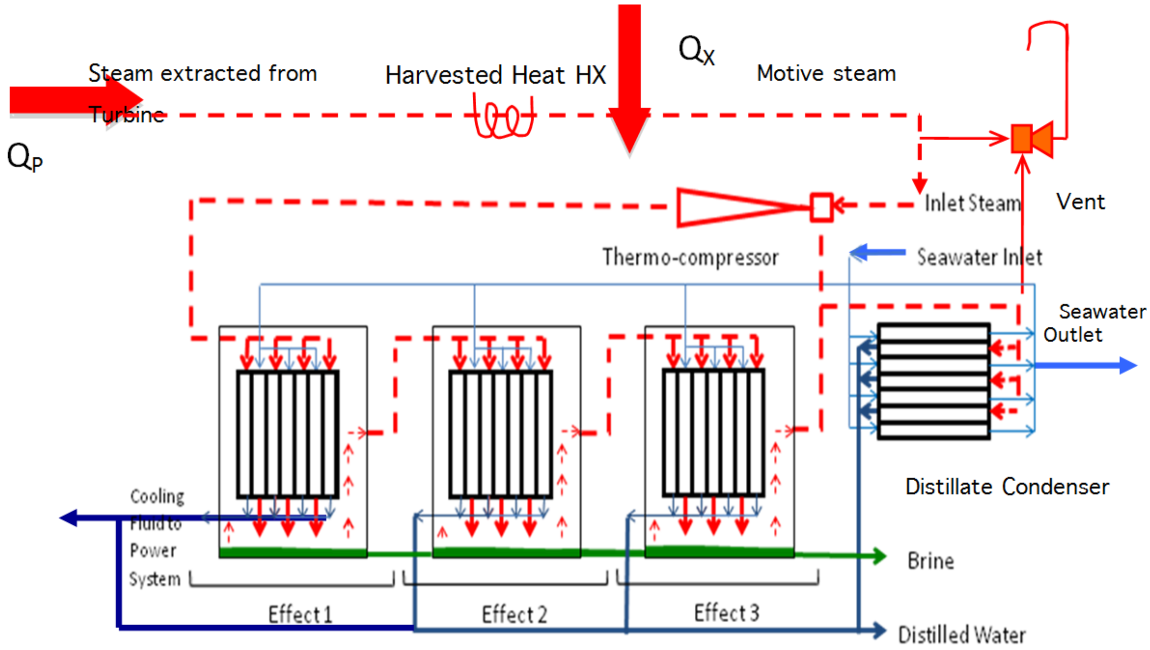

Figure 4-4: Process flow diagram for Multiple Effect Distillation (MED) with thermal vapour compression (TVC). A heat exchanger (HX) allows the addition of heat (Q_X) harvested from the solar storage system to the steam extracted from the turbine before it enters the TVC (as motive steam). This is added to the process thermal power (Q_P), which is the dominant energy input to the MED, while electrical energy (to pump the various liquids) is minimal. Vacuum is created by the combination of thermo-compressor and steam ejector, which are both driven by motive steam.

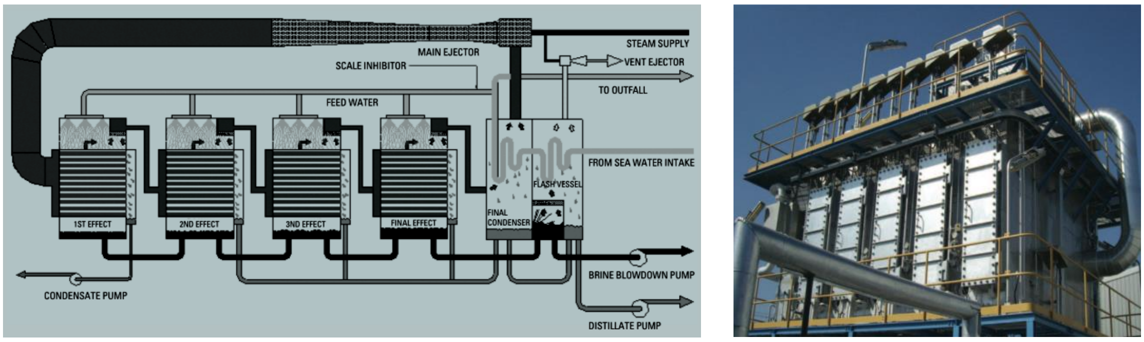

Figure 4-5: Schematic and photo of MED-TVC pilot plant by Doosan Heavy Industries & Construction Co. This is a 5 effect tube-in-shell unit without steam transformer, with 450 ton/day water production capacity and PR=8.

The water production capacity of the MED can be quantified by the Gained Output Ratio (GOR), which is the ratio of the mass of water product per mass of heating steam supplied to the first effect. GOR is a convenient means to assess the performance of a simple MED system since an ideal system whereby water is evaporated and then distilled in a single stage without losses gives GOR=1. Using multiple stages increases the GOR in almost linear fashion. Since motive steam is not always entering and exiting at saturation conditions, and the heat input to the MED system can additionally include heat harvested from other subsystems, a better measure of the efficiency can be obtained by the Performance Ratio (PR). Also dimensionless, PR is defined as the ratio of product water mass over the mass that would be produced by condensing 1 kg of steam with a heat of vapourization of 2,326 kJ/kg:

$$PR = (2326\ kJ/kg) \times \text{Distillate production rate}\ (kg/s) / (Q_P + Q_X)\ (kW) \qquad (3)$$

The above formula implies that the specific energy can be obtained by (2326 kJ/kg)/ PR.

An upper limit on the PR in a standard MED system is the number of effects. The PR (and GOR) can be raised without changing the number of effects by “recycling” the vapour. The most efficient MED process is MED-VC (VC for vapour compression). Thermal VC (TVC) involves using motive steam to drive a thermo-compressor to lower the pressure of the brine in each effect so it evaporates at temperatures closer to the ambient temperature, cf. Figure 4-4 and Figure 4-5. Mechanical VC (MVC) requires electrical energy to drive a mechanical compressor instead, but this can be offset by using an auxiliary turbine driven by the process steam [10]. Another method to increase the performance of MED is by adding heat pumps between one of the effects and the first (hottest) one. For example, GOR values up to 20 have been reported, achieved by using a LiBr heat pump in a 14-effect solar MED system [11], as shown in simplified form in Figure 4-6. Instead of condensing the steam produced in the last effect with cold seawater, the steam is fed to the heat pump (evaporator side) to drive the generation of steam to be absorbed by the strong LiBr-water solution (absorber). The weak solution is then pumped to the generator where the steam is de-adsorbed by using additional energy input (which plays the same role as Q_H). The water tank and steam input and output lines belong to the power production. This modification of the MED process allows additional extraction of thermal energy from the low temperature saturated steam produced from the last effect. This energy would otherwise be lost to the seawater. From a thermodynamics point of view, TVC and MVC are essentially heat pump devices.

Experience with Multistage Flash Distillation (MSF) helps delineate some of the technological challenges with MED. There are significant differences between MED and MSF: temperatures of 70°C vs. 115°C, 600 ppb vs. 50 ppb oxygen content [12]. Poor de-aeration and venting results in the accumulation of stagnant pockets of oxygen underneath the vent channel, causing material cracking failure due to corrosion, especially in the first stages. The reason for the relatively high oxygen concentration in the MED process arises from the fact that no separate de-aeration takes place and the oxygen is released in the first stages. The concentration of the oxygen dissolved in the evaporating brine inside the MED shell is governed by Henry’s law, and it tends to be in equilibrium with the oxygen pressure in the vapour side. As evaporating brine flows towards the bottom of the effect, the oxygen concentration approaches the equilibrium value. The oxygen distribution differs from stage to stage because each stage has a different operating temperature and therefore a different Henry’s coefficient for oxygen concentration. Also hydrazine entrained inside the effect through the motive steam for the thermo-compressor can release ammonia, which can corrode and crack the aluminium brass material. A breakthrough in MED materials technology is the titanium-coated stainless steel heat exchanger introduced by Alfa-Laval, which along with other technological innovations have both decreased the cost and raised the life-time of MED systems to 40 years, cf. [12].

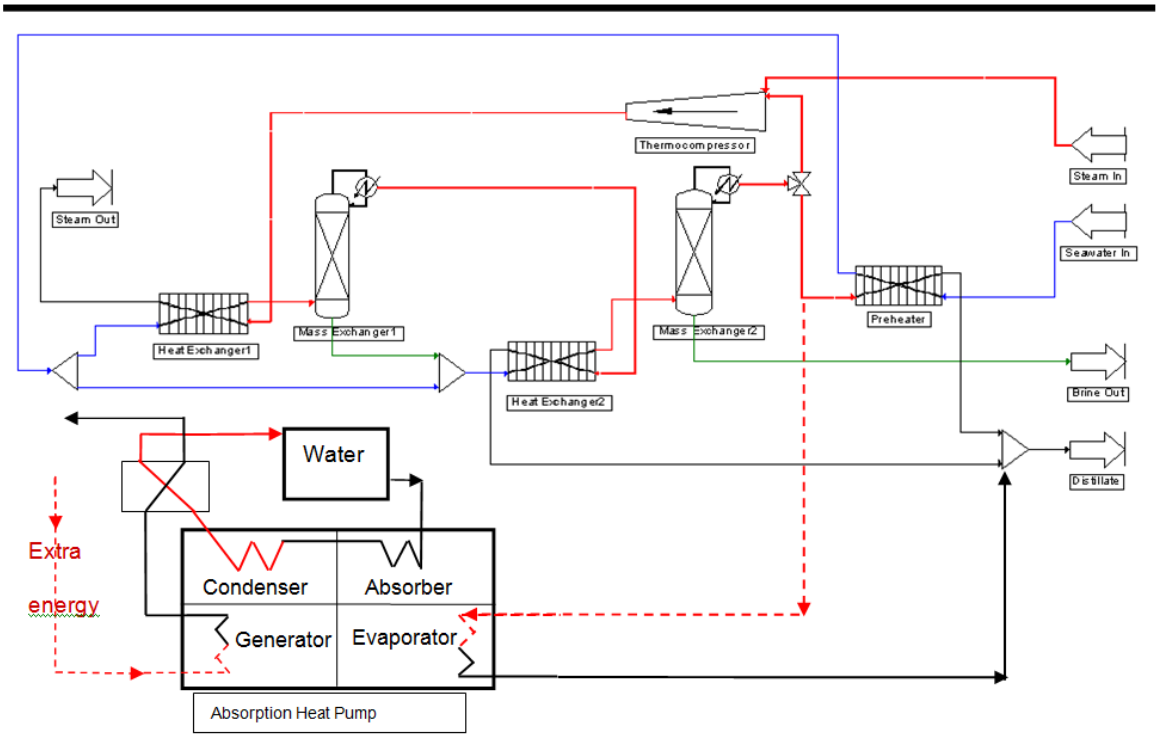

Figure 4-6: Multiple Effect Distillation (MED) system process flow. Thermal vapour compression (TVC), and absorption heat pump, two features are added to the standard MED process to demonstrate the complexity of the thermo-hydraulic connections relative to RO. Only two effects are drawn for simplicity. Blue lines denote seawater feed, black the distillate or condensate water, red the steam, and green the brine.

The designers and manufacturers of water desalination equipment have solved many of the materials problems and improved the design of the multiphase heat exchangers, which can represent up to 40% of the capital cost of MED equipment [23]. Representing the opinion of Alfa-Laval, a lead manufacturer of MED plants, Tonner et al. [13] stated: *"….Only a few studies using plate heat exchangers for thermal desalination have been made, primarily at research level by universities and state owned research centers; and these works so far have only barely approached the most elementary benefits of this technology…"* University researchers have indeed heeded the admonition of industry and there have been a number of publications focusing on the two-phase flow performance of plate heat exchangers, cf [14], and [15].

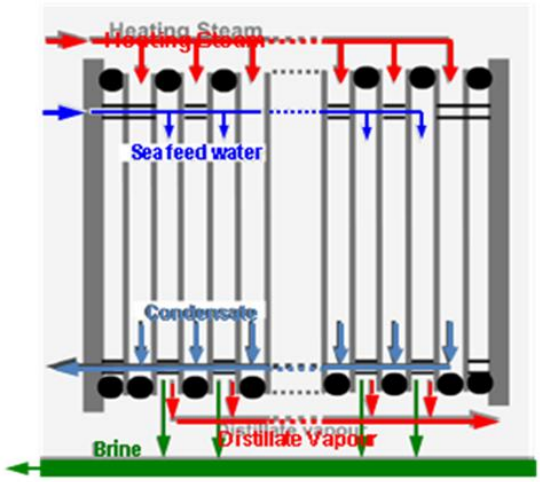

Figure 4-7: MED Alfa-Laval heat exchanger Pressed Plate Falling Film configuration (Maciver et al. 2005) .

Falling film heat exchangers represent the most promising technology, and pilot MED systems have been designed and operated to explore their potential (e.g. project EasyMED, cf. [16]. Heat transfer coefficients of 4 kW/Km^2 have been reported. The industrial versions of these devices employ plate heat exchangers, which consist of several corrugated thin plates stacked in a pack (Figure 4-7). The plate pack is mounted between a fixed and a moveable pressure plate, compressed, and fastened by upper and lower carrying bars. The pressure plates have connections for inlet and outlets for the fluids, and corner ports direct the flow from plate to plate. The configuration creates two interleaved channel systems for the two fluid streams to exchange heat, closely approximating the counter-current flow arrangement. The seawater is introduced in the evaporating side and distributed evenly in each second channel created in the plate assembly. The vapour separates from the brine by gravity. On the condensing side, the steam (for the first effect), and the vapour (for the other effects) flow into the interleaved channels where a fraction condenses to form the distillate. The remaining vapour continues to the evaporator compartment of the next effect. The plate surfaces have chevron patterns that are crucial in controlling the falling films on both the evaporation and condensation sides. The chevrons (with proprietary profile shape, corrugation depth and angle) are gentle, have a corrugation depth of 3.5-4 mm, and an obtuse corrugation angle to support the condensate drain and vapour outlet. The presence of the chevron patterns causes a transition turbulent flow at Reynolds numbers as low as 10. (Laminar flow in shell-and-tube heat exchangers persists to Re as high as 2000.) In addition to better heat exchange performance, the turbulent falling film decreases fouling. For up to 130 °C and 25 bar, temperature resistant gaskets (glued or fastened) seal the plates around their edges. Typically, high quality Nitrile gaskets are glued on the plates, with expected life of over 10 years.

In summary, there are a number of challenges for MED to be overcome, which essentially provide the motivation for additional research. Compared to the RO technology, MED has been less developed and thus presents several technological challenges. Unlike MSF, where the process configuration and thermodynamics did not substantially change over in the last 30 years, the MED process affords many opportunities for further improvement in efficiency and reducing costs by choosing better heat exchangers, and modifying process flow configuration, operational patterns, and thermodynamic conditions. Unlike RO, whose performance is not affected in a dual-purpose plant because membrane separations are driven by electrically powered pumps, MED systems have to be designed and operated with the optimization of the whole dual-purpose plant in mind.

4.3.2. MED Energy Requirements.

The thermodynamic performance of MED depends on the process configuration. Darwish et al. [17] and Darwish and Abdulrahim [18] review many of the standard process flow configurations employed in practice, while Semiat [8] discusses some novel modifications. The most efficient MED process is MED-TVC (thermal vapour compression), which involves using low or medium pressure steam to take part of the vapour raised in one of the effects and recycle it into higher pressure vapour to be used as heating media for the first effect. The use of the motive steam to create vacuum lowers the electrical energy requirements of MED-VC to less than 1 kWhe/m^3.

The estimation of energy requirements for a given MED system starts with the application of the first law of thermodynamics (conservation of energy, COE) and mass balance (conservation of mass, COM) to the open system under steady-state operation, for every effect (stage) and component, as depicted in Figure 4-8.

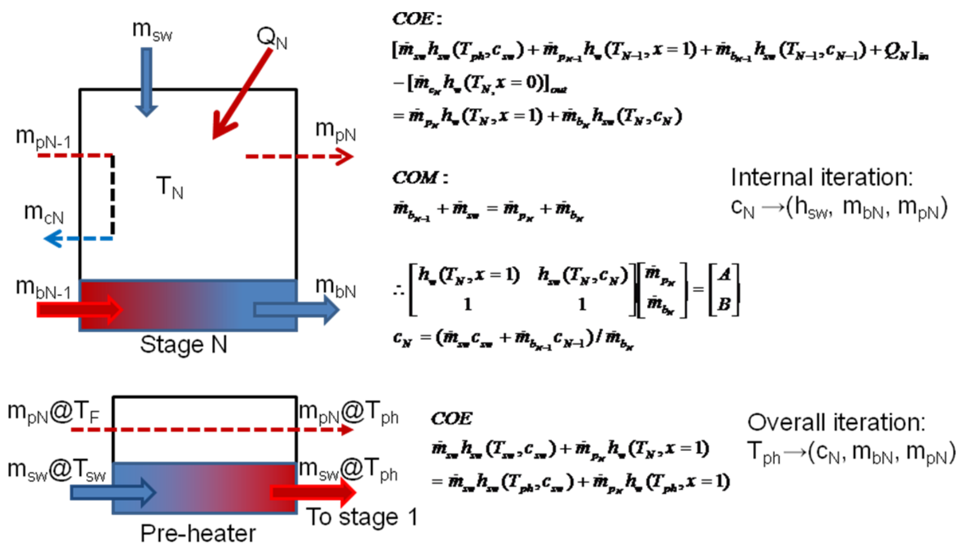

Figure 4-8: Mathematical model representing mass and energy balances in a single MED effect

The mathematical model was integrated to explore the performance of MED under a given process flow (forward or parallel feed, etc.). We concluded that a parallel-feed system gives the best performance in terms of distillate production. The thermo-compressor was modelled by using one-dimensional compressible fluid mechanics as in [19] and [20]. We validated our model of MED with TVC by using case studies of operating MED-TVC plants, as reported by Amer [20] who provides all the requisite input and output parameters. Two cases were considered involving the Mirfa 4-effect plant and the Al-Taweelah A1 6-effect plant in the United Arab Emirates. Our model is accurate for low-pressure motive steam conditions (less than 3 bar).

We simulated a plethora of MED systems consisting of 5 to 20 effects, with and without TVC devices. For simulations of MED systems with TVC, the steam extracted from the turbine enters the steam ejector system, and it is mixed with vapour from the last effect. In cases of low steam pressure (less than 1 bar), two steam ejectors (or more) are required for the system to function. A fraction of the steam flows into the first ejector, and the remaining amount of the steam drives the second ejector. As expected, the highest distillate production rate was obtained for a MED-TVC with the maximum number of effects (20). There is a limitation regarding the harvested heat Q_X that can be added to the steam extracted from the turbine: there is a maximum heat input to the process steam and it corresponds to the attainment of sonic conditions at the end of the heat exchanger chocked Rayleigh flow), cf. [21].

We are reporting a set of high GOR results in Table 4-1 with input values summarized in Table 4-2.

System	Q_X [MW]	Thermal power to 1st effect [MW]	Extracted Steam Pressure (bar)	# of TVCs used	Seawater flow [kg/s]	Distillate [kg/s]	GOR
1	0.7	9.84	0.5	2	153	50.126	14.32
2	0.7	11.02	1.0	1	172	56.075	16.02
3	0.7	10.29	0.5	2	160.5	52.458	14.99
4	1.3	11.62	1.0	1	181	59.364	16.87
5	1.3	10.94	0.5	2	170	58.282	16.65

Table 4-1: Inputs and outputs of high-GOR MED-TVC simulations

Steam flow-rate [kg/s]	1^{st} effect temperature [°C]	Last effect temperature [°C]	Seawater temperature [°C]	Seawater salinity [ppt]	Maximum salinity [ppt]
3.5	55	35	25	40,000	80,000

Table 4-2: Input conditions for MED-TVC simulation

In the following, we are focusing on a system chosen to produce the same distilled water output as case 1, which is 209.8 m^3/hr. As Table 4-1 indicates, a possible choice is system 5 involving the input of Q_X= 1.3 MWth harvested from the solar collection system. The following case can now be defined:

Case 2: A parallel-feed MED-TVC system with 20 effects is considered. Seawater enters all effects with 25 C and 40,000 ppm salinity, and steam extracted at 0.5 bar with mass flux 3.5 kg/s (the maximum rate that process steam can be extracted from the turbine) is first heated by 1.3 MWth of heat harvested from the CSPond lid, enters the TVC, and then the first MED effect. The system can be abstracted by the 3-effect system of Figure 4-4 if effects 2-19 are replaced by effect 2. The net power output from the power block drops to 3.071 MWe. From that amount, we have to subtract the power required to drive the MED auxiliaries, which we estimate at 0.8 kWe/m^3. This means that the net power available from the turbine (coupled to system 5) to the electrical grid is 2.903 MWe.

Although extreme, high GOR values have been reported and studied in single-purpose MED systems, cf. [11] and [20], and they always involve additional heat input (either through a heat pump or a TVC). The auxiliary electrical energy estimate for system 5 was derived on the basis of data provided by manufacturers of MED equipment, and is consistent with state-of-the-art MED systems with vapour compression [10]. A list of commercial suppliers of water treatment technologies is given in Table 0-2 in the Appendix A.5. Unlike RO, which is decoupled from the thermodynamics of power production, a single representative value for PR (and thus the specific energy) for Cyprus seawater desalination should not be derived for the dual-purpose plant. The MED systems are very complex and the energy requirements depend on the particular process configuration selected when the system is integrated with the power cycle.

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Chapter 5. Power Generation

5.1. Introduction

Today, steam turbines with widely varying configurations, sizes and application purposes are used extensively in the electricity generation and process industries. These steam turbines represent a significant part of the capital and operating costs of most plants, and therefore optimizing their selection and sizing is of major economic importance for the viability of the plant. However, the selection of the optimum steam turbine based on type and size for any given new plant is not a simple process, since a number of criteria have to be examined and be satisfied. The main criteria, apart from the economic ones, include the actual plant steam operating conditions at the interfaces to the steam turbine, the existing power system capacity, and the stability and reliability conditions and requirements that are in place to safeguard that the safe and reliable supply of electricity throughout the electricity network is not disrupted by the introduction of a new power plant.

In this work, the optimum steam turbine based on type and size is selected for integration in the proposed concentrated solar power plant with desalinated water co-generation, to be built on the island of Cyprus. The main objectives of this work are to identify steam turbines suitable for power and desalination co-generation plants, to investigate the current and future Cyprus power system reliability and stability conditions and requirements and finally, to perform simulations for the actual selection and sizing of the most appropriate steam turbines.

The identification of steam turbines currently integrated in concentrated solar power plants is presented and the actual selection of the optimum steam turbine based on type and size for integration in the proposed plant is performed. For the selection process, the

Steam Pro software module of the Thermoflow Suite 18 package [1] is used. Finally, the conclusions of this work are summarized in the last section.

5.2. Steam turbines currently integrated in CSP plants

Although not many CSP plants have been in operation up until today, the number of CSP plants currently under construction is increasing continuously at a very high rate [2]. The same holds true for the number of CSP plants that have been officially announced for commencement of construction during this year. The location of these plants is mainly in Spain or the USA, and the technology most frequently chosen is the parabolic trough technology with capacities usually at 50MWe per plant. The reason is that these countries can offer attractive financial incentive schemes to CSP plant project-owners, which constitute the project profitable [3].

For CSP plants (whether of the parabolic trough or the solar tower technologies) the incorporation of a Rankine steam cycle is crucial, in order to achieve electric power generation. Currently, saturated steam cycles are usually employed in this type of plants, while superheated steam cycles are expected to be used in the forthcoming ISCC plants (Integrated Solar Combined-Cycle plants) that employ combined-cycle technology. A table showing the steam turbines currently employed in all CSP plants (whether operational or under construction) with capacity higher than 5MWe, is shown in Table 5-1. The steam turbines for which there is publicized official information for integration in announced CSP plants are shown in Table 5-2. A short description of each of the steam turbines currently used (or to be used) in CSP plants is provided in this section, which is an update of [3] concerning the steam turbines currently integrated in CSP plants is provided.

5.2.1. Siemens SST-700DRH

It is clear from Table 5-1 and Table 5-2, that the Siemens SST-700DRH (based on the standard SST-700 steam turbine) is currently established in the CSP market as the dominant steam turbine to be used in the steam Rankine cycle of solar thermal power plants - especially those plants based on the parabolic trough technology.

General description

The SST-700DRH is a dual casing reheat steam turbine specifically designed and manufactured by Siemens (based on the standard SST-700 steam turbine) in order to meet the specific requirements of solar thermal power plants. To justify the high investment cost for a CSP plant, which will not be run twenty-four hours per day, high demands for efficiency are imposed on the steam turbine used in the process. For this reason, Siemens has cooperated closely with leading solar thermal manufacturing companies to develop and fine-tune the SST-700DRH steam turbine, now optimized for solar steam cycles and capable of generating up to 175MWe in CSP applications. This highly efficient turbine with its high-speed, high-pressure module enables a smaller solar mirror collector field with associated reduction in investment cost for generation of the required electrical power output. Alternatively, the surplus can be put into thermal storage to extend the production time for the plant.

The reheat solution improves efficiency and reduces problems with erosion/corrosion and moisture in the LP turbine. Also when focusing on annual power production, the short start-up times the turbine can provide are of great benefit to the CSP plant owner. Daily cycling and temperature variations require special attention. Therefore, the SST-700DRH, with its low-mass rotors and casings, is ideal for daily cycling and has a low minimum load, enabling maximum running hours per day for plants without thermal storage. The cycle has also been optimized for stand-still at night and rapid restart in the mornings. The SST-700DRH uses high quality materials specially chosen for long and trouble-free operation in a solar plant, bearing in mind the potential wear and tear of the special cycle conditions [4].

Name	Location	Country	Technology	Inlet steam conditions	Capacity (MWe)	Steam Turbine
Operational						
Solar Energy Generating Systems (SEGS) I - IX	Mohave Desert, California	USA	Parabolic Trough	100 bar, 370°C	354 (Table 10 for more details)	na
Nevada Solar One	Eldorado Valley, Nevada	USA	Parabolic Trough	86 bar, 370°C	64	Siemens SST-PAC-700
Lidell Power Station	New South Wales	Australia	Fresnel reflector	na	35	na
PS10 Solar Power Tower	Sanlucar la Mayor, Sevilla	Spain	Solar Tower	40 bar, 250°C	11	GE Oil & Gas (Thermodyn)
Under Construction						
Andasol 1	Andalucia	Spain	Parabolic Trough	na	50	Siemens SST-700DRH
Andasol 2	Andalucia	Spain	Parabolic Trough	na	50	Siemens SST-700DRH
La Risca (Acciona 1)	Badajoz	Spain	Parabolic Trough	na	50	Siemens SST-700DRH
Solnova 1	Sanlucar la Mayor, Sevilla	Spain	Parabolic Trough	100 bar, 390°C	50	Siemens SST-700DRH
Solnova 3	Sanlucar la Mayor, Sevilla	Spain	Parabolic Trough	na	50	Siemens SST-700DRH
Energia Solar de Puertollano (Iberdrola 1)	Puertollano	Spain	Parabolic Trough	na	50	Siemens SST-700DRH
Extresol 1	Badajoz	Spain	Parabolic Trough	na	50	Siemens SST-700DRH
PS20 Solar Power Tower	Sanlucar la Mayor, Sevilla	Spain	Solar Tower	na	20	na
Solar Tres	Andalucia	Spain	Parabolic Trough	na	19	Siemens SST-600
Beni Mathar plant	Beni Mathar	Morocco	Parabolic Trough (ISCC)	100 bar, 540°C	20 (solar plants)	ALSTOM
Hassi R'Mel plant	Hassi R'Mel	Algeria	Parabolic Trough (ISCC)	100 bar, 540°C	25 (solar plant)	Siemens SST-900

Table 5-1: Steam turbines employed in CSP plants

Name	Location	Country	Technology	Inlet steam conditions	Capacity (MWe)	Steam Turbine
Ivanpah Solar	California	USA	Solar Tower	550°C	500 + 400 (optional extension)	Siemens SST-900
Extresol 3	Badajoz	Spain	Parabolic Trough	na	50	Siemens SST-700DRH
Andasol 3	Andalucia	Spain	Parabolic Trough	na	50	MAN Turbo AG
Helios 1	Cuidad Real	Spain	Parabolic Trough	na	50	Siemens SST-700DRH
Helios 2	Cuidad Real	Spain	Parabolic Trough	na	50	Siemens SST-700DRH
Lebrija 1 (Solel & Sacyr)	Lebrija	Spain	Parabolic Trough	na	50	Siemens SST-700DRH

Table 5-2: Steam turbines to be integrated in announced CSP plants

Design features (based on the SST-700)

The SST-700 dual casing turbine can be equipped with a single valve or a multi-valve inlet as well as with a variety of extraction control arrangements. In order to make the best use of large changes in volumetric flow from inlet to outlet, the SST-700 turbine steam expansion is divided into two different modules: one high-pressure turbine (HP) and one low-pressure turbine (LP). The use of two separate modules operating at different and optimized speeds is the optimal design for large expansion coefficients, which is the case for both high live steam data and large low pressure exhaust steam flows. The two modules can be combined to provide the turbine configuration that is most suitable for a specific application. However each module can also be utilized on its own, e.g., the high pressure module can be used as a separate back-pressure unit. Condensing turbines feature as standard an axial exhaust connected to water-cooled condenser or connected to an air-cooled condenser. The axial exhaust saves foundation height and cost and improves efficiency. Downwards-directed exhaust for underslung condensers are available as an option.

The configuration of the SST-700 turbines permits considerable operational flexibility. With a symmetrical casing and small dimensions of the hot parts, resulting in low thermal and mechanical inertia, the SST-700 turbine can accept very short start-up times and rapid load changes if required. Optimum performance is assured by choosing dimensions for each cylinder appropriate to volumetric flow and by using two different and optimized speeds for the HP and LP turbines. Internally controlled process steam extraction provides a constant extraction pressure over a broad range of steam flows, a feature that makes the SST-700 steam turbines both flexible and easy to operate. Bleed extractions are available and can be equipped with external pressure control valves [4].

5.2.2. Siemens SST-600

The SST-600 (to be used in the Solar Tres parabolic trough solar plant [4]) is a single casing steam turbine, designed for operation with speed ranging from 3000 to 15000 rpm for generator or mechanical drives up to 100MWe. The turbine is used for both condensing and back-pressure applications, either geared or directly coupled. Typical fields of application are chemical and petrochemical industry, pulp and paper mills, steel works, mines, power plants, seawater desalination plants and waste-to-energy plants. The SST-600 is used as compressor drive, generator drive or boiler feed water pump drive.

The SST-600 consists of three main modules: inlet, intermediate and exhaust sections. The complex inlet section consists of emergency stop valve, control valve, internal casing with blading and external casing. The intermediate section can be designed for straight flow, or equipped with bleeds and/or controlled extractions. A wide range of exhaust pipes and types is available for back-pressure and condensing applications. These pre-designed modules are combined to a single unit for optimum matching of the required parameters [4].

5.2.3. Siemens SST-900

The Siemens SST-900 steam turbine (to be used in the Hassi R'Mel ISCC solar plant [4]) is a single-casing steam turbine with up to 250MWe power output, normally providing direct drive of a 3000 or 3600 rpm generator. The SST-900 steam turbine series is designed and manufactured to meet the specific demands of power generation in condensing and back-pressure applications in non-reheat or (in combination with HP module) for reheat applications in industrial plants, combined-cycle plants, fossil fuel steam plants, waste-to-energy plants, district heating plants and other plants in the oil and gas industry.

The SST-900 turbine is built from a series of proven standard components, each of which contributes to high reliability, flexibility and availability. Although the turbine components are selected from standardized building blocks, the steam path, extraction/admission location, size and inlet systems are customized to fit the specific requirements of each project. The SST-900 has been designed with short start-up time and can handle quick load changes since it is a compact low weight, impulse blade turbine. High thermal efficiency can be achieved across a wide range of loads. The SST-900 can be equipped with a single valve or multi-valve inlet as well as with various types of extraction control arrangements. Volutes for even steam distribution to the first inlet stage or nozzle groups around a control stage protect the main turbine casing from very hot inlet steam. A single inlet volume provides optimal performance for combined-cycle sliding pressure operation [4].

5.2.4. GE Oil & Gas

The GE steam turbine generator manufactured for use in the PS10 solar tower plant [5] was specifically customized for the requirements of this CSP plant. The design of this steam turbine differs from the turbines Thermodyn (the French affiliate of GE) typically builds for industrial applications and more closely resembles the turbines used by the French Navy for electricity generation or the propulsion of nuclear ships, submarines or aircraft carriers. This is because the inlet steam for the solar plant operation is saturated, which requires the turbine to have a specific design that prevents blade erosion due to the high humidity ration of the steam that flows through the various stages.

The GE Navy steam turbines are generally of the single casing, condensing type (MC series) and use impulse blading for high reliability and efficiency, covering applications up to approximately 40MWe. The modular structured design permits a high degree of customization to meet the specific steam cycle needs, and can provide controlled or uncontrolled extraction/injection of steam at any possible pressure level for optimum integration. The inlet section has a hydraulically actuated multi-valve system and the turbine is controlled by partial or full arc of admission. The exhaust flange orientation can be axial or radial to accommodate the plant layout and for building optimization. The turbine design meets the API 612 requirements [5].

5.2.5. MAN Turbo

MAN Turbo offers a highly comprehensive range of steam turbines with proven performance for industrial applications, as well as municipal power utilities. The steam turbines are available in various models and sixes: condensing turbine, back pressure turbine, extraction turbine and the highly standardized MARC series (Modular Arrangement Concept). The condensing turbine has a split cast steel casing. The exhaust casing is welded to the turbine casing casting. One advantage of this design is the simple and reliable sealing of the machine. Leakage problems and associated power losses, such as may occur at intersecting split joints following a fairly long period of operation, are thus avoided [6]. As an alternative to the radial exhaust flow configuration, the condensing turbine is also available with an axial exhaust flow module to carry low-pressure steam to the condenser.

The back pressure turbine consists of a horizontally split casting inclusive of control stage casing along with a transition and exhaust casing. The extraction turbine has adjustable stator blades and overflow throttle to control extraction quantity of steam and pressure. The extraction valves are located on the top of the casing. Extraction nozzles can be fitted underneath or to the side. Finally, the MARC concept allows individual installation of the unit according to the customer's requirements and via standardization simultaneously fulfils all requirements regarding operational safety, efficiency and availability.

5.3. Optimum selection of steam turbine

The work performed in this section is focused on the selection and sizing of the optimum steam turbine to be integrated in the proposed concentrated solar power plant with desalinated water co-generation. In order to perform the selection and sizing of the optimum steam turbine, the Steam Pro software module of the Thermoflow Suite 18 package [1] is used. The investigation process covers all three major types of steam turbines, that is, condensing, back-pressure and extraction turbines, and also five different power capacity sizes for the turbine, that is, 4, 10, 25, 50 and 100MW.

Firstly, the software used for the simulations is briefly introduced and then the input data and assumptions are discussed. Finally, the results obtained for each of the investigated steam turbine types are presented and discussed.

5.3.1. Simulation software

The steam turbine optimum selection is carried out using the Steam Pro software module of the Thermoflow Suite 18 package. This module is used for the design of conventional steam plants, while other modules exist for the design of combined cycle units (GT Pro), and for performance evaluation of either conventional (Steam Master) or combined cycle (GT Master) units.

The Steam Pro module computes, based on the user inputs, the mass and heat balances of the plant, and also performs the design of the various plant subsystems and equipment. The program offers considerable flexibility, allowing the user to enter design specifications and requirements down to minute detail, but it also offers suitable default options based on the main design specifications.

In addition to the unit size and basic turbine configuration the user is able to specify details of the plant location, fuel specifications, steam turbine design parameters, boiler thermal and size parameters, feed heater train specifications and interface to process streams, either steam or water. Program outputs include all operating parameters, at full load, as well as the design specifications of the plant subsystems (steam turbine, boiler, feed heaters, condenser, and motors).

For the simulation presented in this report the boiler is considered as a black box, as the solar field design will be radically different from the conventional boiler design options available in the Steam Pro module. Wherever necessary the default boiler selections were overwritten to eliminate interactions of the boiler design with the steam turbine cycle. In all the presented results and calculations the solar field interfaces are reported at the turbine inlet and at the exit point of the last feed water heater.

5.3.2. Design grid

The purpose of this investigation is to establish the interface conditions between the steam turbine and the solar field, and between the steam and the desalination plants. The possible interfaces between the steam plant and the desalination process are those given in Table 5-3.

The design considerations for each of the three turbine configurations, condensing, extraction and backpressure), are discussed below and the available simulation results are presented. A detailed operational description of each configuration is provided in [3]. The simulation results presented in the following sections were obtained by modelling in the Thermoflow Suite 18.

	MSF	*MED, MED TVC*	*MVC*	*RO*
Condensing turbine			√	√
Extraction turbine	√	√		
Backpressure turbine	√	√		

Table 5-3: Possible interfaces between steam plant and desalination plant

5.3.3. Condensing turbine

In general, the Rankine cycle efficiency can be improved by:

a) Increased turbine inlet pressure,

b) Increased turbine inlet temperature,

c) Decreased turbine exhaust pressure.

While most CSP plants use saturated steam turbines, it is implicitly assumed that the current design will proceed with superheated steam. The efficiency of a saturated steam turbine is significantly lower to that of a superheated steam turbine, requiring that a higher percentage of the collected solar energy be rejected in the condenser. In the results that follow the lower temperatures for each simulated pressure are very close to the saturated steam conditions.

Simulations were run for turbine inlet temperatures of up to 580°C. Practically, designs over 550°C start posing design challenges. It is recommended that maximum turbine inlet temperature is held at 540°C, in line with most turbine manufacturers standard specifications.

For large machines the inlet pressure can be increased up to 140bar. This high pressure poses several problems for smaller machines though, the main ones being increased leakages though glands and increased inter-stage leakage. These effects are evident in the simulation results of the smaller sized turbines, 4MWe and 10MWe, where lower pressures result in increased turbine efficiencies. The turbine exhaust pressure is at 50mbar, 33°C in all cases, which corresponds to steam quality of 0.85 at the turbine exhaust. The five simulation models, for each of the 4, 10, 25, 50 and 100MWe plants are shown in Figure 5-1 respectively.

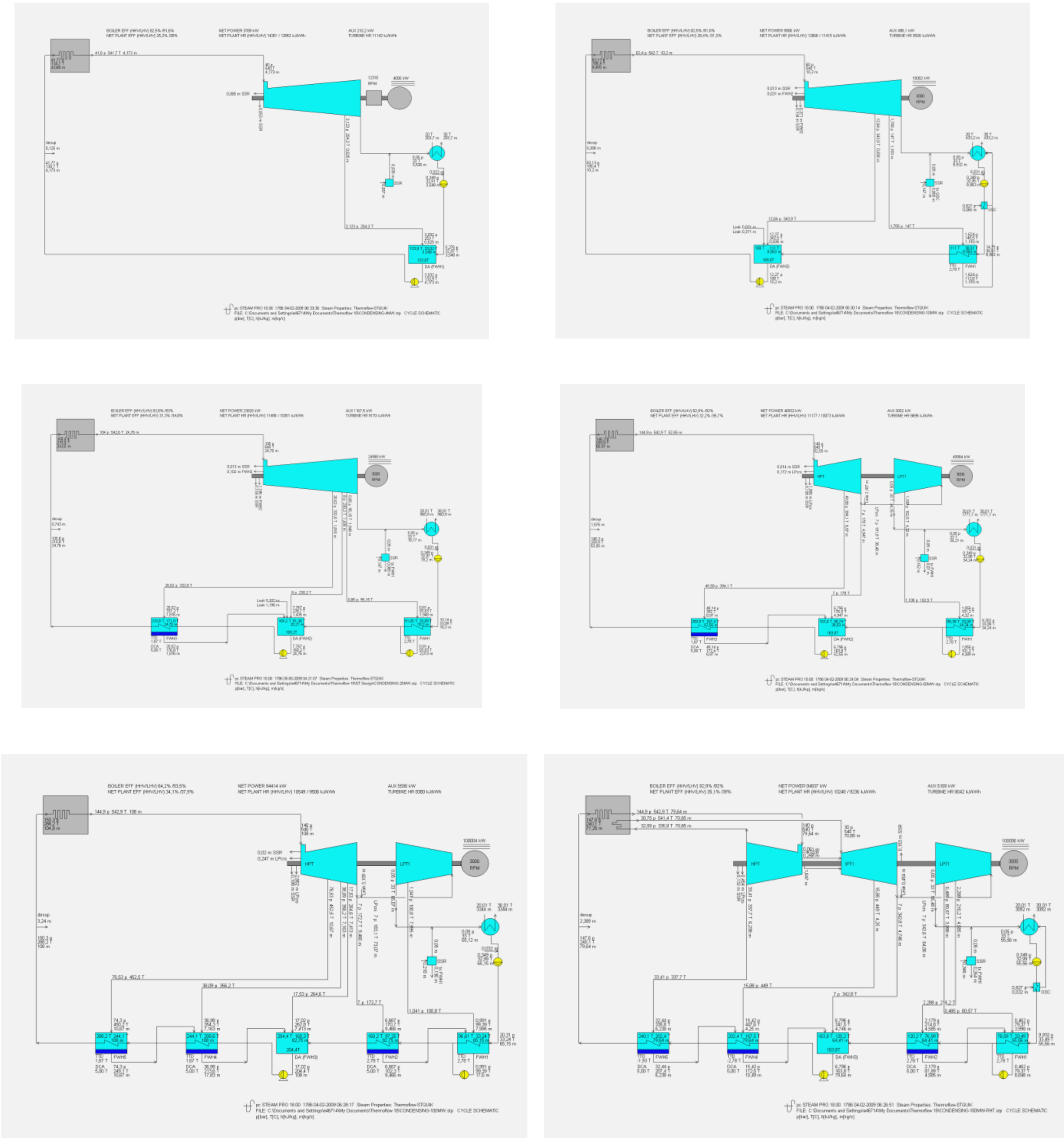
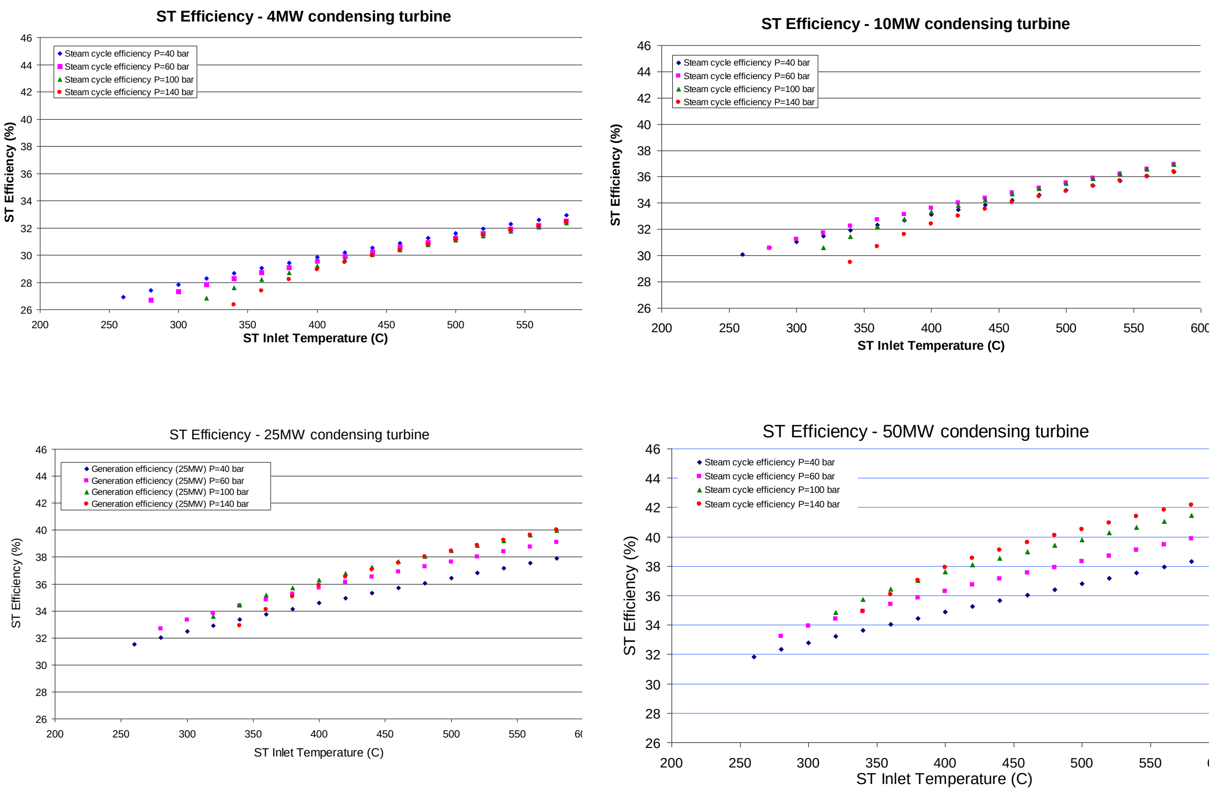
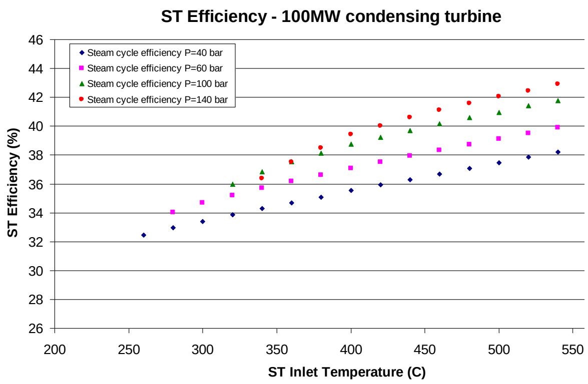


Figure 5-1: Condensing turbines at 4,10,25,50,100 and 100 with reheat MWe

The feed water heater configuration is selected to be the typical one for each size, as per industry practice, to reflect a reasonable balance between efficiency and cost. Further optimization of the selected designs, at a later stage, may yield additional small efficiency gains. The models were run for four pressures, 40, 60, 100 and 140bar. For each pressure a series of temperatures were considered, ranging from just above saturation up to 580°C, in increments of 20°C. The efficiency of the simulated turbine designs is plotted in Figure 5-2 for the 4, 10, 25, 50 and 100MWe designs respectively. A consistent trend in all cases is the increasing efficiency at higher temperatures, as expected from an elementary cycle analysis.

The 4MWe turbine results indicate the 40bar turbine inlet pressure to be the best option. At higher pressures the turbine leakage losses outweigh the thermodynamic cycle gains of the increased pressure. The 60bar turbine inlet pressure yields the best efficiency for the 10MWe turbine, while the 25MWe turbine attains its best efficiency at 100bar turbine inlet pressure. The 50MWe and 100MWe turbines reach their peak efficiencies at 140bar inlet pressure. This result holds true for all temperatures except the lowest ones (340°C and 360°C), where the 100bar inlet pressure yields slightly better of equal efficiencies.





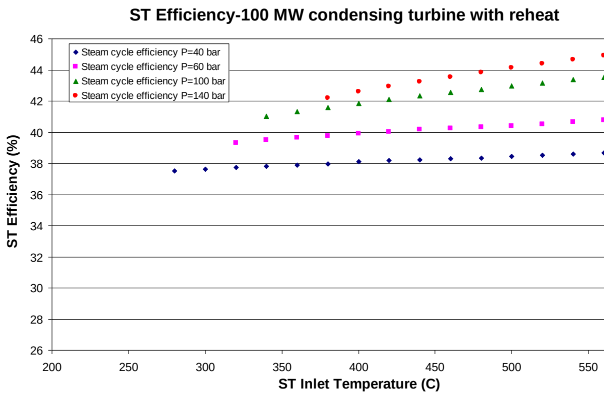


Figure 5-2: Condensing turbine efficiencies. Steam Turbine Efficiency is defined as the electrical power output/thermal input to turbine

Bearing in mind the turbine inlet temperature limitation at 540°C, mentioned above, the suggested optimum condensing turbine designs along with their key interface parameters with the solar field are summarized in Table 5-4.

Additionally to the above base case models, the 100MWe turbine was also simulated with a reheat loop included in the model as shown in
Figure 5-1. The results presented in Figure 5-2, as expected, show a marked efficiency improvement in all cases. It is of interest to note that lower inlet temperature designs benefit more from reheat than higher temperature ones. Should the project proceed with lower temperature inlet conditions, then the possibility of reheat must be seriously considered.

Condensing turbine summary table						
		Turbine size (MWe)				
		4	*10*	*25*	*50*	*100*
Efficiency	*%*	*32.29*	*36.24*	*39.22*	*41.37*	*42.92*
Inlet pressure	*bar*	*40*	*60*	*100*	*140*	*140*
Inlet temperature	*°C*	*540*	*540*	*540*	*540*	*540*
Inlet steam flow	*kg/s*	*4.17*	*10.2*	*24.76*	*52.55*	*108*
Return temperature	*°C*	*135*	*190*	*211*	*260*	*288*
Net heat consumption	*MWth*	*12.4*	*27.6*	*63.6*	*120.7*	*233*

Table 5-4: Optimum condensing turbine designs

5.3.4. Extraction turbine

The extraction turbine design is based on the condensing designs presented in the previous section. In this case, instead of designing for a particular plant capacity, the turbine inlet conditions (pressure, temperature and mass flow) are fixed to those of the selected, optimum, condensing turbine designs. An additional extraction port is added to the turbine, to supply the extracted steam to the desalination plant. Its supply pressure and flow rate can be varied within the appropriate design limits to investigate the effects of extraction to the available power and heat. All other design parameters, such as turbine casing configuration, heater supply pressures and boiler feedwater pressure and temperature, were carried into the extraction turbine design in as much detail as possible. The configuration of the extraction turbine designs is shown in Figure 5-3, for each of the five turbine sizes considered.

The general operating parameters of the various thermal desalination technologies are summarized in Table 5-5. While these parameters are not exact, they are fair approximations of the actual desalination plant conditions.

The extraction turbine was simulated for extraction pressures of 1, 2 and 6bar for the 4, 10 and 25MWe designs. For the 50 and 100MWe turbines the 6bar extraction pressure was reduced to 5.83bar, to avoid design modifications from the condensing turbine baseline design, which could possibly invalidate the comparison between the various parameters. The condensate return pressure was assumed to be 80°C in all cases.

	Supply pressure [bar abs]	***Condensate return temperature [°C]***
MSF	*2*	*90-95*
MED	*1*	*70-75*
ME-TVC	*6*	*70-75*

Table 5-5: Operating parameters of desalination plants

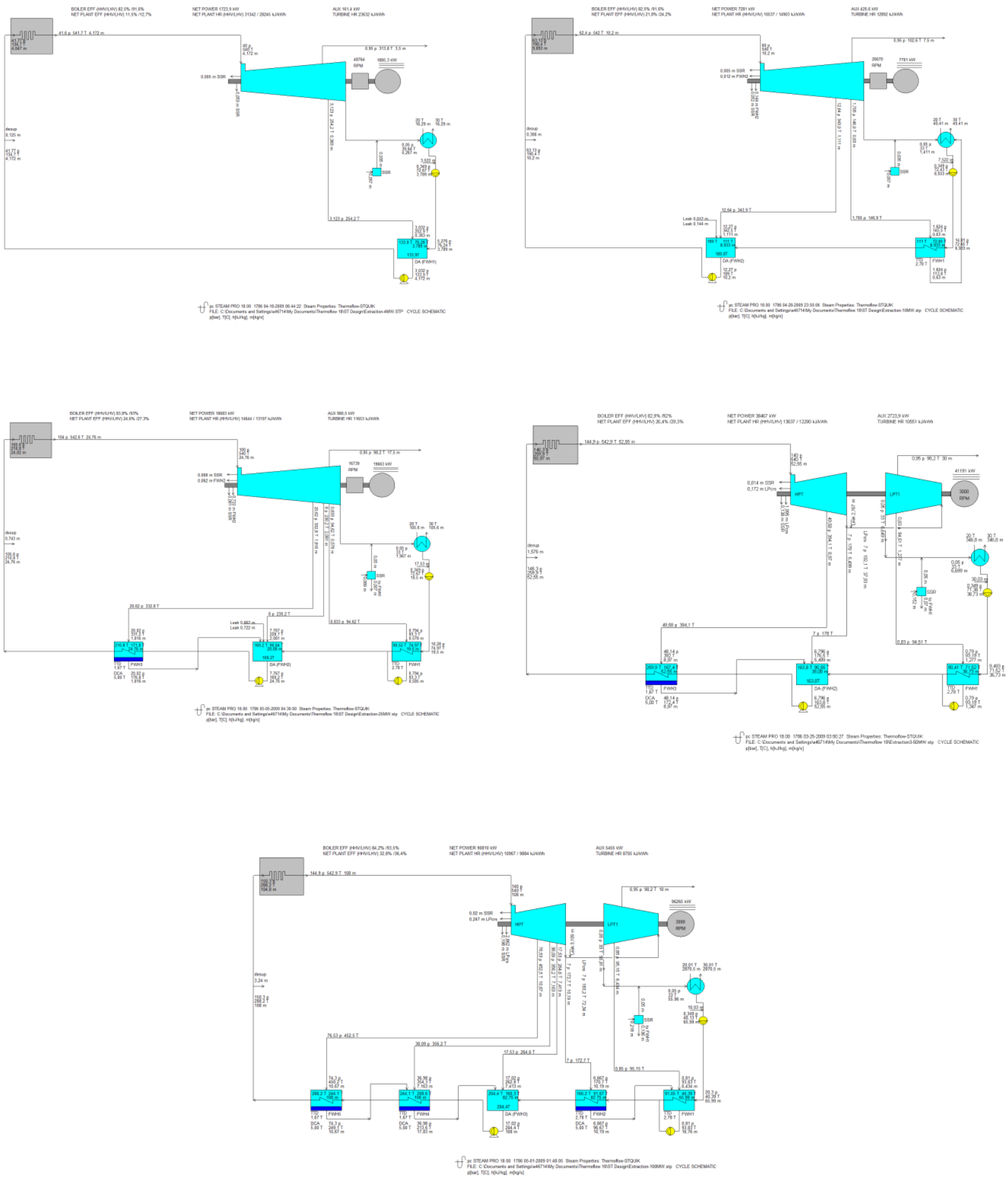


Figure 5-3: Extraction turbines at 4,10,25,50and 100 MWe

For each simulated plant size the extracted steam flow rate was varied within appropriate limits and step sizes, so as to have results for 6 to 7 extraction flow rates for each extraction pressure. As a validation, each model was also run with zero extraction flow rate and its results were verified to coincide with the condensing turbine design results. The efficiency of each size of plant is shown in Figure 5-4.

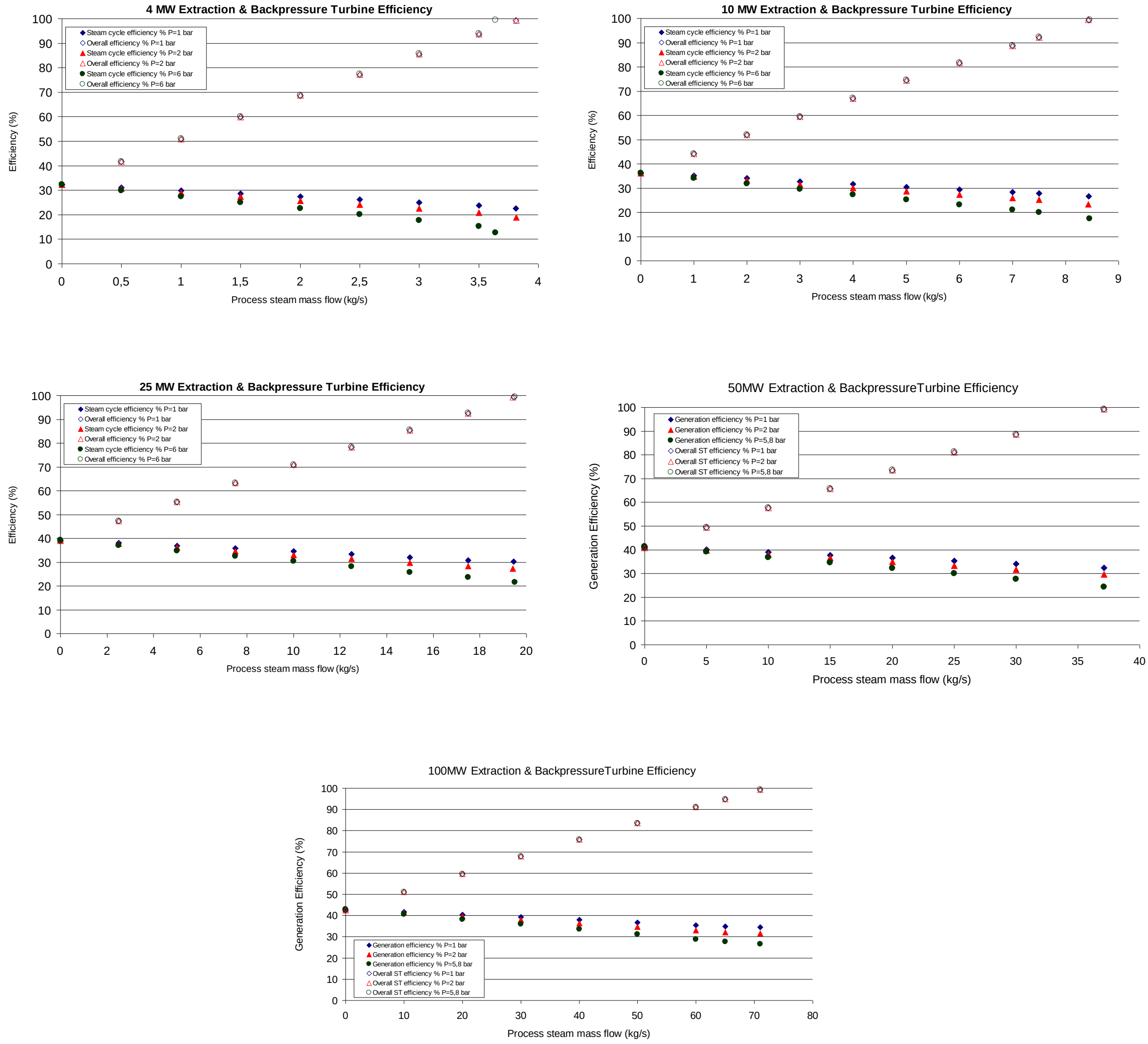


Figure 5-4: Turbine efficiency: Extraction and backpressure at 4,10,25, 50 and 100 MWe. The Overall efficiency corresponds to the ratio for thermal energy utilization

In all cases the generation efficiency (or turbine efficiency) is reduced with increasing process steam extraction, more so at increased extraction pressures. The Overall efficiency (ratio for thermal energy utilization), taking into account both electricity generation and heat output, shows significant improvements, as the amount of process steam is increased. It is notable that the overall efficiency is not affected by the extraction pressure, but depends only on the extraction steam quantity.

5.3.5. Back pressure turbine

To obtain a meaningful comparison, the condensing and extraction turbine design was replicated in as much detail as possible to the backpressure design, for each of the five plant sizes under consideration (Figure 5-5).

Extraction points for the feed water heaters were adjusted in number and pressure to correspond to the condensing turbine designs. This resulted in similar quantities of bled steam to the heaters and more importantly to the same return temperatures to the solar field. Also, as in the extraction turbine, the steam to the desalination plant was returned to the steam cycle at 80°C. The model was run with predefined turbine inlet conditions - pressure, temperature and flow rate - as in the extraction turbine models, and the exhaust pressure was sequentially adjusted to the three extraction pressures considered in the extraction turbine analysis. By necessity, the last heater, which was operating at a pressure of about 1-3bar in the original designs, is now operating at the respective turbine backpressure for each case. Also, the simulation program does not allow a split casing backpressure turbine, thus necessitating the use of a single casing turbine, with a small associated efficiency loss.

The results of the backpressure turbine simulations fall very nicely in line with the extraction turbine simulation results. In Figure 5-4 the backpressure turbine results are shown as the last point to the right, at highest mass flow rate to the desalination process.

The main advantage of the backpressure turbine is that is dispenses with the condenser, thus saving some capital costs. Aside from this, the backpressure design adds several difficulties in the design and operation of the plant. With the power and desalination plants coupled in this way, both will have to start-up, operate and shut-down simultaneously. Further, the ratio of power to desalinated water in this plant will be fixed at the time of design, in this way removing all the operational flexibility present in the previous two designs.

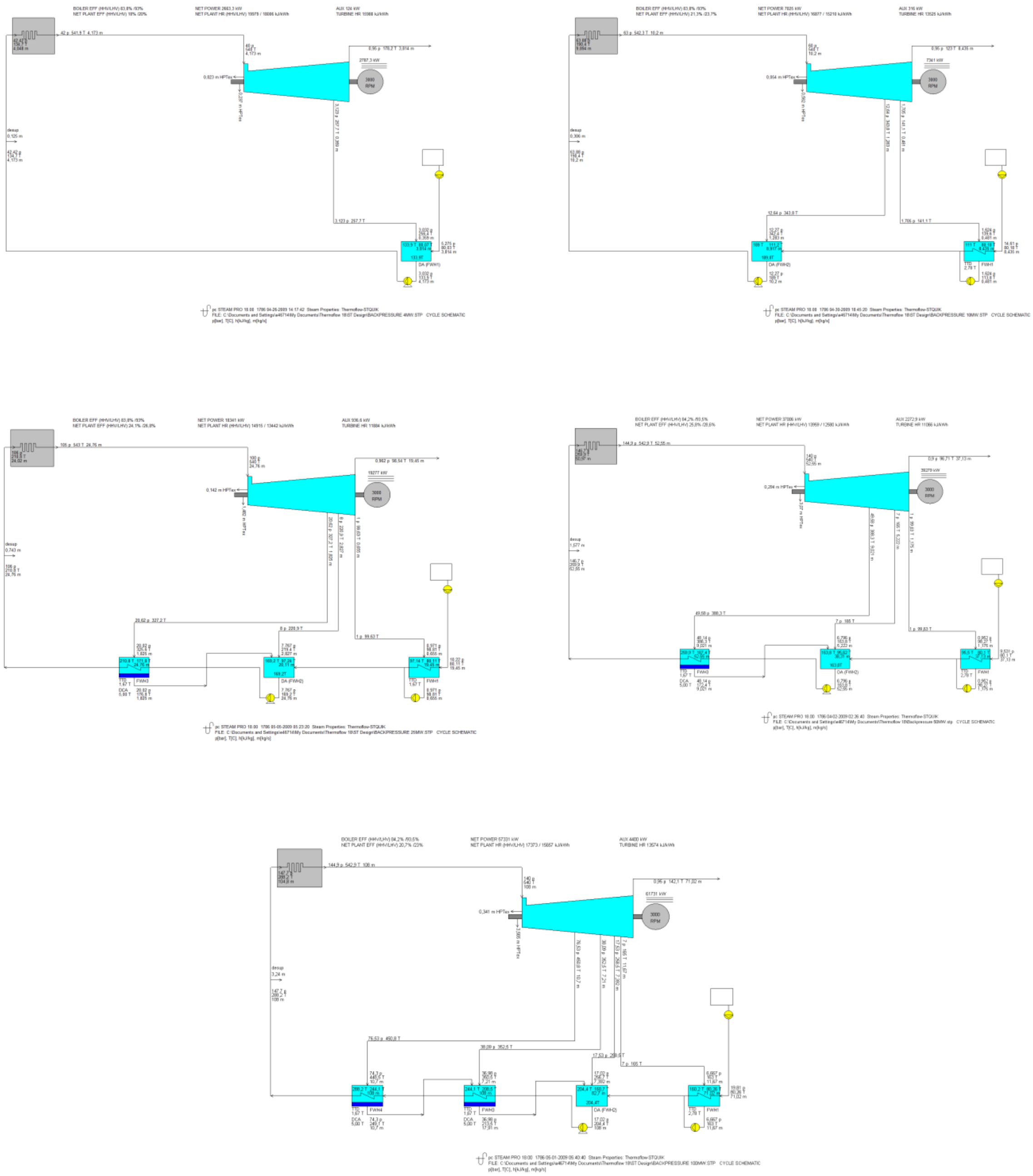


Figure 5-5: Extraction Turbines at 4,10,25,50 and 100 MWe

5.3.6. Discussion

The simulations run include condensing turbine designs for five turbine sizes (4, 10, 25, 50 and 100MWe) and for turbine inlet conditions that cover most of the range of standard industrial conditions. For each turbine size the appropriate steam inlet conditions, that yield the highest efficiency, have been identified. The electricity produced by the condensing turbine can be used to run a RO desalination process. Excess power can be fed to the grid, while in periods of solar plant shutdown the grid can supply the required energy to the RO desalination process.

If a thermal desalination process (MSF, MED) is to be coupled to the CSP plant then an extraction or backpressure turbine must be used, to supply the needed steam to the desalination process. Extraction and backpressure turbine designs for the five turbine sizes mentioned above have been simulated. The turbine inlet conditions, of mass flow rate, pressure and temperature, are fixed to the optimum conditions identified in the condensing turbine design. This approach in effect fixes the solar field size, for each plant size. In the extraction turbine varying quantities of steam are extracted from the appropriate turbine locations. The extraction point in effect dictates the extraction pressure and temperature. As the quantity of the extracted steam is increased the electricity output of the plant decreases, along with the associated generation efficiency, while at the same time increasing amounts of thermal energy are made available to the desalination process. Increasing the extraction pressure results in further electricity generation reduction, with an associated increase in the thermal energy made available for desalination. The choice of extraction pressure will depend on the requirements of the selected desalination process.

In the back pressure turbine design the condenser is replaced by the desalination process, which will now have to continuously handle all the turbine steam. Power generation and thermal power available for desalination are in line with extraction turbine results. The back pressure turbine, however, offers no flexibility in adjusting the power to desalination ratio, a feature which is available in the extraction turbine design. As this capability is considered important for the current project, it is recommended that the project proceeds with the extraction turbine design, in case a thermal desalination process is deemed advantageous to the RO process.

5.4. Conclusions

Today, steam turbines with widely varying configurations, sizes and application purposes are used extensively in the electricity generation and process industries. These steam turbines represent a significant part of the capital and operating costs of most plants, and therefore optimizing their selection and sizing is of major economic importance for the viability of the plant. However, the selection of the optimum steam turbine based on type and size for any given new plant is not a simple process, since a number of criteria have to be examined and be satisfied. The main criteria, apart from the economic ones, include the actual plant steam operating conditions at the interfaces to the steam turbine, the existing power system capacity, and the stability and reliability conditions and requirements that are in place to safeguard that the safe and reliable supply of electricity throughout the electricity network is not disrupted by the introduction of a new power plant.

In this work, the selection of the optimum steam turbine based on type and size for integration in the proposed concentrated solar power plant with desalinated water co-generation, to be built on the island of Cyprus, was performed. The main objectives of this work were to identify steam turbines suitable for power and desalination co-generation plants, to investigate the current and future Cyprus power system reliability and stability conditions and requirements and finally, to perform simulations for the actual selection of the most appropriate steam turbines.

The current and future Cyprus power system capacity, reliability and stability conditions were investigated via the use of the WASP software tool [7] which is a specialized simulation software used widely for the selection of the optimum expansion planning of the generation system. The actual selection of the optimum steam turbine based on type and size for integration in the proposed plant was performed by using the Steam Pro software module of the Thermoflow Suite 18 package. Simulations were run for 5 plant sizes, ranging from 4MWe to 100MWe, and for each plant size the optimum solar field interface conditions have been identified. To establish the steam turbine to desalination interface the three main desalination technologies, RO, MED and MSF, are considered and analyzed. Further three turbine configurations, condensing, extraction and backpressure, were simulated, each offering a different mode of interface to desalination.

Based on the input data and assumptions made, the WASP simulation analysis showed that future large scale deployment of concentrated solar power plants on the island of Cyprus will not disrupt the future stability and reliability of the Cyprus power system and that the reserve margin of the system is maintained above threshold values. Regarding the work on the actual selection of the optimum steam turbine for integration in the proposed plant, the Steam Pro simulations revealed that the most appropriate steam turbine type to be coupled to a RO desalination plant is the condensing turbine, with excess power to be fed to the grid while in periods of solar plant shutdown the grid can supply the required energy to the RO process. However, if a thermal desalination process is deemed preferable (either MSF or MED) to the RO process, then the extraction type turbine is recommended to be used.

5.5. Chapter References

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Chapter 6. Electricity Production and Demand in Cyprus

6.1. Electricity Production

Cyprus has no indigenous hydrocarbon energy sources and energy-wise is almost completely dependent on imported fossil fuels. In terms of renewable energy sources solar energy is solely and widely used for water heating in the domestic and tourist sector. It has been estimated that about 90% of individual homes, 80% of apartments and 50% of hotels are equipped with solar-water heating systems, making Cyprus the country with the world-wide highest installed solar collectors per inhabitant (1 m^2 of installed solar collectors per inhabitant).

For many decades the power industry in Cyprus developed on the basis of available technology and know-how, and today it constitutes a key sector of the economy. Until 2004 the Electricity Authority of Cyprus (EAC) [1] was solely responsible for the generation, transmission and distribution of electricity in Cyprus. This situation, however, changed and the electricity market in Cyprus is now open. A Regulator's Office [2] and a Transmission System Operator [3] have been appointed and new participants are expected to join the electricity sector in the future. However, at the moment, EAC is still the sole producer of electricity on the island and operates three thermal power stations with a total maximum capacity of 1168 MW. Future plans involve the installation of combined cycle technologies on the island using diesel as fuel in the first case and at a later stage natural gas when available to the island. The first combined cycle unit with capacity of 220 MW has begun operation in 2009, while two more combined cycle units of the same capacity are expected to be in operation after the year 2013.

Cyprus' power system operates in isolation and for electricity production relies totally on imported fuels such as, heavy fuel oil and diesel with a share of 98% and 2% respectively. Cyprus economic growth in the past 30 years averages 5.8% per year and 3.1% per year over the last 10 years. In order to support the economic growth experienced in Cyprus the electricity consumption has risen from 2181 GWh in 1995 to 4786 GWh in 2007. This is translated by an 89.6% increase, averaging to 8.1% per year [4].

As mentioned earlier, three thermal power stations are currently operational in the island with a total installed capacity of 1168MWe (see Table 1). Moni power station consists of 6x30 MWe steam turbines and 4x37.5 MWe gas turbines. Dhekelia power station consists of 6x60 MWe steam turbines and a 50 MWe internal combustion engine. Vasilikos power station is the most recent power station on the island and consists of 3x130 MWe steam turbines and a 1x38 MWe gas turbine. The steam units at Vasilikos are used for base load generation, while the steam units of Dhekelia are used for base and intermediate load generation. The steam units at Moni as well as the gas turbines are mainly used during system peak loading. All stations use Heavy Fuel Oil (HFO) for the steam turbine units and gasoil for the gas turbine units.

Future short and medium term expansion plans for the Cyprus generation system involve the commissioning of a combined cycle unit at Vasilikos power station with a capacity of 220 MWe by the end of 2009. During the first few years of its operation it will use gasoil as fuel until the arrival of the natural gas in Cyprus, which is expected to be available on the island after 2014. Two additional natural gas combined cycle units are expected to be installed at Vasilikos power station with a capacity of 220 MWe each by the year 2013-2014. Also in 2010 an additional internal combustion engine with a capacity of 50 MWe at Dhekelia power station is expected to be online. Other plans include the decommissioning of the first three steam units of Moni power station by the year 2013 and the decommissioning of the remaining three steam units one year later (after year 2013). The decommissioning of Dhekelia power station will be effected in three stages by withdrawing the first two steam units by the year 2014, the next two steam units by the year 2018 and the last two steam units by the year 2022.

Plant (MW)	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2018**	**2022**
Moni	330	330	330	330	240	150	150	150
Dhekelia	410	460	460	460	460	340	220	100
Vassilikos	428	648	648	648	1088	1088	1088	1088
Total	**1168**	**1438**	**1438**	**1438**	**1788**	**1578**	**1458**	**1338**

Table 6-1: Current and future electricity production capacity

Concerning the penetration of renewable energy sources for power generation, it is currently negligible in Cyprus. It amounts to a few cases of small PV systems installed in homes, and to a smaller degree, biomass gasification (using wood, agricultural wastes, olive kernels, almond husks, etc.). Despite the almost zero penetration of renewable energy sources technologies in Cyprus, a large amount of licenses have been recently granted by CERA pertaining to electricity generation from wind parks and to a smaller extent, biomass plants. The wind park installations that have been so far approved account for a total generation of 467 MWe, while there are still pending applications for approval for another 246 MWe of wind energy. The biomass plants that have so far been approved amount to approximately 8MWe Regarding concentrated solar power (CSP) technologies, a number of CSP plant license applications are currently pending approval at CERA.

In view of the new European Union (EU) energy policy for climate change [5] setting RES targets for year 2020 Cyprus' commitment to the EU to have a contribution by renewable energy resources will be 13% of the total energy consumed by 2020. A series of measures and incentives are currently being discussed that are expected to be announced in the near future. Briefly, solar thermal power plants are eligible for feed-in tariff with a ceiling of 25 MW by the year 2015 (for relevant tariffs see Cyprus Institute of Energy [6]). The purchase contract period is 20 years and the relevant feed-in tariff is €0.26 /kWh.

6.2. Energy Demand

Due to the increasingly dry and warm weather conditions of recent years, there has been a considerable increase in the demand for electricity, especially during the summer months (see Figure 6-1). In particular, in 2008, Cyprus was faced with situations where the demand was in some cases exceeding the maximum electricity production capacity of the 3 power stations, a situation which created many problems and should always be avoided as ideally the maximum capacity should always be 20% greater than maximum demand.

As expected, the demand for energy is expected to rise over the next years. According to scenarios and projections of EAC the peak demand is expected to rise according to the following Figure 6-2 [1].

Correlating EAC's forecasted production capacity as outlined in Table 6-1: with the forecasted peak electricity demand one can easily see that after 2014 the peak demand is forecasted to be greater than the production capacity of EAC. This by no means implies that the island's needs will not be covered completely. The reason for this is because it is expected that new companies will enter the electricity production market following the arrival of natural gas in the island and because RES are expected to have an impact by that time.

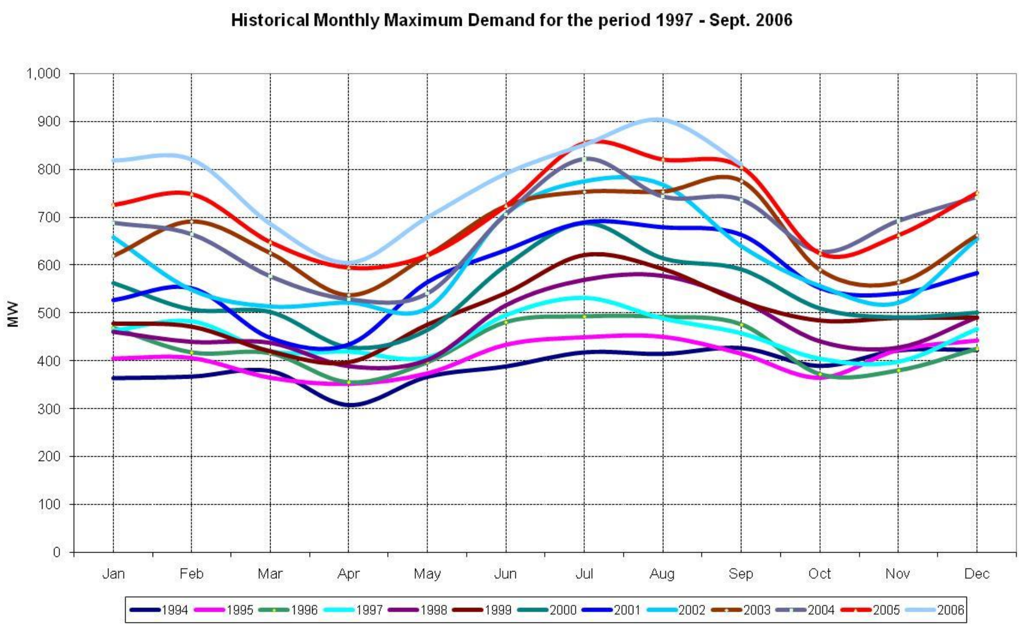

Figure 6-1: Variation of peak energy demand [2,3]

As far as the latter is concerned, it is worth pointing out that if Cyprus is going to be successful in meeting the EU RES directive and produce 13% of its electricity demand by RES, then by 2020 234 MWe will have to be produced by RES.

6.3. Cost of Electricity

The charging system that EAC uses for the price of electricity correlates the price of electricity with the price of the fuel used to produce it [1]. Specifically, the base price of fuel (currently HFO) is set at €85.43/metric tonne (MT) and the additional charge on the cost of electricity is 0.0014 eurocents/kWh for every 5 eurocent increase in the base price of the fuel – this additional charge is added on a fixed charge which relates to the units of electricity consumed by each consumer.

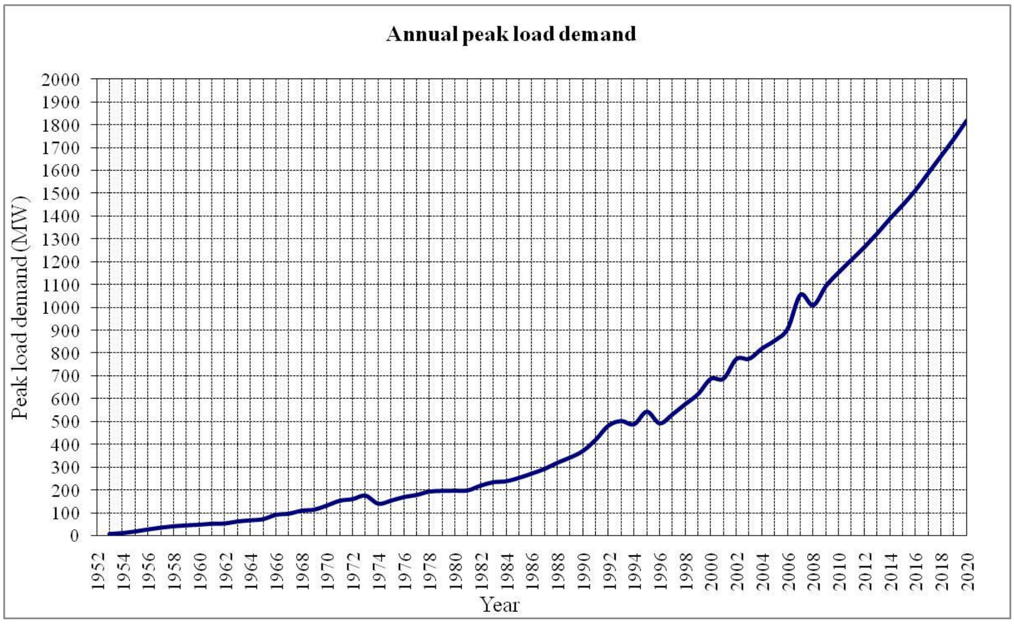

Figure 6-2: Forecast of peak electricity demand until 2020

To demonstrate how this system works, we can compare this additional charge in 2 cases: in August 2008 when the cost of HFO was €472.18/MT and June 2009, when the cost was €239.18. The additional charge to the fixed charge of electricity was €0.11/kWh (resulting in electricity costs being higher that €0.20/kWh) in August compared to €0.04/kWh in June 2009.

Given the above example it is easy to understand that predicting the cost of electricity in the years to come is not an easy task, since the cost of electricity directly relates to the price of the fuel used to produce it and if the current plan materialises, natural gas instead of HFO or diesel will be used for electricity production after 2014 [7] so the existing pricing model may need to be revised. In addition, it is worth pointing out that no work has started on the LNG terminal yet and hence no forward contracts have been signed for the supply of gas to Cyprus – both of these factors, including their hidden costs make it even harder to predict the price of fuel and hence electricity in the years to come.

6.4. Chapter References

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Chapter 7. Water Production and Demand in Cyprus

7.1. Water Demand – Desalination

Cyprus, like all other countries in the Mediterranean region, has a semi-arid climate and limited water resources. Following the independence of Cyprus in 1960, the Government of Cyprus placed great importance on water management in order to secure an adequate supply of good quality water to the island's inhabitants. The main policy of the Government, implemented through its relevant authorities, was to increase water supply by constructing dams and conveyance infrastructure under the motto "No drop of water to the sea". Due to this policy, the capacity of dams increased from 6 million cubic meters in 1960 to 327.5 million cubic meters today [1,2,3].

In addition to dams, groundwater (accumulated due to the limited surface runoff in Cyprus) has traditionally provided a resource of water needed for domestic use and irrigation. However, throughout the years, and due to the gradual decrease of rainfall, the groundwater resources of the island have been heavily over-pumped, especially during periods of drought. It is estimated that groundwater resources are overexploited by about 40% of the sustainable extraction level. The existing conditions have resulted in saline water intrusion and consequent quality deterioration in coastal aquifers and depletion of inland aquifers. Seawater intrusion in aquifers has also resulted in spoiling valuable underground water storage room. As a result, the contribution by groundwater to the island's water resources has significantly diminished during recent years.

With dams and groundwater being the primary water resources of the island, it has always been essential that water consumed during the dry summer months is replaced by the water of rainfall during the winter months. Over the last 30 years though, rainfall has gradually and significantly decreased (Figure 7-1), resulting in the gradual depletion of the water resources. It is worth pointing out that the average rainfall of the 1990-2000 decade decreased by 15% compared to the decades of 1960-1990 [1]. In addition, the frequency of draughts (<80% of average rainfall) has significantly increased with the decade of 1990-2000 experiencing 7 years of draughts.

The two major water-consuming sectors in Cyprus are irrigated agriculture and domestic use. Agriculture accounts for approximately 70% of total water use, while the domestic sector (which includes tourism) accounts for the remaining 30% of water use. The reduced rainfall of recent years had a heavy impact on the island's water resources, resulting in a reduction of 70% of the water resources available for agriculture and 20% of the resources available for domestic use. The conditions made it imperative for the Government to look for alternative methods by which to provide good quality water to the island's inhabitants – one obvious method, considering that Cyprus is an island, was sea water desalination and hence the first desalination plant in Cyprus was built in Dhekelia and started contributing fresh water to the system in 1997.

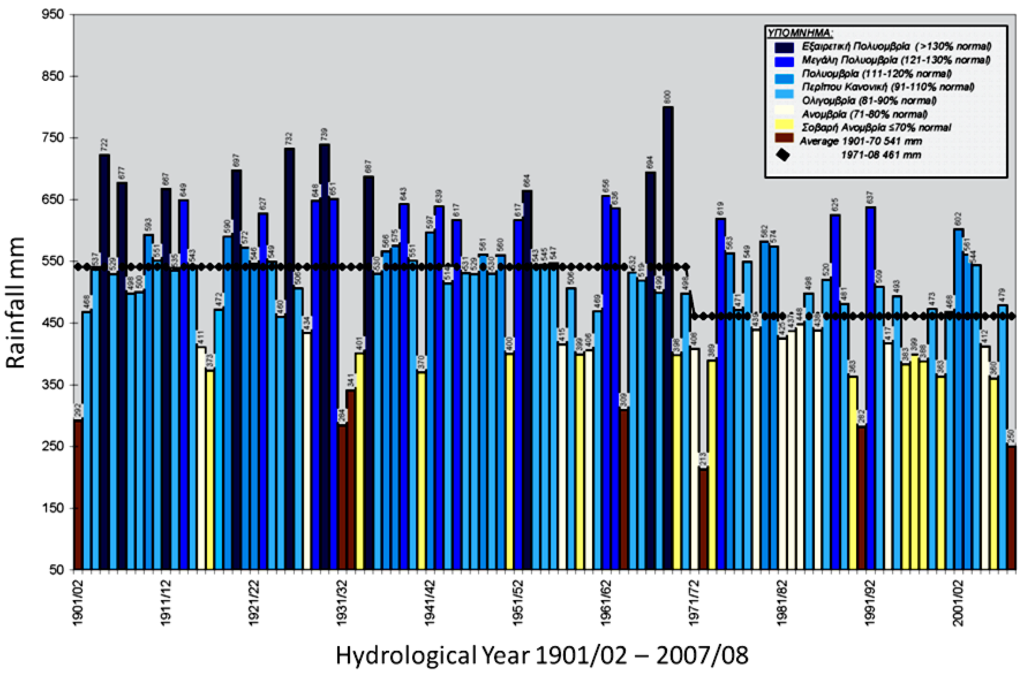

Figure 7-1: variation of rainfall during the last century [1]

Since then desalination, has played and will continue to play a major role in the supply of fresh, potable water for domestic use (Figure 7-2).

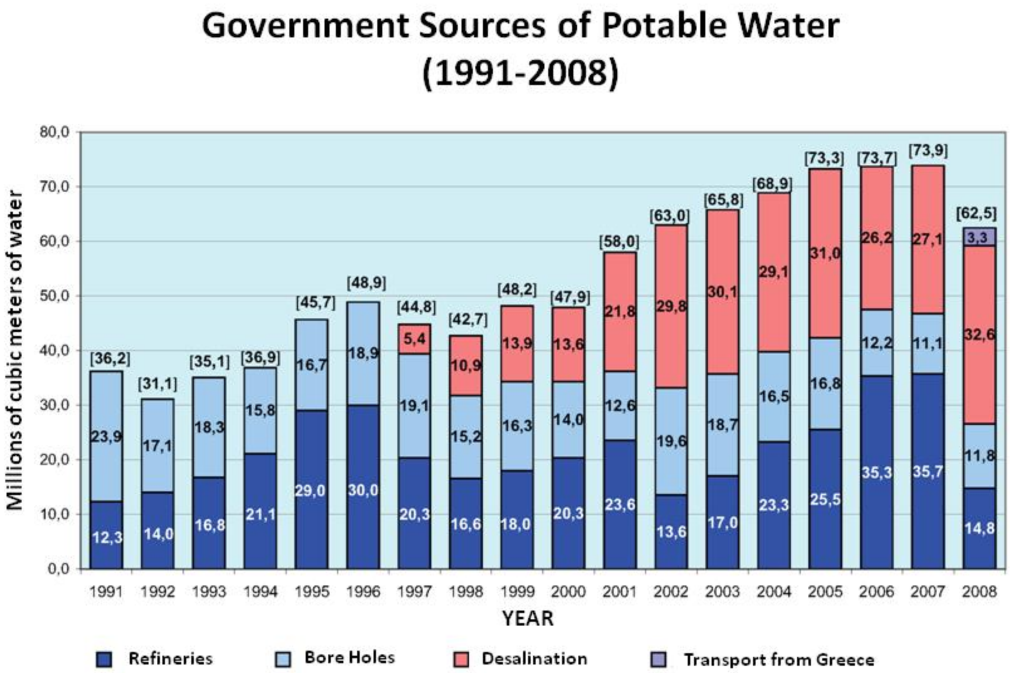

Figure 7-2: Sources of fresh water [1]

It is worth pointing out that conditions were so bad and resources so low in 2008, that water had to be shipped from Greece to Cyprus using specially modified tankers – this was at the huge cost of approx. €6-7/m^3 (compared to approximately €0.7-1/m^3 of the cost of water produced from the island's desalination plants). The needs and shortages of 2008 prompted the relevant authorities to increase the capacity of the 2 existing desalination plants (Dhekelia and Larnaca), fast track the commissioning of ship-based units and also approve the construction of new land based units. The desalination capacity over the next few years is forecasted as in Table 7-1.

The government of Cyprus is focusing its efforts to ensure that there is a guaranteed supply of fresh, potable water which can cover the demands in the island, irrespective of the weather conditions (i.e. rainfall). In addition, this supply of water has to be provided at the lowest possible cost to both the local authorities and in turn to the people – a prime example of how proper planning can prevent huge costs was the desperate but yet essential shipping of water from Greece at a price more than 6 times higher compared to the cost of water produced by the desalination units – furthermore, it is worth pointing out that the urgent increase in the capacity of the Dhekelia and Larnaca desalination units came at a premium cost, as the additional water produced was more expensive that the water produced from the existing capacity of the plants.

Production (m^3/day)	***2007***	***2008***	***2009***	***2010***	***2011***	***2012***
Dhekelia	*40,000*	*50,000*	*60,000*	*60,000*	*60,000*	*60,000*
Larnaca	*52,000*	*62,000*	*62,000*	*62,000*	*62,000*	*62,000*
Moni (ship based)			*20,000*	*20,000*	*20,000*	*20,000*
Garillis Aquifer			*10,000*	*10,000*	*10,000*	*10,000*
Paphos (ship based)				*30,000*	*30,000*	*30,000*
*Limassol***						*40,000*
*EAC***					*20,000*	*50,000*
TOTAL Maximum Capacity	*92,000*	*112,000*	*152,000*	*182,000*	*202,000*	*272,000*
TOTAL (m^3/year)*	***30,222,000***	***36,792,000***	***49,932,000***	***59,787,000***	***66,357,000***	***89,352,000***

** The total desalination capacity calculation of m^3/year assumes 365 day operation and on average 90% production of maximum capacity throughout the year.*

***The Limassol and EAC desalination plants are just in the preliminary planning phase – no official agreements have been signed yet*

Table 7-1: Desalination Capacity 2007-2012

To be specific, additional water (i.e. water produced following the capacity increases) cost from Dhekelia plant rose from €0.64/m^3 to €0.78/m^3, whilst from Larnaca plant the cost rose from €0.68/m^3 to €1.32/m^3. Finally, it is also worth pointing out that although ship based units, like the one in Moni can be commissioned within a short period of time and hence quickly address urgent demand, the cost of water is also much higher €1.32/m^3 compared to the conventional land based desalination plants [2].

The water shortage of 2008 was addressed with considerable cuts to each household, whereby the relevant water authorities limited the supply of fresh water to each household to 3-4 nights a week. This prompted people to use water much more conservatively, hence helping in overcoming the severe shortage – in 2008, 62.5 million m^3 of fresh water were consumed compared to approximately 73.5 million m^3 in the previous 3 years (2005-2007). Forecasts for water demand until 2020 are based on 2 scenarios: 1.13% and 2.26% population increase – included in these 2 scenarios, is the “population” increase due to increased number of tourists arriving in the island. Applying these demand increase scenarios to the demand of 2008 (Figure 7-3) one can see that the demand will vary between 72-82 million m^3 of fresh water in 2020 – Alternatively, if we apply the same scenarios to the 2007 demand (i.e. where no severe water cuts were imposed, we can expect a demand of 85-98 million m^3 in 2020.

Referring back to the table of planned capacity additions to the island’s desalination units and comparing these with the forecasted water demand outlined above, it can be easily concluded that if the government of Cyprus wants to decouple the supply of fresh water from rainfall and cover all its needs from reliable, non-weather dependent resources (i.e. desalination units) more desalination plants will have to be constructed in the island (EAC and Limassol units are still only in the preliminary planning phase so they are not considered to be certain planned capacity additions). In addition, ship based units must at some point be replaced by land based units which are capable of producing water at a much lower cost.

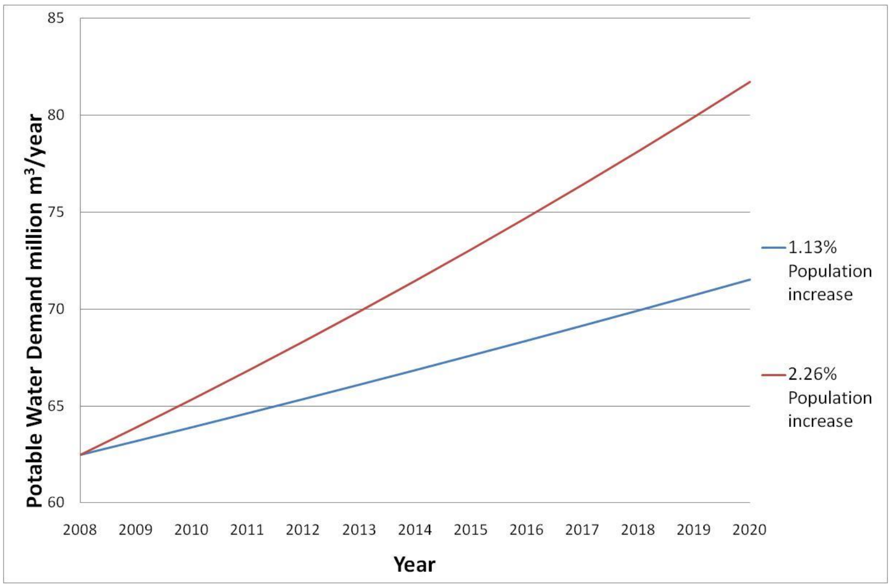

Figure 7-3: Water demand projections based on conservative water use of 2008

Since desalination is a very energy intensive process, special consideration must also be given to making sure that any new desalination additions are as “green” or energy efficient as possible.

7.2. Note on Desalination Costs

Desalination costs (to be specific for the case of Cyprus, desalination by reverse osmosis) have fallen significantly over the years. Figure 7-4, below is an estimate (since only 2 plants have ever been operational) of how the costs have fallen for an average desalination plant in Cyprus [4,5]. It has to be noted however that, as seen by the graph, we should not expect considerably significant further reductions in the cost of water produced by reverse osmosis desalination plants (which is the technology of choice in Cyprus) over the next years as reverse osmosis technology in now a mature technology. It is also important to understand that economies of scale play an important role in desalination [4,5] – it is more expensive to produce water from a small capacity plant than from a large capacity plant, with the critical size, i.e. the size after which capacity of the plant does not significantly influence cost of water being 50,000m^3/day [5].

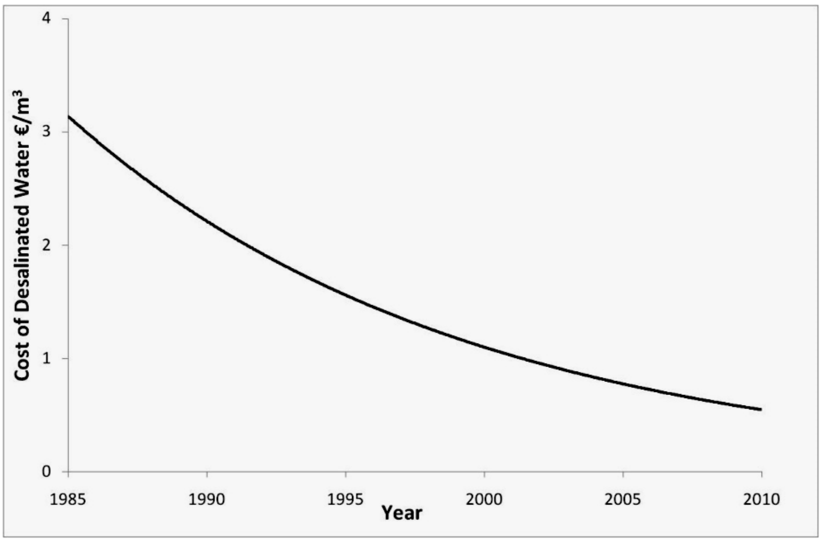

Figure 7-4: Cost of desalinated water produced by RO over the last 25 years. Compiled from data from the Cyprus Water Development Department.

7.3. Chapter References

[1] Water Development Department website: ***www.moa.gov.cy/wdd***

[2] 2008 Annual Report, ***Water Development Department***

[3] Cyprus National Report, ***Convention on Protection and Use of Transboundary Watercourses and International Lakes, 2004***

[4] Evaluating the costs of desalination and water transport, Yuan Zhou, Richard S.J. Tolb, ***Water Resources Research, 2005***

[5] Basic cost equations to estimate unit production costs for RO desalination and long-distance piping to supply water to tourism-dominated arid coastal regions of Egypt, A. Lameia, P. van der Zaaga, E. von Münch, ***Desalination 225 (2008)***

Chapter 8. Design and Modelling of a Solar-Powered Co-generation of Electricity and Desalinated Seawater plant

In this Chapter, a conceptual design for a co-generation of electricity and water plant which will be powered by concentrated solar power is presented. This design is optimized for Cyprus but also suitable for other islands and isolated coastal regions in the Mediterranean region. The proposed design of this plant is based on constraints that have influenced the technological choices, performance parameters and operating schemes.

The basic constraints for the proposed unit were the following:

- The unit must present a co-generation solution bespoken for Cyprus' needs and conditions. Cyprus has an isolated grid and is depended completely on fossil fuel.
- The unit must operate independently, i.e. powered only by the sun. It should not employ a combined cycle with fossil fuel. This crucially demands the presence of a storage solution with the capacity to allow a 24hour base-load operation.
- The unit must be able to combine both electricity and water production in the most efficient way. It is desired that all low-grade heat be used to enhance its performance and introduce savings into its operation.
- The availability of flat land by the coast is very scarce and when not, extremely expensive to be used for such projects.

Satisfying the constraints stated above has led to a design addressing the intermediate and long term needs of the island; it is not meant to provide a cataloguing of what might be available in the market today. The design employs technologies which are both commercially available and some that have not yet reached a level of technological maturity for base-load operation. In this Chapter, the integrated design of a CSP-DSW plant is presented. In the following Chapters, the components of the proposed plant are presented and analysed in detail and the level of maturity of each technology, as well as the shortcomings and challenges in the development of various components is identified.

8.1. Introduction

Seawater desalination by renewable energy sources (RES) has recently received considerable attention [25, 24, 12, 17, 16]. Utilization of concentrating solar power (CSP), in particular, for large-scale seawater desalination has been considered by several investigators, most notably, at the German Aerospace Center (DLR) [34], the Plataforma Solar de Almería [24] in Spain (the AQUASOL project). “Acquasol 1” project [20], a large-scale CSP-desalination plant currently under development in Australia, is also noteworthy. The present report deals with system-level models, systems integration, dynamic simulation, and systematic optimization of the plant for combined electricity generation and seawater desalination via solar-thermal energy. The conceptual design for the plant includes three major sub-systems: the solar energy collection and storage, the electricity and process steam generation, and the seawater desalination. Figure 8-1: Conceptual Process Flow Diagram depicts the conceptual process flow diagram. The conceptual design and the thermal storage medium of the CSPonD has gone under several major changes since the project has commenced. The system best understood by WP6 is selected for the models presented here. Specifically, a single storage tank filled with a nitrate salt (60 wt% $NaNO_3$, 40 wt% KNO_3) is considered here. Although a standard MED system from the literature is considered in the modelling and optimisation of the whole system, WP5 responsible for the design of desalination system, has designed and proposed a hybrid MED-thermal vapor compression (MED-TVC) design. Although the MED-TVC design was not considered due to time limitations in the system’s integration, the MED-TVC system has an advanced design with efficient heat integration schemes and will be presented seperately in a following section and compared, although it must be noted that the MED-TVC design has only be simulated in a one-dimensional modelling scheme.

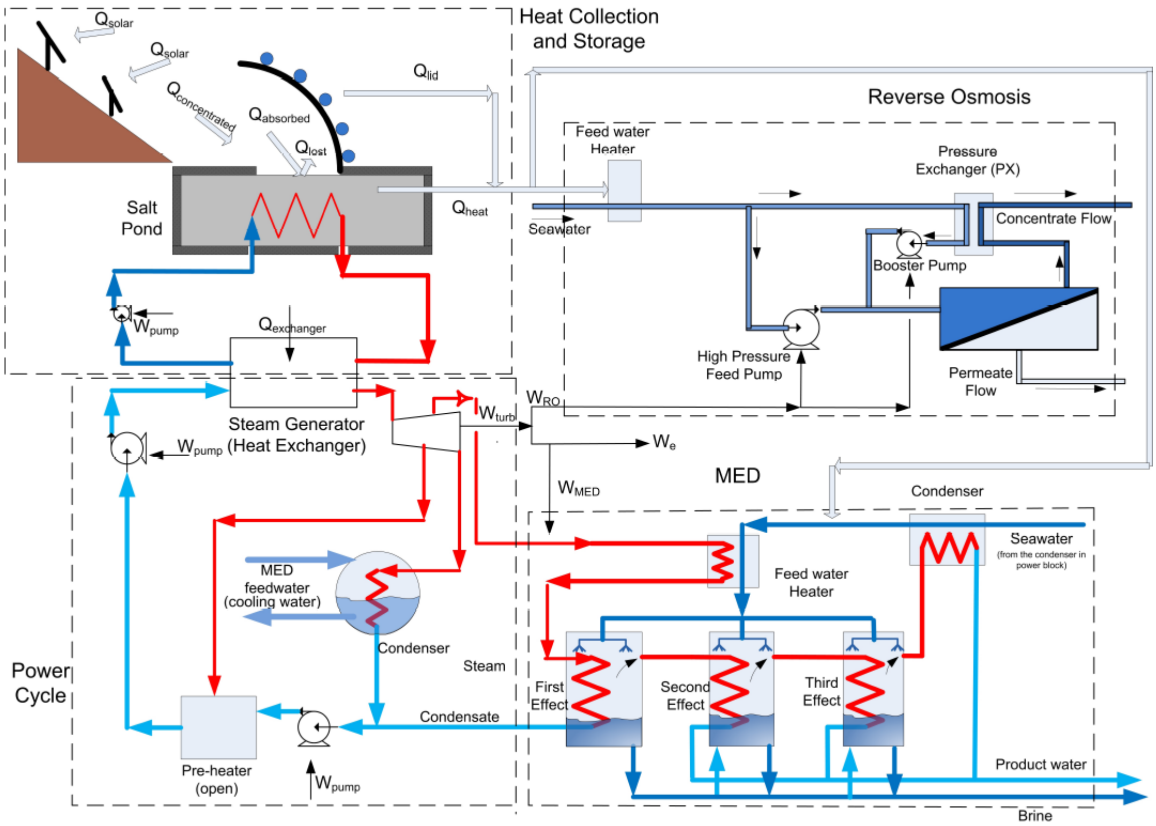

Figure 8-1: Conceptual Process Flow Diagram

8.2. Goals and Methodology

The goal of the study is optimization of operation for a plant based on technological considerations in collaboration with the other work packages. This is briefly described in the following, along with the tasks involved and the methodology implemented, or to be implemented.

8.2.1. Goals

There are two main goals, namely (i) selection of optimal process alternatives (i.e. process synthesis) and (ii) optimization of a given process (i.e., optimal design and operation). The former is based on technological considerations in collaboration with the other work packages. The latter is further split into optimization at nominal conditions and optimization rigorously accounting for time-variability and uncertainties. The approach proposed is model-based and utilizes concepts which are typically applied in the chemical industry.

8.2.2. Tasks

Modelling

Semi-detailed physics-based models are required for all elements of the plant prior to any optimization. Dynamic models are required rather than steady-state models due to the inherent dynamic nature of solar energy irradiance. The models need to be detailed enough to allow for implementing possible design and operation alternatives.

Process Synthesis

In process synthesis, alternate design and/or energy flow diagrams are investigated and the optimal process is selected. In the present project, several design options are already selected and set based on the experience, discussions among the project PIs, and/or literature review, e.g., the solar-thermal vs. photovoltaics; beam-down system vs. central receiver system vs. the CSPOND concept; and MED vs. RO vs. hybrid MED/RO for seawater desalination.

Optimization of the Nominal Process

The step following process synthesis is the optimal design and operation. The operation must be optimized, including the specification of operating temperatures, pressures and energy-flows.

Incorporation of time-variation and uncertainties

The incoming solar energy per unit time shows variation in at least three time scales (hourly due to position of sun; weather changes; seasonal variation; and random variation). The demands for water and electricity show similar time variability (with match or mismatch relative to the solar energy availability). Short-term variations are deemed to be handled by the thermal energy storage and suitable operating strategies (e.g., partial-load during overcast). These factors are incorporated in the design and operation of the system.

8.2.3. Methodology

The optimal design and operation is determined via dynamic optimization. A dynamic model of the entire plant, including heliostats, receiver, thermal storage, power generation and desalination is developed in an equation-oriented simulator, JACOBIAN [21]. The models are tested with measurements, available models in the literature, and/or commercial software packages (including STEAM PRO [38] models developed by WP4, led by the Electricity Authority of Cyprus). The sequential method of optimization is used where the optimization is decoupled from the simulation, thus resulting in relatively small optimization problems. Heuristic global optimization is performed, by combining a multistart procedure with IPOPT [35] as the gradient-based local solver. This procedure is parallelized in a cluster of distributed-memory PCs.

8.3. Technology

Solar-thermal power plants utilize the solar energy to generate electricity. The heat collected from converting solar energy to thermal energy is used in a conventional power cycle to generate electricity. The main components of a solar-thermal power plant are the energy collection system, the receiver system, the thermal energy storage, and the typical components used in conventional power cycles (e.g., steam turbines and generators). The receiver system converts the solar energy intercepted and reflected by the collection system. In systems with energy storage capabilities, such as the one proposed, the thermal energy in the receiver is first stored into a thermal storage medium to manage the variations in the solar energy influx. The storage system may contain sufficient thermal energy to continue the power generation overnight, or during days with overcast weather. A heat transfer fluid (HTF), possibly different from the thermal storage medium, transfers the energy from the storage medium to the steam generators in the power cycle. In WP3's design, direct coupling of the storage and steam generation is considered.

The intensity of the solar energy received by the collectors is only a few kWh/m^2/day. To achieve higher intensities and ultimately higher operating temperatures, concentrating solar power (CSP) technologies are used. In CSP systems, the surface area from which the heat losses occur, i.e., the receiver aperture, is significantly less than the total surface area of the collectors. Solar towers, parabolic troughs, and dish/Stirling systems are the main CSP technologies. The concentrating systems may also be classified based on the focusing geometry: point (solar towers and dish systems) and line focusing (parabolic and Fresnel troughs).

The technology considered here is the concept known as CSPonD [31]. A brief description suitable for the development of system-level models is given here. In this concept, heliostats positioned on a south-facing hill reflect the light directly onto the receiver on the ground. The potential advantages of this concept is elimination of the need for a tower and the corresponding salt pumping system to pump salts to relatively high altitudes. The receiver in the CSPonD design is a salt pond which also acts as the energy storage. Heat is extracted from the pond to generate steam. Extraction turbines are assumed for the electricity generation. Process steam is extracted from the turbine at various pressures. The extracted steam can be used for heating the condensed steam in the steam cycle (through open or closed feed-water heaters) and seawater desalination (both optional). The heat collected at the lid (i.e., the dome structure in Figure 8-1) is used for pre-heating the desalination feedwater. Detailed technical description of the CSPonD is not considered here, nor is the comparison between the CSPonD and the central tower systems. The reader is referred to the sections of the document that cover the energy receiver and storage system.

Hybrid desalination based on RO and MED is considered for seawater desalination. Recent advances in MED (e.g., reduced scaling, i.e., deposition of heat resistant materials on heat transfer surfaces, and development of advanced heat transfer areas [30]) has renewed the interests in MED. Similarly, RO is rapidly gaining popularity for seawater desalination mostly due to lower membrane cost and development of energy recovery units. Both RO and MED are included in models, mainly to compare RO, MED and hybrid RO/MED, and hence select a suitable desalination technology. RO has a lower energetic requirement than MED in both single-purpose (water only) and dual purpose (water and power) plants [29]. However, the availability of low grade heat from the lid as well as by extraction from the turbine makes the selection of the most suitable desalination system for the proposed plant a non-trivial problem. The proposed method for integrating the collected heat from the lid in MED is pre-heating the feedwater. A potential advantage of having a hybrid RO/MED is blending of the product water from a single-stage RO, resulting in low capital cost and relatively low water quality, with the product water from an MED system. For instance, as it is well-documented [27], the product of RO system in Mediterranean regions may need expensive post-treatment to reduce the Boron level to an acceptable level. Blending the permeate from these two system may eliminate the need for such post-treatment and, in general, result a better overall product quality.

8.4. Modelling

The developed plant model has three major sub-models: solar energy collection and storage, power generation, and seawater desalination. System-level models are developed based on the best available model in literature or developed from first principles. The models calculate the energy and mass balance in each sub-system. Most importantly, the models calculate the instantaneous solar energy influx to the receiver, the transferred energy to the power block, and the energy (thermal and electric) available to the desalination facility and provided to the power grid. Further, models are developed to calculate the energy consumption and production rate of the seawater RO (SWRO) and MED processes. The main sub-models are described in the following sections.

8.4.1. Solar Irradiance

A detailed model [5, 3] is used to calculate the hourly distribution of solar irradiance. The beam (direct), diffuse, and global irradiance (sum of direct and diffuse) on the earth surface are calculated. The model takes into account the optical transmittance through scattering (Mie and Rayleigh scattering) and absorption. The model calculates both beam and diffuse radiation as a function of location (latitude and longitude), time (day and hour), and the weather conditions (relative humidity and visibility). The inputs used to calculate the beam, diffuse, and global irradiance in Cyprus are shown Table 8-1.

Parameter	***Value***
Geographic longitude θ	*33° E*
Geographical latitude ϕ	*35° N*
A coefficient required to calculate aerosol scattering α	*1.3 (the suggested typical value)*
Turbidity coefficient β	*0.1 (the suggested value for visibility of 29 km)*
Solar constant I_0	*1366.1 W/m²*
Relative humidity RH	*70%*
Site's height H	*50 m*

Table 8-1: Key inputs used with the solar irradiance model

As shown in Figure 8-2, there is a good agreement between the model predictions and measurements [7] on the ground in Cyprus. The models predictions also agree well with the published data for the daily global radiation on a horizontal plate in Cyprus [18, 14]. It should be noted that the model is not based on fitted parameters on measurements, i.e., the parameters used in the solar radiation model are based on the location and weather conditions listed in Table 8-1.

The model has been tested under various conditions and the results show that it captures the effect of seasonal changes, the weather conditions and location on the beam irradiance very well. Additional figures showing a good agreement between the model predictions and the measurements on the ground and/or the published data are available in the Conceptual Design Report [2] prepared in July 2009 by the system integration and optimization group. The model effectively provides the necessary tools to accurately simulate the input solar power to system. Furthermore, several weather scenarios and seasonal changes can be easily modeled and the corresponding operation strategies can be studied.

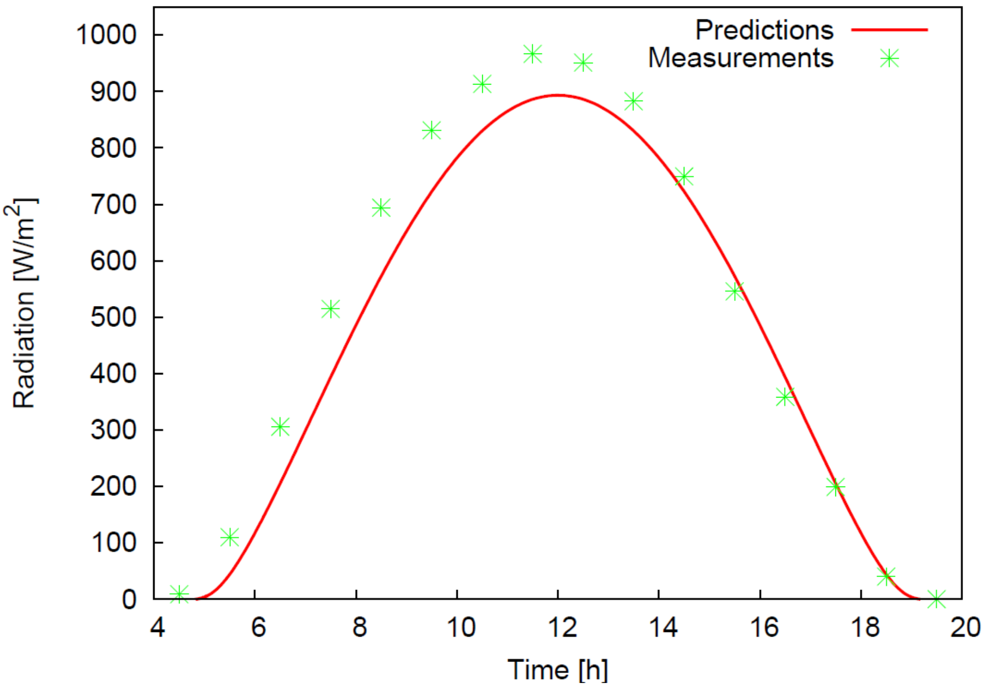

Figure 8-2: Model predictions for the global irradiance compared with measurements on ground. Measurements are from Cyprus Meteorological Data from MENOGEIA Station (June 21, 2004).

8.4.2. Heliostats

Heliostats are reflecting mirrors that track the sun in two directions throughout the day. A drive system adjusts the orientation of individual mirrors continuously to ensure that the reflected sun's rays that bounce off the mirror are directed towards the receiver system. This is to maximize the overall energy flux concentrated onto the receiver.

Shading and blocking, and the size of the reflected image from the heliostats put design limits on the heliostats' layout. Shading refers to the blockage of the incoming rays from receiving the heliostats, and blocking refers to the blockage of the reflected rays from one heliostat by another heliostat. Hence, shading and blocking put limits on the usage of the ground. As a result of these design limits, the ground usage, defined as the ratio of the total area of heliostats to the total area of the heliostats field, is around 0.3-0.5 for traditional central receiver systems on flat land [13]. Ray-tracing methods are commonly used for optical analysis of the heliostats [11].

The three most important parameters required to calculate the energy reflected onto the receiver are: a) the mirrors' reflectivity, b) the so-called “cosine efficiency” [37], and c) the shading and blocking effects. The algorithm described in Heliostat Placement is used for calculation the cosine efficiency, spillage, shading and blocking.

8.4.3. Receiver

The receiver system considered is a salt pond that receives the concentrated solar energy through the aperture. The net energy collected in the pond is the summation of the energy reflected into the pond from all heliostats, minus the radiation and conduction losses. Following the CSPonD concept, the receiver system (the salt pond) is the energy storage medium too. The temperature distribution in the pond is assumed approximately uniform; however, the salt temperature changes with time as a function of the energy withdrawal rate from the pond, the thermal energy losses, and mass of the salt in pond. The salt pond also has a lid (i.e., a dome structure partially covering the pond). The lid captures the energy contained in the evaporated salt from the pond. The percentage of radiation heat losses from the pond captured by the lid is a function of geometry and size determining the view factor between the pond and the lid. It is hypothesized that the salt evaporated from the pond condenses on the lid, re-melts and re-enters the pond. Simple spreadsheet calculations showed that the mass losses from the pond, and therefore the decrease in total energy storage capacity of the pond due to evaporation, are negligible. It should be noted that the effect of salt condensing on the lid, and the ensuing re-melting, followed by re-entering to the pond, is neglected here. This is due to the uncertainties around the effect of such phenomena on the lid temperature. It is our understanding that the CSPonD team is considering these issues in their design, but no conclusion has been conveyed to WP6 yet. The energy captured by the lid (i.e., fraction of radiation heat losses from the pond, neglecting the energy from condensing salt) is used elsewhere in the plant, e.g., feed-water heaters in MED or RO. However, WP6 is now considering the possibility of using the collected heat for pre-heating water before the steam generator. The input parameters used for the salt pond are listed in Table 8-2.

Parameter	Value	Description
$A_{heliostats}$	10^5 m^2	Total mirror area
D_{pond}	25 m	Pond diameter
D_{lid}	25 m	Diameter of lid
$A_{aperture}$	200 m^2	Aperture area
M_{salt}	14080 Mg (Ton)	Total mass of salt
$T_{\min}$	538 K	Minimum allowable salt temperature
$T_{\max}$	873 K	Maximum allowable salt temperature
C_p	1.607 kJ/kg/K	Heat capacity of salt mixture

Table 8-2: Key input parameters used for thermal energy receiver and storage.

8.4.4. Multi-effect Distillation

In MED, the latent heat of condensation is used in a series of evaporators to produce fresh water from seawater. The steam extracted from the turbine is condensed in the first of effect of the MED system. The condensate returns to the steam cycle, while the vapor generated from the first effect enters the second effect. The latent heat of condensation of the vapor entering the second effect is used to generate vapor in the third effect, and this process is repeated subsequently to the last effect. In each effect, seawater is sprayed on the tube bundles containing steam, i.e., if each effect is assumed a tube-shell heat exchanger, the tubes contain steam and the shell contains seawater. The pressure and temperature decreases from the first stage (hottest) to the last stage (coldest) successively.

The performance of the MED process (defined as the energy and cost per unit of fresh water produced) has significantly improved due to recent advances in this industry. The development of thin film technology in plate type heat exchangers has presented an important breakthrough for MED [28]. In addition, the introduction of efficient scale inhibitory chemicals has reduced scaling in MED effects. Scaling in MED, which is mostly due to spraying the feed water with high salinity on the heat transfer tubes, puts limits on operating temperatures. An 8-effect MED system with parallel feed system is considered herein corresponding to standard designs for this scale. In Chapter 11 a novel MED-TVC design is proposed with higher GOR and less power requirement. ~~A similar feed~~

~~arrangement but with higher number of effects is considered by the desalination research group at the University of Illinois at Urbana-Champaign (UIUC). It is also understood that the design presented by WP5 (desalination research group) uses an steam ejector that would create the required partial vacuum in all effects. Briefly, steam ejectors use the potential energy of a high pressure stream ("a motive fluid", here a small fraction of the steam extracted from the turbine) to velocity energy which in turn creates a low pressure zone that draws in and entrains a suction fluid (here non-condensible gases (NCG) from the last effect). Hence, steam ejectors reduce the power requirement of MED significantly. Steam ejectors require steam to be extracted from the turbine at relatively high extraction pressures. On the other hand, the power lost due to extraction at extraction pressures higher than 1 bar becomes very significant.~~

The heat rejected by the condenser in the power block (Figure 8-1) is used to pre-heat the MED feedwater, which is further heated at the lid and then by the steam extracted from the turbine (both optional). Seawater desalination by MED is simulated using the models developed by Darwish et al. [10, 8, 9].

Parameter	***Value***	***Description***
T_{steam}	*65-90 °C Depending on optimal parameters*	*Charge steam temperature*
$N_{effects}$	*8*	*Number of effects*
C_{feed}	*42 g/L*	*Concentration of feed water*
T_w	*Depends on optimal operating conditions*	*Feed water temperature*
$C_{brine}^{\max}$	*80 g/L*	*Maximum allowable brine concentration*
M_{feed}	*Depends on optimal operating conditions*	*Feedwater flow rate*
TBT	*Depends on optimal operating conditions*	*Top brine temperature*
L	*2382 kJ/kg*	*Latent heat of vaporization and condensation*
C_p	*3.9 kJ/kg/K*	*Average specific heat capacity of water*
BPE	*0.7 K*	*Boiling point elevation*
ΔT	*2 K*	*Average temperature drop across effects*

Table 8-3: Input parameters of the MED model

The electric energy consumption of MED, although relatively small compared to the thermal energy requirements of MED, is not negligible. The reported numbers in literature are as high as 2.3 kWh/m^3 [4]. A constant 2.0 kWh/m^3 is assumed here for the electricity consumption in MED. As it will be shown in the following, the temperature range considered here is slightly higher than the temperature range considered for typical MED systems. Hence, a lower vacuum is required (i.e., higher operating pressures), and therefore the use of an average electricity consumption as 2 kWh/m^3 is justified. Main design parameters of the MED system considered here are given in Table 8-3.

The most basic performance indicators for MED are the gained output ratio (GOR), defined as the mass of distillate water to the charge steam, and the minimum required specific heat transfer area (SA) [10, 8], defined as the heat transfer area required per unit volume of the distillate water. High GOR and low SA (specific heat transfer area requirements) are desired. GOR is calculated from the optimal operating conditions while SA is not considered in the optimization as it requires detail cost models for the entire process.

8.4.5. Reverse Osmosis

RO is a membrane-based, pressure-driven filtration technology. Semi-permeable membranes used in water desalination have high permeability for water and very low permeability for dissolved substances. Hence, by applying a pressure difference across the membrane the water contained in the feed water is forced through the membrane whereas most of the dissolved substances are rejected. The water passing through the membrane, i.e., the permeate water, has a low concentration of dissolved substances. The concentration of dissolved substances in the permeate flow is a function of the feed water quality and membrane characteristics. The permeate flow rate is a function of several parameters such as feed pressure, feed-water total dissolved concentration (TDS), membrane characteristics, and recovery ratio, defined as the ratio of the permeate flow rate over the feed water flow rate. The performance of RO is also affected by several other phenomena such as fouling and concentration polarization. Thorough discussion of these phenomena is outside the scope of this article; they are explained in detail elsewhere (e.g.,

[39]). However, they are briefly introduced here because they are important parameters that affect the performance of an RO system significantly. Membrane fouling refers to the accumulation of foreign materials on the active surface membrane. In presence of the fouling layer on the surface of the membrane, the resistance of the membrane to the flow of water through the membrane increases. Consequently, fouling affects the pressure requirement for the RO, and hence the energy cost of the process. Concentration polarization refers to the concentration of solute at the vicinity of the membrane surface, i.e., its boundary layer. The solute concentration in a thin boundary layer at the feed side of the membrane surface is higher than the solute concentration in the bulk of the feed water. Like membrane fouling, concentration polarization has effects on the permeate water flow rate and the minimum required feed pressure. To prevent membrane fouling, RO requires relatively expensive pre-treatment compared to a low temperature MED.

The pressure difference across the membrane must be higher than the osmotic pressure difference between the feed water and the permeate water. Osmotic pressure is the pressure produced across the membrane due to the total dissolved solids (TDS) concentration difference between the solutions on the two sides of the membrane (feed and permeate). In seawater RO (SWRO), the feed pressure required to overcome the osmotic pressure of the feed side is high (50-80 bar, depending on the concentration and quality of the feed water). The pressure difference between the feed and concentrate streams is small (1-5 bar). Hence, the concentrate flow contains a considerable amount of energy that is usually recovered using various energy recovery systems such as pressure exchangers [6, 15] or Pelton wheel turbines [1].

The actual energy consumption of the RO process is required for the system-level model. Unfortunately, most of the available RO models in literature give the minimum energy requirements for separation, which is significantly lower than the actual energy consumption of the SWRO. Furthermore, they do not consider several non-idealities such as concentration polarization and fouling formation. Here, a model developed by leading membrane provider DOW Chemical Company [23] has been extended by the authors [26] to estimate the actual energy consumption of SWRO using FILMTEC SW-380 membranes, which are large, high-flow membranes with low energy consumption. High efficiency pressure exchangers (PX) are also assumed in the model for estimating the recovered energy from the high pressure concentrate flow. The DOW model was also modified to account for variable loading conditions.

The permeate water flow rate is directly proportional to the membrane's active surface area S_e, the permeability of the membrane A_{perm}, and the "net driving pressure" P_{net}, which in return is a function of the feed pressure at the inlet of the vessel P_f, the osmotic pressure in the concentrate flow $\overline{\Pi}$, and the average pressure losses between the feed and concentrate flows: $P_{net} = P_f - \overline{\Pi} - \Delta P_{fc}/2$.

Constants	*Unit*	*Value*
Feed Salinity C_f	*g/L*	*35* [4]
Feed Water Temperature T_w	*K*	*298* [5]
Membrane's Effective Area S_e	m^2	*35*
Total Number of Elements N_e	-	*64*
Membrane's Permeability A_{perm}	*l/m*^{2} */h/bar*	*1.2*
Fouling Factor FF	-	*0.85*
Membrane's Salt Rejection Rate r	-	*0.9975*
Inlet Pressure at the Suction of the High Pressure Pump P_{in}	*bar*	*3*
Efficiency of Pressure Exchangers η_{PX}	-	*0.95*
Efficiency of High Pressure Pump η_p^{hp}	-	*0.90*
Efficiency of Booster Pump η_p^{hp}	-	*0.60*
Efficiency of Electric Motors η_m	-	*0.95*
Efficiency of High Pressure Pump η_{VFD}	-	*0.96*
Feed Pressure at the Inlet of Pressure Vessels P_f	*bar*	*70*
Average Pressure Loss per Vessel ΔP_{fc}	*bar*	*2*

Table 8-4: Constants used with the RO model

[4] *35 g/L is the condition used for generating Fig. 3. The value used for the Cyprus is 42 g/L.*
[5] *298 K is the condition used for generating Fig. 3. The value used for the operation of the plant considered here depends on optimal operating conditions.*

Other factors that affect the permeate water flow rate through the membrane are the feed water temperature T_w, membrane fouling effects, and the concentration polarization, which increases the membrane's overall resistance to the flow through the membrane. DOW's semi-empirical models give a very good estimate of the permeate flow rate and the energy consumption of the RO systems. Figure 8-3 show the specific energy consumption of the system obtained from sample runs of the RO model under the conditions shown in Table 8-4. As shown in Figure 8-3, the energy recovery units recover significant amount of energy pertained in the concentrate flow, especially at lower recovery ratios. The lowest energy consumption is at a relatively low recovery ratio (Figure 8-3) for the system considered. One should note that this is not necessarily the optimal operation point.

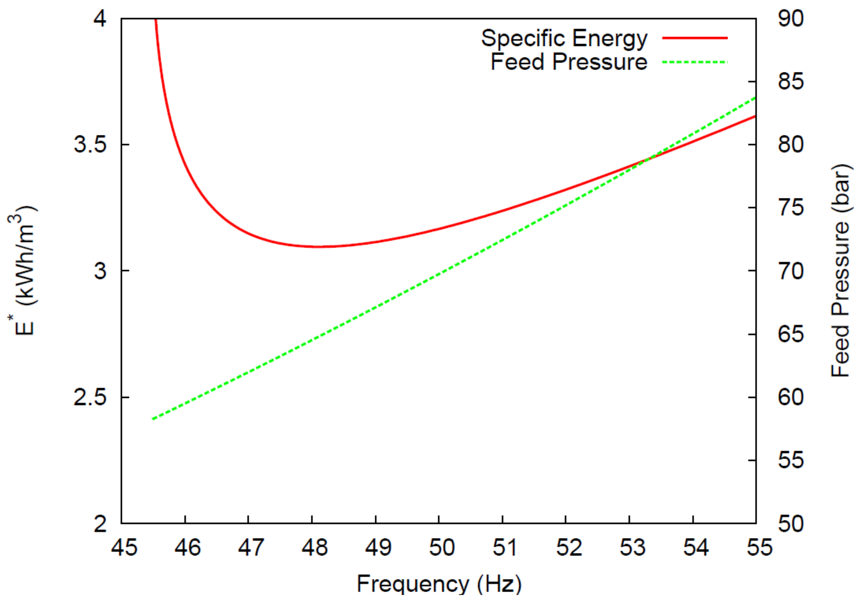

Figure 8-3: Specific Energy Requirement of the RO System

That is, high recovery ratios reduce the pre-treatment chemical costs, while low recovery ratios here lead to a lower energy consumption. Hence, a true optimal recovery ratio depends on the relative costs of these operations.

Published reports and papers on actual RO plants in operation do not provide the complete system specifications and operating conditions, namely, the feedwater salinity (before and after pre-treatment), membrane size and model, number of membranes in the system, feedwater temperature, etc.

Key Inputs		
Feed Flow Rate [m^3/d]	*3750*	
Recovery Ratio	*0.4*	
Total Number of Elements in System	*64*	
Total Active Area [m^2]	*64 x 35*	
Key Outputs - Case 1: $TDS = 35000$ ppm, $T_w^{RO} = 25^\circ C$		
Description	**JACOBIAN RO Model**	**ROSA**
Feed Pressure [bar]	*69.8*	*66.9*
Total Work Requirement [kW]	*375.5*	*365.0*
Specific Energy Consumption [kWh/m^3]	*6.01*	*5.84*
Key Outputs - Case 2: $TDS = 43000$ ppm, $T_w^{RO} = 25^\circ C$		
Description	**JACOBIAN RO Model**	**ROSA**
Feed Pressure [bar]	*79.3*	*75.9*
Total Work Requirement [kW]	*428.9*	*414.1*
Specific Energy Consumption [kWh/m^3]	*6.86*	*6.62*

Table 8-5: Comparison of JACOBIAN RO model with FilmTec's ROSA software [19]

As such, the model can not be validated with actual measurements from an RO plant. The RO model is tested using FilmTec's ROSA (Reverse Osmosis System Analysis) design software [19]. The JACOBIAN RO model was modified to test with ROSA. Specifically, ROSA does not consider any energy recovery device, neglects the energy consumption by pumps other than the high pressure RO pumps. As shown in Table 8-5, there is a good agreement between the RO model prediction and the prediction by ROSA. The maximum error between the software and model predictions is below 5% across all predictions.

8.4.6. Power Block

The JACOBIAN model for the steam cycle (power block) is based on the steam cycle design (i.e., STEAM PRO model) developed by the work group responsible for the power block (WP4, the Electricity Authority of Cyprus). The steam cycle has the following major elements: a steam generator, an extraction turbine, a condenser, an open feed-water heater, and two circulating pumps. Properties of steam are required over a wide range of temperature and pressure to carry out the necessary calculations for the steam cycle. The required thermodynamic properties of steam and water (specific enthalpy, entropy, and volume) are modeled using “The IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam” [36], a very well-documented and tested model. An extraction turbine, as recommended by WP4, is assumed with steam being extracted at two pressures. One extraction point provides the charge steam for the MED process and the other extraction point provides the steam required for the feed-water heaters (Figure 8-1) in the power block. Turbine calculations are performed using an assumed isentropic efficiency. Knowing the inlet condition, the extraction and exhaust pressure, the isentropic efficiency can be used to obtain the actual steam properties at the extraction points and the exhaust. The models for the steam generator, condenser, and feedwater heater are based on energy and mass balance with appropriate assumptions where streams are mixed.

STEAM PRO was used to estimate the turbine's leak at various inlet steam flow rates which was found to be 1.4% of the inlet flow rate. The efficiency of turbine, gearbox, generator, and the pumps was fixed based on the nominal capacity. The results, shown in Table 8-6, show a good agreement between the model predictions and STEAM PRO, provided by WP4, given that no parameter was fitted.

Key Inputs (4 MW $_e$, Full-load)	
Parameter	*Value*
Inlet Steam Rate $\dot{m}_{in}$	*4.172 kg/s*
Ext. 1 Steam Rate $\dot{m}_{ext.1}$	*3.500 kg/s*
Inlet Steam Temp. T_{in}	*540 °C*
Inlet Steam Pressure P_{in}	*40 bar*
Ext. 1 Steam Pressure $P_{ext.1}$	*6.000 bar*
Ext. 2 Steam Pressure $P_{ext.2}$	*3.123 bar*
Exhaust Pressure $P_{exh.}$	*0.050 bar*
Key Outputs (4 MW $_e$, Full-load)	

Description	***JACOBIAN***	***STEAM PRO***
Gross Electricity Generated	*1815 kW*	*1885 kW*
Turbine's Mechanical Losses	*93 kW*	*98 kW*
Condenser Heat Rejection Q_c	*667 kW*	*652 kW*
Temperature at Ext. Point 1	*324 °C*	*320 °C*
Temperature at Ext. Point 2	*260 °C*	*255 °C*
MED Ext. Steam Flow Rate	*0.412 kg/s*	*0.383 kg/s*
Key Inputs (4 MW$_e$, Partial-load)		
Parameter		*Value*
Inlet Steam Rate $\dot{m}_{in}$		*3.8 kg/s*
Ext. 1 Steam Rate $\dot{m}_{ext.1}$		*3.0 kg/s*
Inlet Steam Temp. T_{in}		*540 °C*
Inlet Steam Pressure P_{in}		*35 bar*
Ext. 1 Steam Pressure $P_{ext.1}$		*6.000 bar*
Ext. 2 Steam Pressure $P_{ext.2}$		*3.123 bar*
Exhaust Pressure $P_{exh.}$		*0.050 bar*
Key Outputs (4 MW$_e$, Partial-load)		
Description	***JACOBIAN***	***STEAM PRO***
Gross Electricity Generated	*1675 kW*	*1615 kW*
Turbine's Mechanical Losses	*87 kW*	*94 kW*
Condenser Heat Rejection Q_c	*1041 kW*	*1010 kW*
Temperature at Ext. Point 1	*337 °C*	*328 °C*
Temperature at Ext. Point 2	*279 °C*	*265 °C*
Feedwater Ext. Steam Flow Rate	*0.391 kg/s*	*0.359 kg/s*

Table 8-6: Model Predictions under Full-load and Partial-load Operation Compared with ST PRO Models (provided by WP4)

8.5. Operation

The operation of the plant is simulated by an integrated "plant" model which connects all JACOBIAN sub-models with each other in one system-level model. The process flow diagram (i.e., mass and energy flows) is simulated in the plant model. A variable is defined to implement various weather scenarios (e.g., multi-day overcast weather, random weather variation, etc.). Operating regimes and control strategies can be easily modeled and simulated using the plant model.

The operating challenges of the plant include short-term and long-term variations in the available solar energy irradiance. Short-term variation is due to the changes of irradiance due to the position of the sun (e.g., morning vs noon vs night) and weather fluctuations (e.g., a cloud reducing the direct irradiance). Long-term variation refers to the difference of solar irradiance between summer and winter. The short-term variations are proposed to be addressed mainly by the energy storage and control strategies. Long-term operation requires more complex solutions, e.g., incorporation of water storage systems. The focus of research has been on short-term operation and optimization. Long-term operation (operation over the entire year) has yet to be simulated and optimized. A fixed conceptual design for the MED and the salt pond, as well as time-dependent functions for the electricity and water demand (if applicable) are required to proceed with further optimization.

8.6. Optimization of Short-term Operation

Optimal operation under constant operating conditions (i.e., nominal optimum) is discussed in this section. The conditions considered include constant (time-invariant) operation conditions, cloudless sky, and short-term optimization (24 hour) using a heuristic global optimization approach (multistatrt) and IPOPT [35] as the NLP local solver. Design parameters, optimization variables, the objective function, the design constraints, and the results for three case studies are presented in the following. A mid-summer day, June 21, is selected for all optimization case studies.

Three case studies are considered in the following:

1. Maximizing income using actual water and electricity price (the feed-in tariff in Cyprus), considering a minimum allowable demand for water and electricity. Both RO and MED are considered.
2. Maximizing a weighted energetic function. MED is considered only.
3. Maximizing income using typical water and electricity prices, neglecting all incentives. Water and electricity price of 0.92 €/m^3 and 0.12 €/kWh, respectively, are used for this case study. Both RO and MED are considered.

8.6.1. Design Parameters

Key design parameters (the constants in the problem) are given in Table 8-7. To optimize the design of the plant (i.e., optimal size) several of these parameters could be treated as optimization variables adjusted systematically to maximize the profit or return on investment. Best results are obtained when optimization of the design and time-dependent operation or simultaneously is considered. The result of such optimization will be available at a later stage of this ongoing research. Optimization of operation for a rather fixed plant design is considered here. Furthermore, the capital and operating cost should be added to the simulation models. Incorporating capital and operation cost into the optimization would allow optimal sizing of the plant (i.e., heliostats, total mass of salt, number of elements in RO system, etc.). These parameters strongly affect the net profit, and hence are important for optimal design of the plant. Herein, the optimal operation is considered for a fixed plant size.

Key Parameters	***Value***	***Comments***
Heat Collection		
N_{day}	*150*	*June 21 st*
η_{opt}	*0.78 x 0.99 x 0.94 [40]*	*Optical efficiency, product of cosine efficiency, shading, blocking, and mirror reflectivity, respectively*
Power Block		
η_{isen} *[-]*	*0.78*	*Turbine's isentropic efficiency (assumed constant across all stages)*

T_{inlet}	*813.15 [K]*	*Steam inlet temperature*
P_{inlet}	*40 [bar]*	*Steam inlet pressure*
$P_{exhaust}$	*0.05 [bar]*	*Exhaust pressure*
RO		
TDS	*42 [g/L]*	*Seawater's total dissolved solids*
r	*0.9975*	*Membrane's salt rejection*
S_e	*35 [m^2]*	*Effective area per membrane*
N_e	*64*	*Total number of elements (membranes) in system*

Table 8-7: Key design parameters

8.6.2. Optimization Variables

The optimization variables, objectives, constraints and the parameters (i.e., constants) are discussed in this section. The optimization variables, objective function and constraints are scaled to a range around 1. The sensitivity of the objective function to the design and operation variables is calculated in JACOBIAN and used to select the optimization variables. Variables to which the objective function is most sensitive are selected as optimization variables.

8.6.3. Objective Function

As mentioned above, two objective functions are selected for optimization case studies: maximum income and a maximum weighted energetic function. A selling price of 0.26 €/kWh [22] for electricity and 0.92 €/m^3 (0.54 £/m^3 [32]) for water is used to calculate the income, considering the current feed-in tariff rate in Cyprus. The income here is expressed in the units of € per kWh of energy used per day:

$$Obj_1 = \frac{C_1 F + C_2 E}{E_{sun} - \Delta E_{stored}}$$

where C_1 is the price of water [€/m^3], F is the water production per day [m^3/day], C_2 is the price of electricity [€/kWh], E is the electricity production [kWh/day], E_{sun} [kWh/day] is the total energy collected and concentrated into the pond, and ΔE_{stored} is the change in the stored energy in the pond [kWh/day]. ΔE_{stored} accounts for the possible difference between the initial and the final temperature in the pond. In other words, including ΔE_{stored} penalizes operation strategies that result in final temperature lower than the initial temperature. An alternative implementation would be to enforce that the final temperature is close to the initial temperature. The maximum weighted energetic function is defined as

$$Obj_2 = E + C_{w-e} F$$

where $C_{w-e} = 4$ kWh/m^3 is a constant used to convert the water produced per day [m^3 /day] to an equivalent electricity production [kWh/day]. The advantage of such function is that it is independent of regional electricity and water prices, or in the present case, independent of feed-in tariff and water prices. The disadvantage of using such weighted energetic function is neglecting economical parameters such as capital cost.

Constraint	***Lower Bound***	***Upper Bound***	***Description of the Constraint***
T_{salt} *[K]*	*818*	*873*	*Minimum and maximum allowable temperature of the salt mixture*
$\int_0^{24} Q_{MED} dt$ *[m^3]*	*1000 for case study 1 and 0 for case study 2 and 3*	-	*Minimum allowable water production from MED*
$\int_0^{24} Q_{RO} dt$ *[m^3]*	*1500 for case study 1 and 0 for case study 2 and 3*	-	*Minimum allowable water production from RO*
$\int_0^{24} W_e^{net} dt$ *[MWh]*	*48 for case study 1 and 0 for case study 2 and 3*	-	*Minimum allowable power production*
$Q_{pwt} + Q_{distitateT}$ *[m^3/s]*	*0.0087 for case study 1 and 0 for case study 2 and 3*	-	*Minimum allowable water production rate*
W_e^{net} *[MW]*	*1.0 for case study 1 and 0 for case study 2 and 3*	-	*Minimum allowable electricity generation rate*

T_w^{RO} [K]	298	308	Maximum allowable feedwater temperature in RO
P_f [bar]	65	83	Allowable operating pressure in RO
T_f^{MED} [K]	-	$T_{N_{eff}}^B - 2$	Maximum allowable feedwater temperature in MED
T_{lid} [K]	-	723	Maximum lid temperature
$\dot{m}_{in}$ [kg/s]	2.10	4.172	Turbine's inlet steam flow rate
$\dot{m}_{exhaust} - 0.05\dot{m}_{in}$ [kg/s]	0	-	The exhaust flow should be at least 5% of the inlet flow

Table 8-8: Constraints of optimization

The constraints of the problem are shown in Table 8-8. Path constraints, such as $T_{min} < T_{salt} < T_{max}$ for any $t \in [0,24]$, are formulated as integral constraints [33]. For instance, the corresponding path constraint for T_{salt} is formulated as $CONS_1 = 0$ where $CONS_1$ is calculated from:

$$CONS_1 = \int_0^{24} \left[\max\left\{ (T(t) - T_{max}), 0, (T_{min} - T(t)) \right\} \right]^2 dt$$

8.7. Optimal Operating Conditions

8.7.1. Case Study 1: Maximum Income

The optimal conditions, found using a heuristic global optimization approach (multistart) and IPOPT [35] as the gradient-based local solver, are shown in Table 8-9. The results are the best found, but global optimality is not guaranteed. A few conclusions can be drawn from the introductory case study presented here. The optimizer chooses minimum extraction pressure for both the open feedwater heater and MED process. The optimal steam extraction rate for MED is the lowest steam extraction rate that results in the minimum allowable water production from MED. This shows that under the values used for the electricity and water prices, water production through the MED system selected is not economically favorable. Note that the objective function used here accounts for income from operating a fixed design. Optimizing for a more complex objective function such as maximum return on investment may yield different results. The energy flow diagrams corresponding to these cases studies are shown in Figure 8-5 and Figure 8-6. MED system specifications under optimal operating conditions for this case study are shown in Figure 8-4.

The optimizer chooses operating conditions for RO that might seem unexpected, and hence require further explanation. The optimizer chooses maximum pre-heating for RO at a rather low production rate. Note that the system selected for RO is capable of operating between approximately 1400 to 1600 m^3 through adjusting high pressure pump shaft frequency and preheating. The resulting specific electricity consumption with maximum preheating (i.e., feedwater temperature of 308 K) is between 3.2 to 3.7 kWh/m^3, depending on shaft frequency. Hence, given the electricity and water price used, one expects the optimizer to choose a shaft frequency close to maximum water production.

Optimization Variable	***Lower Bound***	***Optimal***	***Upper Bound***
Energy Storage (Salt Pond)			
$\dot{E}_{out}$ *[MW]*	*8.20*	*16.25*	*16.25*
ΔT_{MED}^{lid} *[K]*	*0.00*	*7.66*	*50.00*
ΔT_{MED}^{PB} *[K]*	*0.00*	*0.00*	*10.00*
ΔT_{RO}^{lid} *[K]*	*0.00*	*10.00*	*10.00*
Power Block			
$\dot{m}_{ext,1}$ *kg/s*	*0.25*	*1.625*	*3.50*
$P_{ext,1}$ *[bar]*	*0.25*	*0.25*	*2.00*
$P_{ext,2}$ *[bar]*	*1.0*	*1.0*	*6.00*
T_{out}^{FWH} *[K]*	*337*	*337*	*474*
Reverse Osmosis (RO)			
N *[Hz]*	*45*	*50*	*60*
Multi-effect Distillation (MED)			

Table 8-9: Results of optimization

The optimizer on the other hand chooses the minimum shaft frequency that results in water production through RO higher than the specified minimum allowable water production from RO. The reason for this as follows: while the production rate of the system increases linearly with increasing the shaft frequency N , the power consumption increases as N^2; hence, increasing shaft frequency (i.e., increasing water production from a fix design RO) is economical only if the increased water production (proportional to N) multiplied by water price is higher than the increased power requirement (proportional to N^2) multiplied by electricity prices.

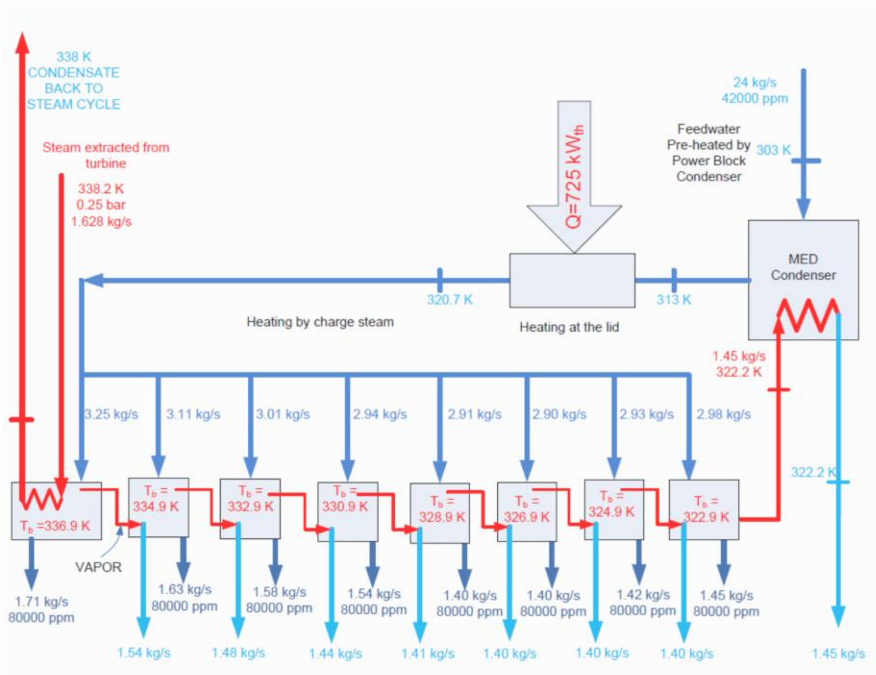

Figure 8-4: Specification of the MED system selected under optimal operating conditions (case study 1)

The profit can be further increased through selling the renewable electricity to the grid at the feed-in tariff rate and purchasing back the required electricity for desalination from the grid at the electricity market price, which is lower than the feed-in tariff. The significant difference between the feed-in tariff and the purchase rate for buying the electricity of the grid does not promote direct use of RES for producing water.

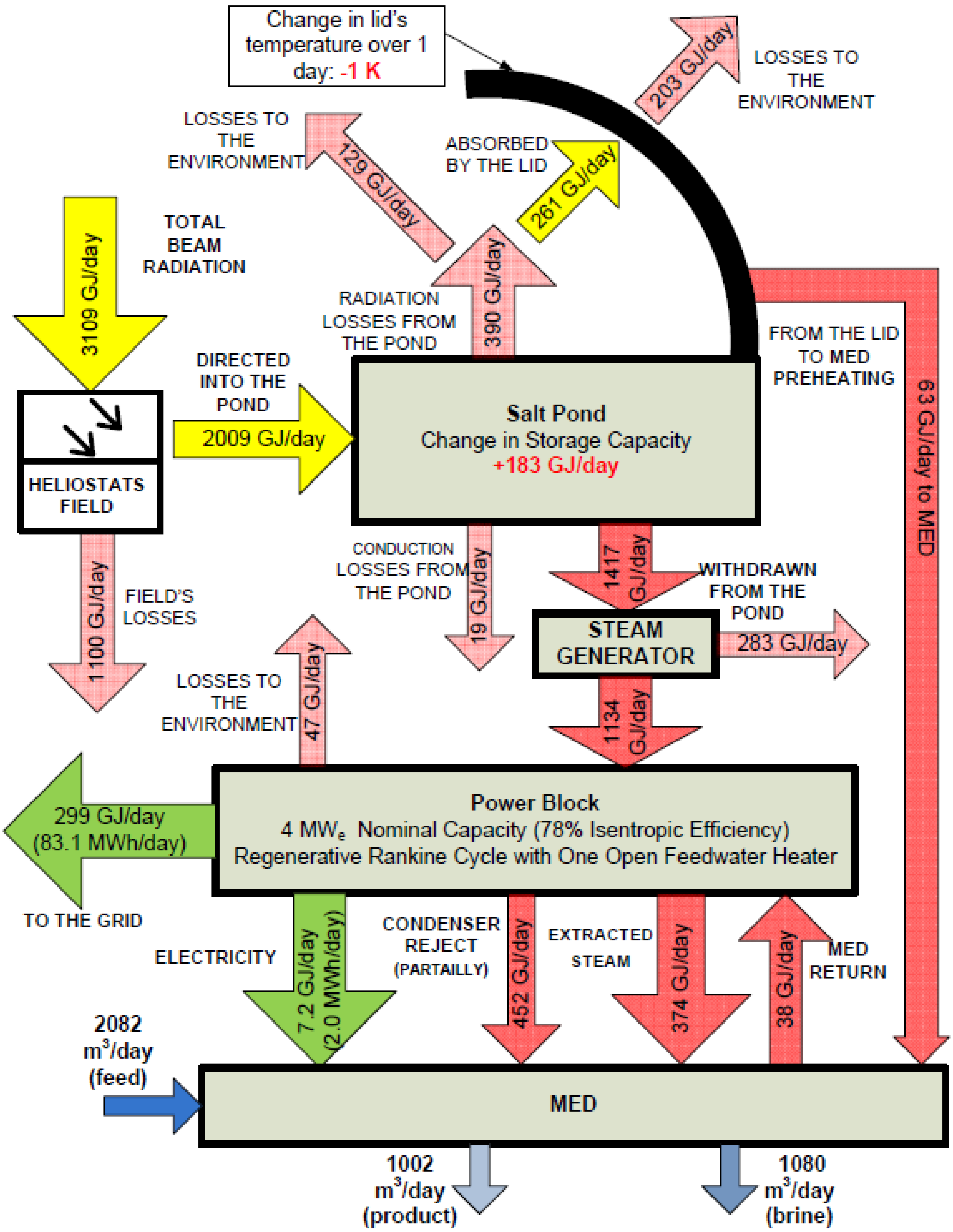

*Figure 8-5: Plant's overall specification based on optimization results (case study 1: **Obj_1** with constraints corresponding to case study 1 given in Table 8). An MED system is considered for desalination*

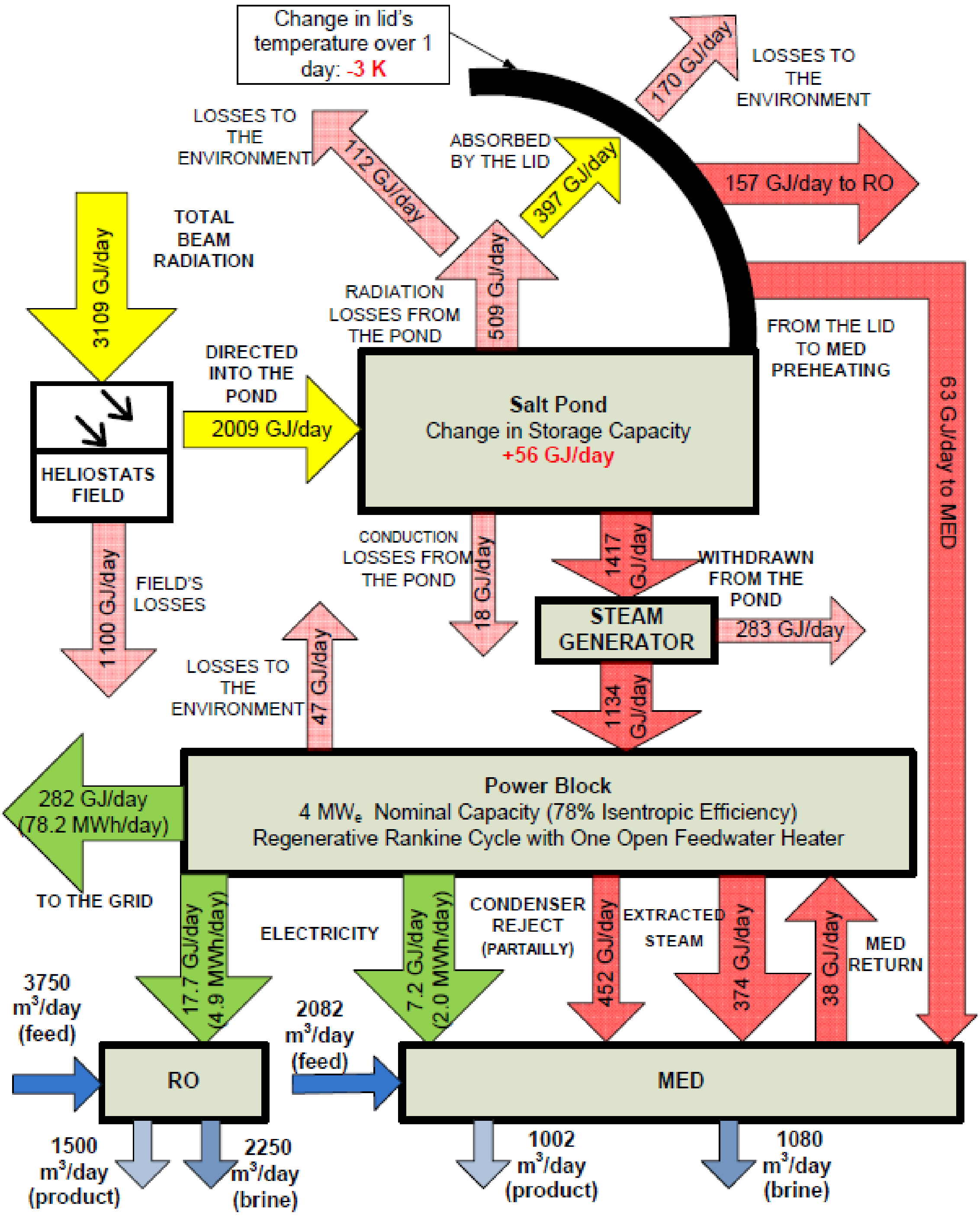

Figure 8-6: Plant's overall performance based on optimization results (case study 1: Obj_1 with constraints corresponding to case study 1 given in Table 8-8). A hybrid RO/MED system is considered for desalination

8.7.2. Case Study 2: Maximum Weighted-Average Energetic Function

Optimal operation using the weighted energetic objective function, as defined above by Obj_2, with no constraints for the water or electricity produced is considered. As mentioned above, RO uses electricity exclusively but MED uses process steam at temperatures around 65-85 $^\circ$C and electricity. The advantage of this objective function is that it provides results to compare the energetics of MED vs. RO, assuming RO uses approximately 4 kWh/m^3.

The result of this case study suggest **no water production through MED**. Optimizing for maximum income (0.26 €/kWh and 0.92 €/m^3 for water) with no constraint for the water production resulted in same conclusion, i.e., zero steam extraction for MED. The penalty paid (i.e., less electricity produced) for extracting steam at fixed pressure of 0.5 bar, as an example, and variable steam rate is studied in the following. Figure 8-7 shows the produced electricity as a function of the extracted steam. Figure 8-8 shows the achieved weighted sum of electricity and water as a function of GOR, steam extraction and assuming a (rather small) electricity consumption of 1 kWh/m^3.

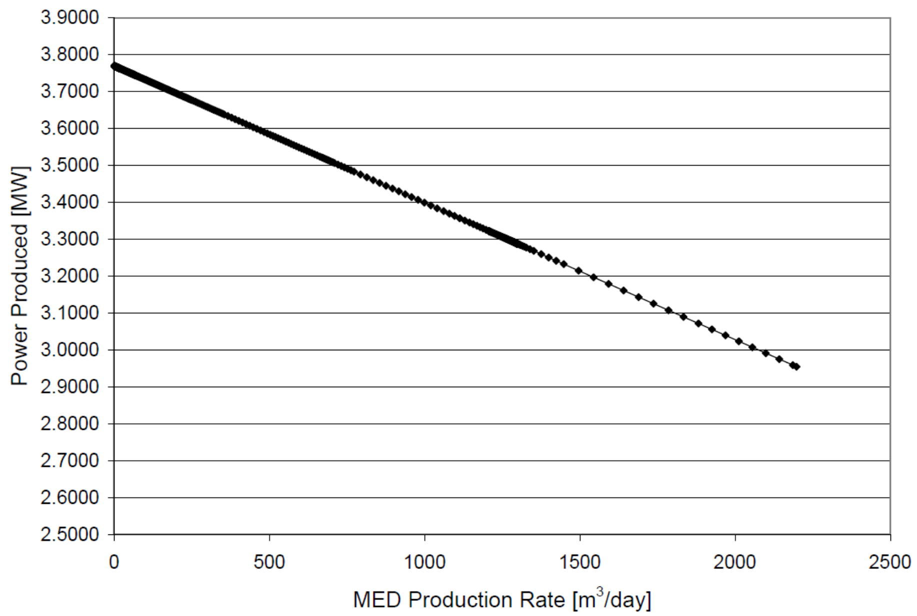

Figure 8-7: Penalty paid (i.e., less electricity produced) for extracting steam at 0.5 bar.
The MED system used has a calculated GOR=7.2
(achieved with significant preheating through the lid and minimum pre-heatiny

This shows that significantly higher GORs are required for making steam extraction for MED attractive from an energy point of view, even with low electricity requirement. These findings are in accordance with Semiat [29] who reports a penalty of 5.2-10 kWh_e/m^3.

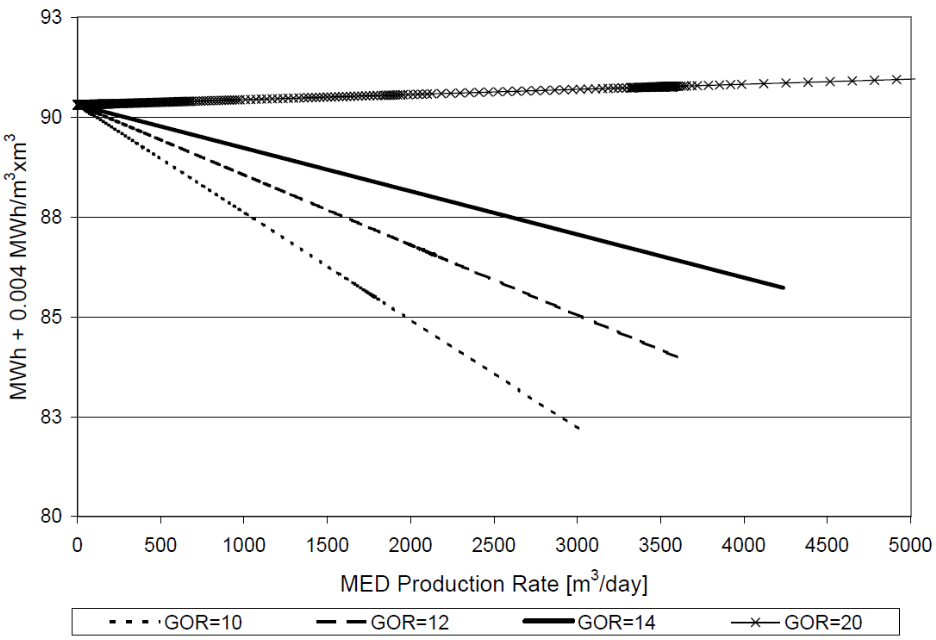

Figure 8-8: : Weighted objective for cogeneration of water and electricity as a function of GOR and MED plant capacity. Extraction at 0.5 bar and the electricity consumption of 1 kWh/m^3 is assumed

	MED Extraction Pressure and Flow Rate			
	No extraction	3.5 kg/s at 0.25 bar (T_{steam}=65, not used for pre-heating pre-MED)	3.5 kg/s at 0.50 bar (steam used to preheat feedwater, final T_{steam} to MED 90 °C)	3.5 kg/s at 1.00 bar (steam used to preheat feedwater, final T_{steam} to MED 90 °C)
MW_e Produced	3.769	3.290	3.071	2.789

Table 8-10: The power lost due to extracting steam team at various pressures

Using the penalty paid for extracting steam at various pressures, as shown in Table 8-10, the minimum required GOR number that would support co-generation using MED can be found approximately as the follows: for extraction pressure of 0.25 bar, the minimum required GOR number is calculated as 12.7; for extraction pressure of 0.50 bar, the minimum required GOR number calculated is 18.5; and for extraction pressure of 1.0 bar, the minimum required GOR number calculated is 25.9. Achieving a GOR as high as 26 with charge steam at 1 bar is believed to be very difficult.

Plant	Qprod [kg/s]	Qsteam [kg/s]	Steam Inlet Pressure [bar]	GOR	# Effects	Wspecific [kWh/m3]	Reference	Equivalent RO Electricity Consumption (MW)
Sidem	139	14.17	0.31	9.08	12	2	[1]	2
Trapani	104.17	6.11	45	17.05*	12	1	[2]	1.5
MEE-FF	57.78	8.89	-	6.5	8	-	[3]	0.83
MEE-P/C	57.78	12.56	-	4.6	8	-	[3]	0.83
Ashdod	201.39	0.25	0.414	N/A	8	2.58	[4]	2.9
MED (PR=8)	219.05	29.89	6.68	7.33	11	1.09	[5]	3.15
MED (PR=10)	219.05	23.68	6.68	9.25	14	1.34	[5]	3.15
MED (PR=12)	219.05	17.56	6.68	12.48	17	1.6	[5]	3.15

*Trapani plant combines steam with some of the distillate produced last effect and sends both through thermocompressor before using it to heat first effect; likely causes GOR to be so high, especially if GOR calculation neglects contribution of recycled distillate; the inlet temperature of the steam is 257°C which also contributes to the high GOR

Reference List

1 M.A. Darwish et al., "Feed Water Arrangements in a Muilti-effect Desalting System"
2 C. Temstet et al., "A Large High-performance MED Plant in Sicily"
3 A.S.Naffey et al. / Desalination Volume 201 (2006) pg 241-54
4 U.Fisher et. Al, "ASHDOD multi-effect low temperature desalination plant report on year of operation".Desalination Volume 55
5 O.J. Morin,"Design and operating comparison of MSF and MED systems" Desalination Volume 93

Table 8-11: Typical steam flow rate, number of effects, and GOR from existing plants found in the open literature.

The following conclusions can be drawn from this case study:

- For small scale (e.g. 4MW) MED with a typical design has too low GOR and too high electricity consumption to be competitive with RO on energetic basis.
- If one can design an MED with higher GOR and lower electricity consumption at the small scale, MED will become competitive even in energetic terms. But for steam extraction rates as low as 3-4 kg/s, the authors are not aware of standard MED system with high number of effects, and consequently high GOR. Table 8-11 provides a brief list of MED plants' specification available in open literature. TVC helps improving GOR, but, as it can be seen from the table, it requires steam to be extracted at higher pressures, hence higher penalty paid due to reduced power production. In Chapter 11 an MED system with relatively high GOR numbers, low electricity consumption ($\leq$ 1kW/ m^3) and low extraction pressures is proposed.

One should note however that comparing MED with RO only from energetic point of view does not necessarily mean that cogeneration by MED is less profitable than using electricity for RO. To make this analysis, production costs need to be considered which require accurate calculation of capital costs and operating costs beyond electricity. RO is believed to have higher operating costs (apart from electricity) than MED due to high membrane replacement and pre-treatment costs for high salinity feedwater. Considering the availability of low-grade heat, one can achieve a relatively high $\frac{GOR}{Number\ of\ effects}$ ratio, which results in low capital cost, and ultimately higher return on investment.

8.7.3. Case Study 3: Maximum Income Neglecting Feed-in Tariff

A case study that is worth presenting here is the case of maximizing income, neglecting the value of feed-in tariff. For this case study, a water price of 0.92 €/m^3 and a electricity price of 0.12 €/kWh is considered. The goal of this case study is twofold: a) assessing the profitability of cogeneration (power and water through extracting steam for MED) under typical electricity and water price ratios, and b) investigating whether considering an incentive for water proportional to the incentive considered for electricity (i.e., FIT) will make extracting steam for MED a profitable option or not. The optimal operating conditions under such conditions are shown in Figure 8-9.

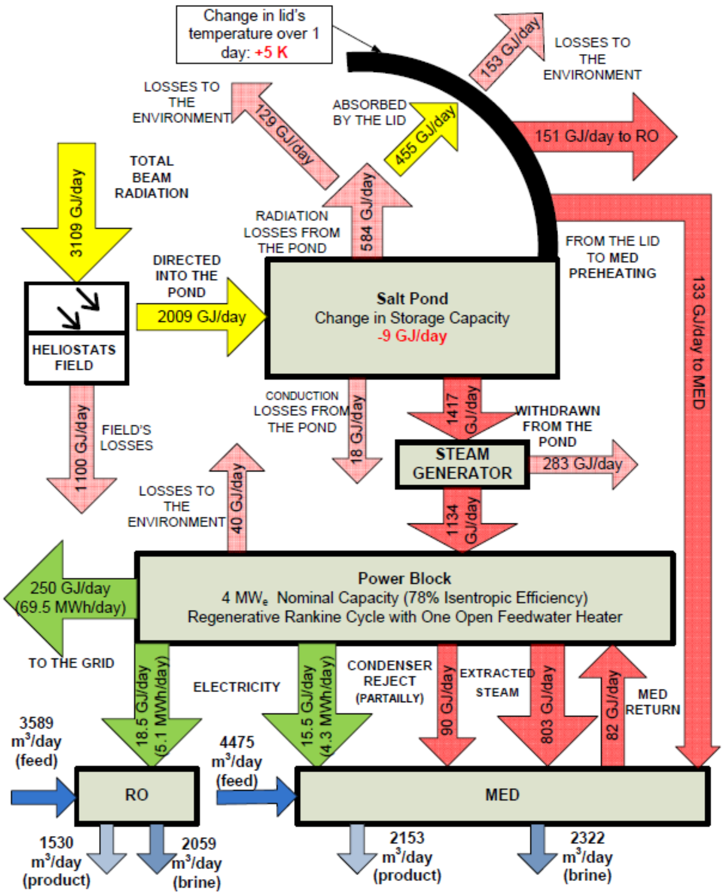

Figure 8-9: Plant's overall specification based on optimization results

(case study 1: Obj_1 with constraints corresponding to case study 3 given in Table 8-8).

It is interesting to see for this case study, extracting steam at 0.25 bar and at maximum rate yields maximum profit. This shows that under typical electricity and water market prices cogeneration through MED is indeed economical.

8.8. Results and Discussions

Optimization results show that the operation of the plant can be effectively optimized using mathematical programming. The sensitivity of the objective function to the optimization variables selected is significant; hence, the operating conditions strongly affects the income. Finding an operation plan that satisfies all design constraints is difficult through a trial and error approach. Hence, optimization not only increases the profit, but also conveniently determines an operation plan that satisfies all design constraints. It is quite evident from the case studies considered that mathematical programming leads to very valuable results. Time-dependent optimization of short-term and long-term operation is expected to yield even more valuable and important results.

The preliminary results obtained from optimization also show the importance of fixing the conceptual design for key elements of the plant (e.g., MED and the salt pond). A final conceptual design of the energy storage and MED is required to proceed with system-level integration and optimization work. Variations in semi-detail design of sub-systems in the plant are expected, and most likely will not affect the plant-level model; however, the design changes have been major and required significant re-work by the system integration and optimization group. The need for answering several key questions, including operation strategies, even for short-term operation is quite evident from the results presented. Recharging strategies and operation methods need to be developed and tested to effectively handle seasonal variations in the available solar irradiation. System-level models are quite useful tools to simulate these strategies.

8.9. Conclusions

System-level models were developed for dynamic simulation and optimization of a plant that utilizes solar energy for combined electricity generation and water production. Dynamic simulations are quite useful tools as they provide insight into the challenges involved in operation of the proposed plant. The sequential method of optimization with IPOPT as the solver and JACOBIAN as the simulator was used. Decoupling simulation from optimization was found to be very effective to handle the problem with such complexity. Constant short-term operation of the plant is optimized, as a case study, to maximize the profit for selling the electricity and water produced. The optimal operating conditions strongly depend on the feed-in tariff rates and the price of fresh water. The current energy policies does not reflect the fact that the water produced by RES should also be considered for incentives. Optimizing for a weighted function of electricity and water production, with no constraint considered for minimum allowable water production, shows that MED energy requirement are much higher than typical RO energy requirements. One should note that the results are valid for the 4 MW_e steam cycle used. In all case studies, the optimizer chose the lowest allowable extraction pressure for MED. The optimal water temperature after the feedwater heater is also the lowest allowable. To meet this temperature, the optimizer chooses extracting at the lowest extraction pressure. The results show that under current electricity and water prices (i.e., no subsidy considered for electricity or water produced by RES), extracting at low extraction pressures yields highest income. Hence, to encourage direct application of RES, it is recommended to consider incentives for producing water by direct application of RES.

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Chapter 9. Proposal for the Receiver and Storage system of a CSP-DSW plant

In this Chapter an innovative solution for the Receiver and Storage system of the CSP-DSW plant is presented. The novel design integrates the receiver and the storage unit into one entity thus simplifying the technical complexity of the two different systems and resulting in a solution that will be financially advantageous. The storage unit becomes the direct receiver of solar radiation and is based on the ordinary salt tank storage solution. The proposed storage compartment is in turn a simplification of the two-tank molten salt used in Power Tower systems.

From the outset of the Study it was understood that the Receiver and Storage system would present the most challenging design aspect of the endeavour. Energy storage is recognized internationally as a critical challenge for the Renewable Energy sector, and has yet to reach the technological maturity required for base-load continuous operation without the use of a combined cycle. The selection of the Central Receiver technology as the preferred choice for the proposed CSP-DSW pilot facility for the coastal environment of Cyprus two options present themselves as offering viable paths for the realization of this technological choice:

I. The tower-receiver technology in conjunction with a dual tank nitrate salt (as implemented, for instance, in the CSP "Solar Two" demonstration facility in the USA)

II. The novel "Concentrated Solar Power on Demand (CSPonD)" technology developed at MIT.

As the solution of the two-tank system is being currently developed by the Spanish - German collaboration and it appears currently to be technically complex and financially demanding we decided to explore in depth the option of the CSPonD. Prof. Slocum and his colleagues at MIT, the developers of the CSPonD, provided both the conceptual and the engineering details of the Receiver–Storage design which is presented in this Chapter.

The detailed design of the CSPonD receiver-storage system which is proposed in the conceptual design of the CSP-DSW cogeneration plant has undergone significant changes during the course of the last eighteen months.

The original Receiver-Storage unit, presented in the interim report, comprised of a single tank filled with chloride salts that would capture and store energy at a very high temperature (800-1000^{o} C). This design holds the promise for future applications as the higher temperatures would allow high-efficiency power production schemes with the use of gas turbines and possibly Stirling engines of a novel design. However as both the heat-exchange technology at such high temperatures and the gas turbine systems are still in a pre-commercial stage, it was opted to design a system with lower temperatures and more conservative, proven, heat-extraction scheme. The chloride salt CSPonD Receiver-Storage option should be viewed as a long term solution, with the lower temperature nitrate salt should be seen as a solution suitable for the intermediate term and a developmental pathway to the optimized high temperature CSPonD.

In the following sections the latest nitrate salt receiver storage design is presented. We note that the research still continues and more design changes and improvements are expected in the following months, as a result of a very active research program at MIT which is being pursued outside the scope of this study. The concept presented here is still evolving, as are the general operational and design parameters. For the purpose of this report, it was deemed appropriate to freeze the parameters and the design at the current stage, especially those entering into integration, optimization and economic analysis calculations performed by other workgroups. Parameters presented within this Chapter are in certain cases not in complete accord with the set used by other partial investigations within this Study, although appropriate note is provided accordingly.

As noted in the Introduction and summarized in the Executive Summary this is a rapidly evolving field, especially if storage options are to be considered. While we propose a conceptual design based on option (II), it is perfectly appropriate to reconsider the merits of option (I) at the time a decision needs to be made. It is also the case that novel thermal storage options are currently under development (such as the thermal storage in concrete pursued by DLR and collaborators) which needs to be monitored.

9.1. Background

Power Towers use a field of heliostats to focus highly concentrated sunlight on a receiver placed atop a tower. This geometry helps to reduce heliostat shadowing and increase optical efficiency, thus increasing the overall efficiency of the steam plant. Although many studies point to central receivers as ultimately being the key to economic CSP [1], production and operating costs have yet to signal that current designs are anywhere near optimal. A variation on the power tower design was developed in 1978 by Ari Rabl of Argonne National Laboratory who proposed a beam-down tower with a ground-based receiver [2]. In 1997, Amnon Yogev of the Weizmann Institute proposed a beam-down Power Tower where the light was to be beamed directly into a molten salt/metal filled container [3]. The Weizmann Institute has done significant experimental work with beam-down towers and ground receivers, especially for reforming materials [4,5,6].

A ground based system is the Odeillo solar furnace facility in the French Pyrenees [7] which uses a large north facing parabola focused on a target built into one wall of a building that holds offices and laboratories. In front of it, on the mountainside, 63 south-facing flat mirror heliostats track the sun's movement and focus it on the north facing parabola. 70 percent of the cost of the installation was devoted to the 5.5-by-7.0-meter heliostats which can withstand 100 km/h winds. Temperatures as high as 3,800^{o}C were quoted as being obtainable with some targets. NREL also has a high-flux solar furnace system where heliostats aim light towards a ground-based secondary reflector system that redirects and concentrates the sunlight to a small aperture receiver.

Conventional CSP systems utilizing pumped molten salts for the heat transfer/storage medium are plagued by many technical difficulties. Long piping runs necessitate the use of heat tracing and control systems to prevent freezing; however these systems have not proven reliable for long-term, worry free operation. For example, the Solar Two CSP demonstration plant was routinely disabled by frozen salt in pipes and failure in high-pressure, high-volume molten salt pumps.[8] Demonstration CSP plants without storage have also typically been designed with a co-firing gas turbine scheme [1, 9]. The idea is to provide the turbine with constant input power, regardless of solar fluctuations. Unfortunately, this smaller, less-efficient gas turbine is driven at nights and during periods of low insolation, offsetting any “clean energy” benefits the CSP field may provide.

Another approach is direct absorption of sunlight by several cm thick salt waterfalls, but the cost of pumps, manifold and piping preheaters, and the effects of fluid flow as a function of varying solar flux, limited the practicality of such systems [10,11]. However, where the control of the salt flow proved a significant challenge, it did illuminate a direction for direct absorber innovation.

9.2. CSP with Collocated Receiver and Storage

In view of the above, a system is proposed with heliostats on a hillside that beam light directly into an open container of molten salt. A small aperture in our receiver located near the base of the hill and at the focus of the heliostats lets the sunlight in, and then it diverges to illuminate a *volumetric absorption* receiver. The light would penetrate the surface of the large molten high temperature salt pond. The system can thus simultaneously collect sunlight while also acting as the beam-down optic, thereby reducing overall system complexity and cost. The use of a hillside eliminates the need for large, secondary beam-down mirrors and compound parabolic concentrators (CPC) that would otherwise need to be placed over a ground based that would otherwise be needed to illuminate a large open molten salt tank.

This proposed system provides several advantages over conventional CSP plants. Concentrated solar radiation is directly absorbed into the molten salt pool, which also serves as the thermal storage medium. Heat flow is regulated from the molten salt pool, providing constant power to a steam generator or other power cycle. *Volumetric Absorption* enables a simpler receiver design, with a passive salt pond (i.e. no high-pressure, high-flow molten salt pumps) that is capable of high temperatures storage. The molten salt surface is self-healing – tolerating high solar flux transients without irreparable damage to the receiver.

There are numerous candidate salts for *volumetric absorption* receivers: mixtures of nitrates, carbonates, and chlorides which can be selected based on operating temperatures, durability, thermal and light absorption properties, materials compatibility and cost. As a near term solution, a sodium-potassium nitrate salt (e.g., Hitec® solar salt: 60/40 wt% $NaNO_3$-KNO_3)[6] is proposed which is already widely used and has a low melting point of 222°C; however, above 593°C, the salt decomposes and becomes very corrosive and dangerous. The advantage of using this salt is that systems have currently been engineered to pump it between hot and cold storage tanks and a steam generator [12]. Cost-savings have been shown with single tank systems relying on temperature stratification via natural thermocline formation [13]. Volumetric absorption allows the bulk of the salt to run closer to its decomposition temperature – as opposed to conventional boiler tubes filled with nitrate salts, whereby irradiance transients and higher surface absorption of tubes in localized areas can exceed nitrate salt peak allowable temperatures or burn out tubes. This salt could be safely used if great care was taken to ensure that no hot spots were created that might lead to localized overheating of the salt. High temperature options include chloride and/or carbonate salts. With these salts, the temperature limits are removed and salt can collect energy and store energy at temperatures significantly beyond where we have materials of construction for power cycles. The preferred high temperature salt is sodium chloride and potassium chloride (50/50 wt% NaCl-KCl), which has a eutectic melting point of about 670°C and a boiling point of 1350°C. This low-cost salt is extremely robust and essentially cannot be damaged. Both salts are relatively transparent to visible light and have high thermal expansion coefficients; as the solar flux increases, it will create more convective mixing to cause the system to self-stabilize. Heat from the salt pond is continuously drawn through a heat exchanger and converted into electricity by a dedicated power cycle.

[6] *(This footnote refers to NaCl/KaCl, not HITEC salt). The following are NaCl/Kcl (50%/50%) properties taken from two sources: - G.J. Janz, Molten Salt Handbook, Academic Press, NY 1967, - http://www.factsage.com/ Melting point 665 °C, Boiling point 1486°C; Density (at 800°C) 1523 kg m^{-3}; Viscosity (at 800°C) 1.2163 mN s m^{-1}; Thermal conductivity (at 800°C) 0.45 W m^{-1} K^{-1}; Specific heat (at 800°C) 1089.9 J kg^{-1} K^{-1}*

This system, which has been developed by Prof. Slocum's team at MIT is call Concentrated Solar Power on Demand, or CSPonD, will thus fill a critical need in solar power, that of energy storage which is required if solar energy is to satisfy baseload needs. CSPonD provides 24/7 power without either (a) extensive combustion of fossil-fuel backup, or (b) very high cost and not yet existent battery storage. As such, CSPonD offers substantial installed capacity for utilities and not simply energy savings: it will be a feasible strategy that is amenable to most high beam irradiation locales and could change the face and perceived feasibility of high grid impact solar power generation.

Table 9-1 shows part of the design spreadsheet used for the initial system feasibility study of the design hypothesis. These calculations include spacing of the heliostats to avoid shading and blocking, and the cosine effect of the sun with respect to the heliostats on the hill and how they must be inclined to direct the sunlight into the pond aperture. To power a 4 MWe steam turbine continuously, 24/7 (7 hours sunshine, 17 hours storage), about 2500 m^3 of nitrate salt is needed. This volume of salt can be fully "charged" with 10 good days of sunshine and is sufficient to run the generator for an additional 24 hours (1 cloudy day). The salt tank would have a depth of about 5 meters and a diameter of about 25 meters. Several systems should probably be ganged together to feed a central 20 MW turbine. Alternatively, the same thermal storage can be achieved with 4300 m^3 of chloride salt, occupying a 5m deep by 33m diameter tank. Although more salt is needed, the benefits of the chloride salt system include increased operating temperatures, leading to increased power conversion efficiencies, and reduced costs, as NaCl-KCl salts are very inexpensive.

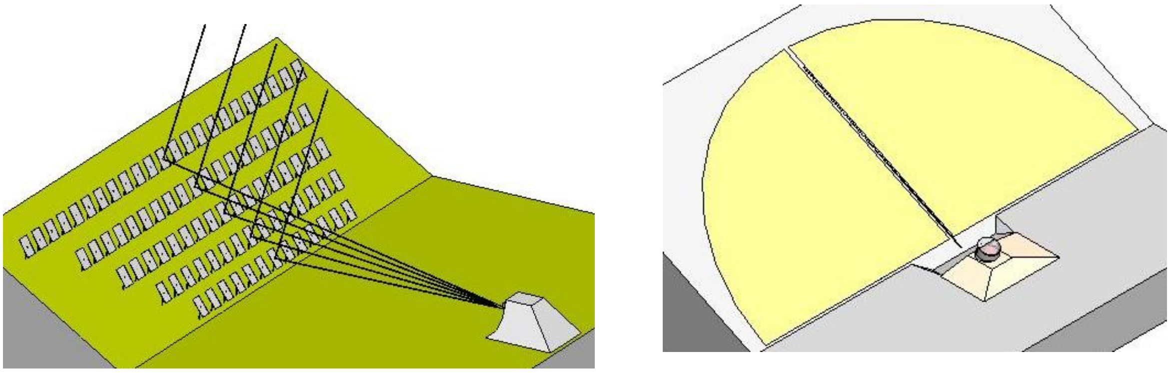
It is important to note that here the CSPonD system is rated by continuous power production, not peak power as is typical of traditional CSP systems without overnight storage. In addition, the efficiency calculated based on assuming the solar input power is the product of 24/7/365 average solar energy incident on heliostat area projected on a plane normal to the peak incoming sun ray axis. Losses include radiation during the day when the aperture is open, conduction, and steam generator system and optical reflection efficiencies.

Basic Parameters of the CSPonD configuration		
Angle of sun above horizon (deg)	*80*	
Distance receiver from base of hill (m)	*200*	
Hill angle (deg)	*30*	
24/7/365 Average daily insolation (W/m^2)	*200*	
Net average 24/7 electric power generation (MW)	*4*	
Azimuth heliostat packing density	*0.7*	
Distance receiver in front of hill base (m)	*200*	
Heliostat arc angle (deg)	*90*	*135*
Heliostat field radius (m)	*390*	*500*
Number of heliostat arc segments, Nseg	*2*	*1*
Number of rows	*74*	*88*
Total heliostat mirror area (m^2)	*141312*	*139357*
Total required land area (hectares)	*27.8*	*33.2*
Unit aperture height (m)	*8.9*	*10.3*
Unit aperture width (m)	*11.1*	*12.9*
Total aperture area (m^2)	*199*	*133*
Salt tank diameter (m)	*25.0*	*24.9*
Salt tank depth (m)	*5*	
Tons of salt required for 24/7 operation	*4512*	*4382*
Net overall solar to electric power efficiency	*24%*	*25%*

Table 9-1: Basic Parameters of the CSPonD configuration

9.3. Heliostats on a hill

There are precedents for locating heliostats on a hillside to direct sunlight to a secondary reflector, then redirecting the power to a receiver on the ground [7,14]. However, up to 10% of the energy is lost with each additional reflection, not to mention high-flux secondary mirror cooling concerns, operation and installation costs. Furthermore, there appears to have been a "land rush" for acquiring rights to flat, sunny land perceived to be needed for other types of solar power systems, which have increased the overall costs of traditional CSP systems. *The system presented here thus reflects the solar energy from a heliostat field on a hillside directly into a lower elevation receiver.* In the northern hemisphere, a south-facing hillside field allows for direct entry into the molten salt pond for a majority of rays as shown in Figure 9-1a and Figure 9-1b. These configurations allow for CSPonD collector fields to be built on otherwise undevelopable, steep terrain – reducing system costs. Methods used by utility companies for emplacing utility poles on moderately steep terrain can be used for heliostat installation, and automated spray systems can be utilized for cleaning the mirrors.



a) *b)*

Figure 9-1: a) Idealized sketch of first few hillside heliostat rows of a CSPonD system
b) Idealized sketch of two, 90° arc-type side by side hillside heliostat fields aimed at a twin aperture central CSPonD receiver

A discussion about the placement of heliostats on a hillside can be found in Chapter 10.

9.4. Collocated receiver/storage system

The *volumetric absorber* receiver/storage system has the following primary functional requirements:

1. Enable sunlight from heliostat field to enter the aperture:
    a. The aperture should close at night, and in general, minimize energy losses when open by careful optical design of the dome over the pond.
    b. The light should penetrate the salt directly: incoming light rays will be refracted into the salt.
2. Contain enough molten salt to store the desired amount of thermal energy
3. Enable the energy to be harvested with either:

a. Heat exchangers in contact with tank wall through a thermal "clutch"; for example a moving plate regulates contact area to maintain constant power
b. Pumps to draw salt from hot top of tank and flow it through a heat exchanger and then back into the bottom of the tank.
c. Movable plate between hot and cold regions of tank, where salt flow around annulus mai9ntains volumetric equilibrium.

The pond cover will be lined with firebrick and backside cooled so the salt vapor rises and condenses on the surface of the firebrick. The resulting white surface will grow until the thickness results in a thermal resistance that condenses the salt vapor, but the surface continually melts and returns liquid salt to the pond. The liquid/solid interface is expected to act as a diffuse reflector to incoming light that reflects off the surface of the salt [15]. An analogous structure in nature is a lava cave shown in Figure 9-2, which is a partial motivation for the proposed receiver.

]

Figure 9-2: Lava cave: what CSPonD might look like to incoming sunrays. from [16]

An important design goal is to shape the cover and its extension in front of the pond to function as a diffuse reflecting concentration booster (refer to herein as a CB, not unlike the CPC units used in beam down towers) [17,18,19,20]. The energy collected by the cover, from condensing the salt vapors and radiation heat losses, is used elsewhere in the plant. The collected cover energy, another design parameter unique to CSPonD systems, can vary from 2-20% of the incident solar power. This depends primarily on the plant layout: hillside topology, operating temperatures, and seasonal and diurnal position of the sun. For instance, in a dual-purpose (water and electricity production) plant using the CSPonD concept, the heat collected by the cover can be used for preheating desalination feed water [21,22]. It is known that pre-heating increases the permeate flux of RO significantly, and enhances the performance in multi-effect distillation (MED) [21,22]. The heat from the cover can be used for desalination.

Figure 9-3 shows a collocated receiver/storage system sized according to Table 9-1. Volumetric absorption allows much higher surface power levels (MW/m^2) and thus smaller heat losses back to space by sending light through the aperture "window" in CSPonD.

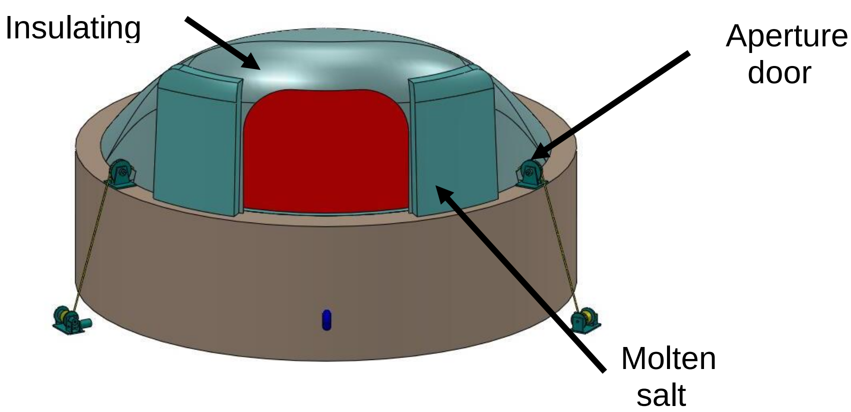
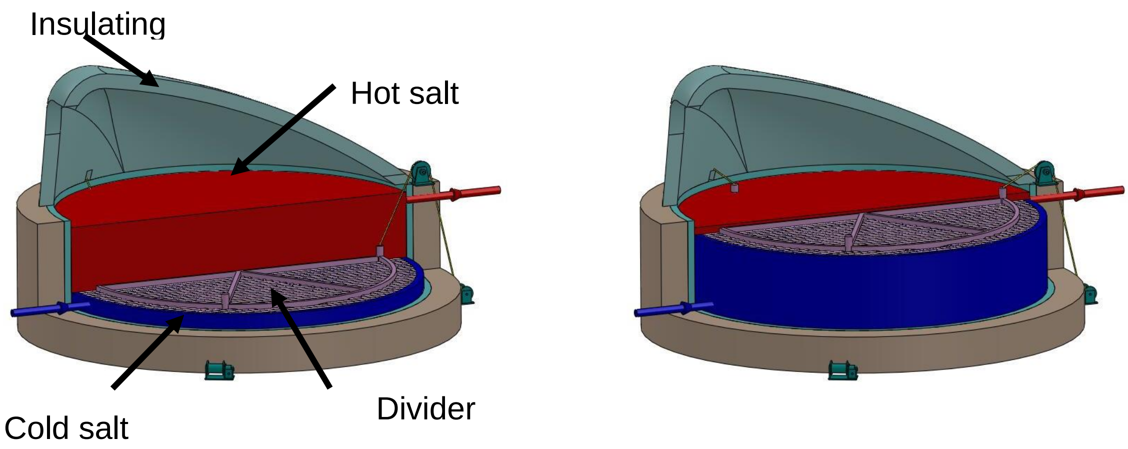


Figure 9-3: Idealized sketch of CSPonD volumetric absorption molten salt receiver/storage system

Figure 9-4a & Figure 9-4b show cross-sections of the volumetric absorption system. The top section of the tank is the hot side, and the bottom section is the cold side. A corrosion and creep resistant alloy plate divides the two sides. The light will penetrate deeply and a small fraction of it will impact the divider plate causing convection currents, heating the 'hot side' to a uniform high temperature. Figure 9-4a shows how at the end of a sunny day, the divider plate has moved down and the hot side is fully charged. Figure 9-4b depicts the system after a prolonged period of heat extraction without any solar input, i.e., after a full cloudy day and night the divider plate has moved up and cold side is full.



a: Cross-section sketch of CSPonD volumetric receiver: at end of a sunny day divider plate has moved down and hot side is fully charged

b: Cross-section sketch of CSPonD volumetric receiver: after prolonged period of heat extraction without solar input, the divider plate has moved up and the cold side is full.

Figure 9-4: CSPonD Receiver

The divider plate would likely be a ribbed plate with insulating fire brick to thermally separate the hot and cold sides. As Table 9-2 shows, however, it would be heavy, requiring substantial actuators. However, only a modest thickness of insulating firebrick is needed to make it near neutrally buoyant in the molten salt. Alternatively, a hollow tubular structure can be used to make the divider plate structure. The hollow chambers could be designed with a slight internal pressure at the operating temperature to minimize stresses in the chamber walls. This could be achieved by making the divider from a series of capped pipes. The drag force on the plate is negligible due to the generous radial clearance between the divider plate and the tank walls, and the Stokes flow of the slowly moving plate and salt. The radial clearance does not present a significant challenge with regard to manufacturing or operation accuracy.

Divider Plate System	***Hitec (Nirate)***	***50% NaCl/KCl***
Divider plate radial clearance with tank walls (mm)	*500*	*500*
Divider plate effective thickness (mm)	*15.0*	*15.0*
Mass multiplier to account for ribbing	*1.5*	*1.5*
Divider plate effective density (steel) (kg/m^3)	*7800*	*7800*
Mass flow salt for power generation (kg/s)	*30*	*44*

'Dark' divider plate velocity up (mm/s)	*0.034*	*0.034*
Normal night-time divider plate distance travelled up (m)	*2.07*	*2.07*
Maximum cloudy day divider plate distance travelled up (m)	*5.0*	*5.0*
Normal daytime divider plate velocity down (mm/s)	*0.082*	*0.082*
Daytime salt velocity (blow-by) through divider plate-tank annulus (m/s)	*0.0015*	*0.0019*
Estimated drag force on divider plate during daytime, Cd =1 (N)	*0.9*	*2.3*
Apparent mass of divider plate (metric tons)	*61.0*	*113.2*
Actuator force required: three actuators (metric tons)	*20.3*	*37.7*

Table 9-2: Divider plate system parameters. The divider plate is "ribbed" for structural reinforcement; it is easily made near-neutrally buoyant by the addition of insulating refractory material to one or both sides.

9.5. Solar Simulator Testing of a Volumetric Salt Receiver

A high-flux large-area solar simulator has been designed and characterized for the purpose of studying *volumetric molten salt receivers*. The light from seven 1500W metal halide outdoor stadium lights is concentrated with a specular aluminium cone, achieving output fluxes greater than 60kW/m^2 (60 suns) at the output aperture (Figure 9-5).

9.5.1. Volumetric Receiver Testing: Single Tank

Optical heating tests of a single tank, *volumetric molten salt receiver* were performed. Figure 9-6a depicts the test receiver, instrumented to determine the temperature distribution of Hitec® solar salt: 60/40 wt% $NaNO_3$-KNO_3 with the solar simulator. A well-insulated stainless steel (type 316L) receiver, 67mm inner diameter x 25cm high was used to contain the salt. The salt was pre-melted to 250°C, and then optically heated with MIT CSP solar simulator. Figure 9-6b shows the appearance of the salt-filled receiver, removed from the simulator, and illuminated with a laser pointer.

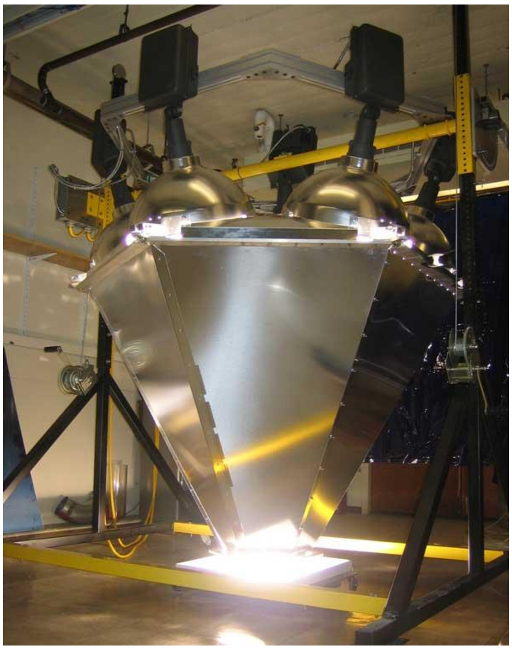
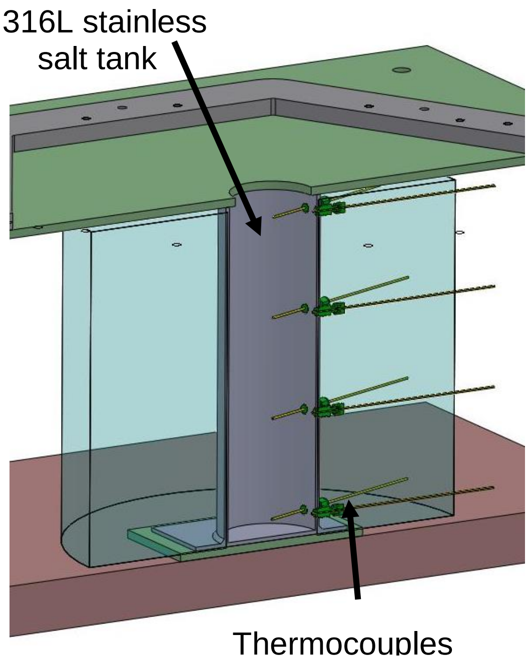
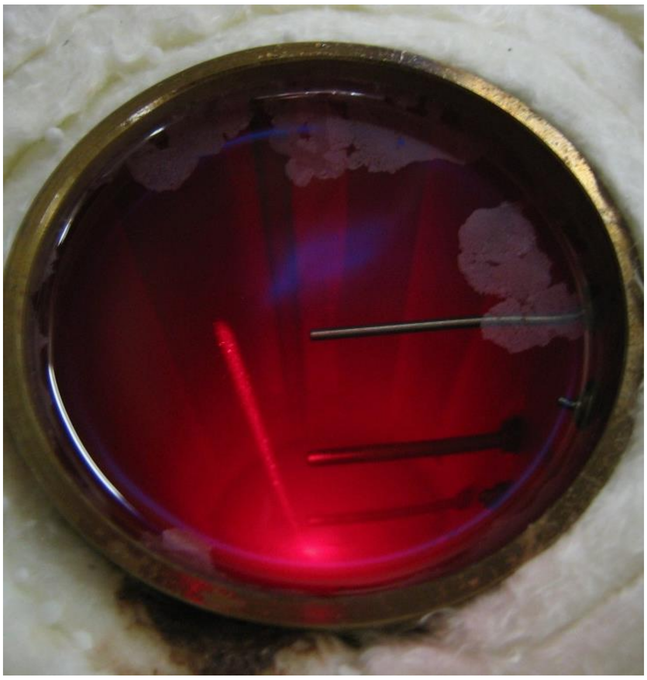


Figure 9-5: Solar Simulator: 7x 1500W metal halide lights capable of producing 60kW/m2 peak intensity at output aperture.





a: ∅67mm ID x 25cm depth salt column receiver with insulation and thermocouple

b: Molten Nitrate (60/40 Na-K) salt mixture at 350℃. Laser pointer (not shown) used to illustrate volumetric absorption of light; note freeze plane of diffusely reflective *instrumentation.* *salt at bottom.*

Figure 9-6: Experimental Salt Receiver

Figure 9-7 plots the temperature distribution in the single tank volumetric receiver at various heating times. Thermal stratification was observed, although the upper third of the salt was nearly at the same temperature as the surface, indicating volumetric energy absorption throughout that region of the receiver.

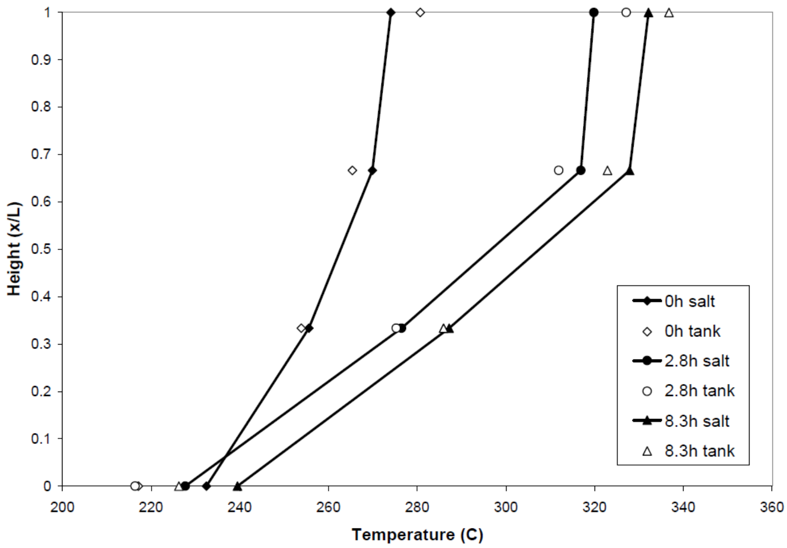
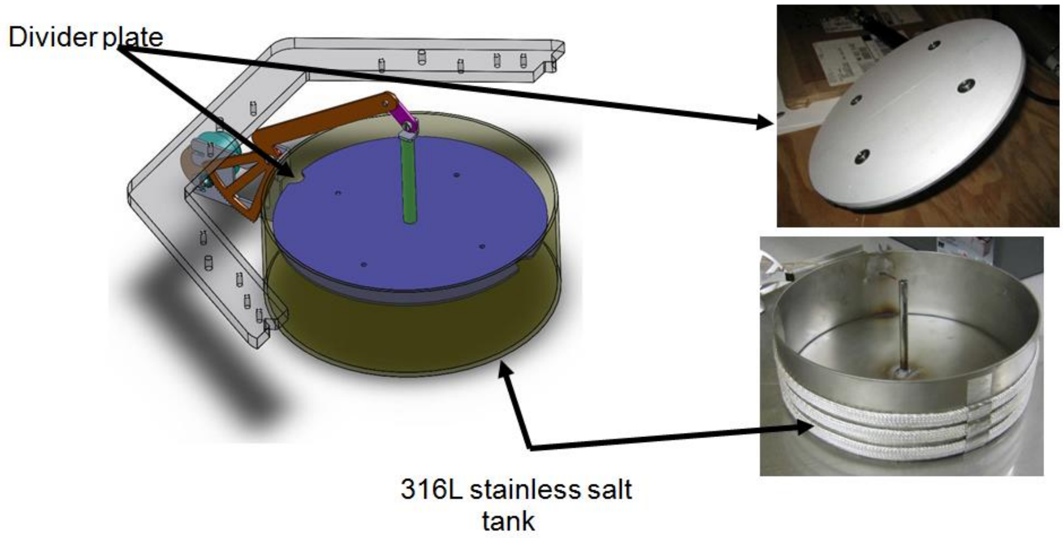


Figure 9-7: Temperature distribution of molten nitrate (60/40 Na-K) salt mixture as a function of depth after 0, 2.8, and 8.3 hours under the MIT CSP Solar Simulator. The tank (∅67mm ID x 25cm depth receiver) wall temperatures are denoted by the unfilled data points – note the top of the receiver is hotter than the salt surface temperature.

9.5.2. Volumetric Receiver Testing: Divider Plate-Equipped Tank

Additional tests were carried out using a tank equipped with a movable divider plate, designed to partition the *volumetric molten salt receiver* into two thermally separated regions. The receiver is shown in Figure 9-8a & Figure 9-8b.



a: ∅28cm ID x 5-8cm depth salt receiver with motorized divider plate positioning linkage.

b: (top) Bottom view of 6.4mm thick silica insulation attached to stainless steel divider plate. (bottom) Volumetric receiver tank, 7L salt capacity

Figure 9-8: Experimental Receiver with plate divider

The well-insulated stainless steel (type 316L, 28cm inner diameter x 8cm high) test receiver was instrumented at several locations with thermocouples. The divider plate was constructed from 3.2mm thick 316L stainless steel with a 6.4mm thick layer of rigid silica insulation board affixed to the underside. Again, Hitec® solar salt: 60/40 wt% $NaNO_3$-KNO_3 was pre-melted to 250°C and optically heated with MIT CSP solar simulator. Figure 9-9a & Figure 9-9b show the appearance of the salt-filled receiver in, and removed, from the simulator.

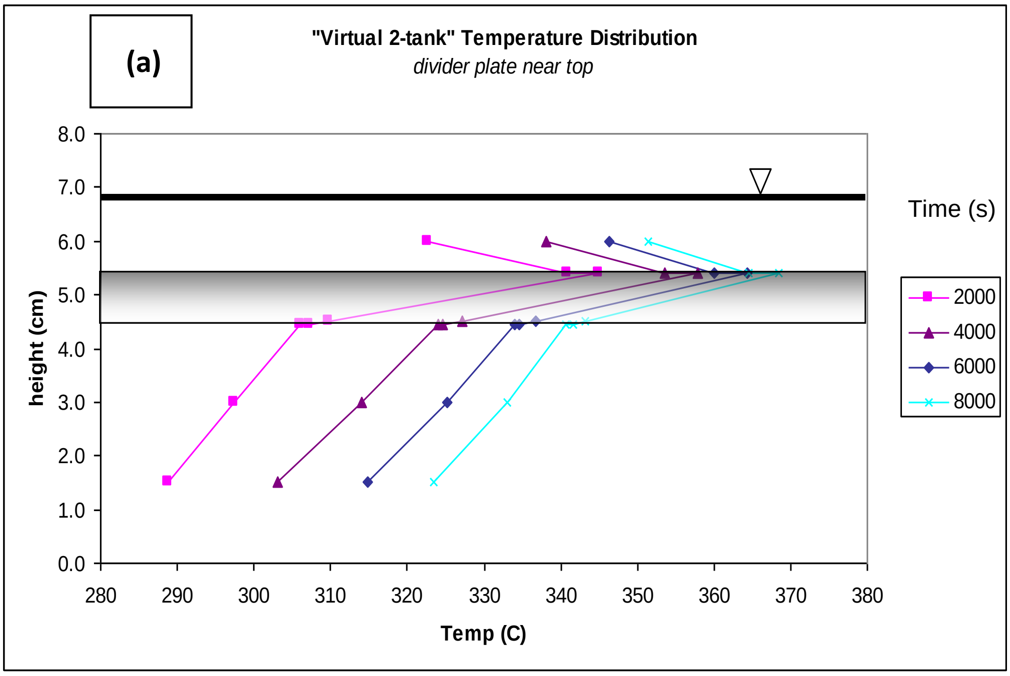
a: Volumetric receiver inside solar simulator output aperture.

b: Close up of salt-filled volumetric receiver. Clearly visible is the divider plate in its raised position near the surface of the salt.

Figure 9-9: Various Pictures of the Volumetric Receiver

Figure 9-10 depicts the temperature distribution of the volumetric receiver for different positions of the divider plate. The divider plate succeeds in providing excellent thermal separation between the upper (hot) and bottom (cold) sections. The bare stainless steel top surface of the divider plate absorbs much more energy than the transparent salt; as a result the hottest region of the receiver is the top surface of divider plate. This is excellent for establishing natural convection cells in the top region and promoting uniform, isothermal conditions which maximize thermal storage in a given volume of salt.

On-going experiments are examining the transient behaviour of a moving divider plate with salt flow from hot to cold, simulating real world operating conditions with heat extraction.



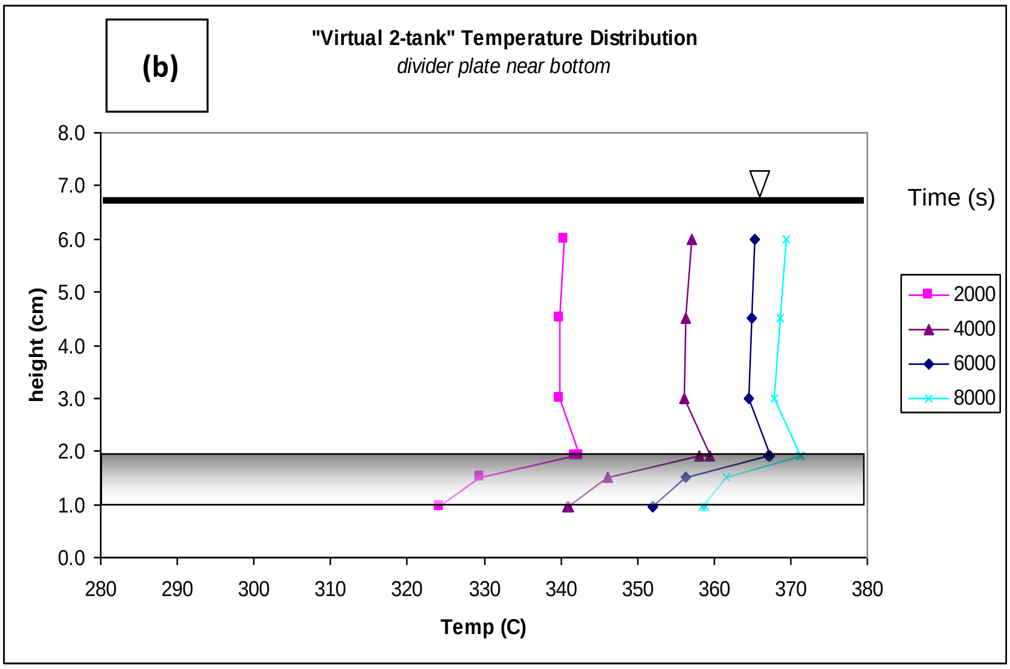


Figure 9-10: Temperature distribution of molten nitrate (60/40 Na-K) salt mixture as a function of depth at various times under the MIT CSP Solar Simulator. The divider plate is denoted by the shaded grey box: near salt surface (a) and near receiver bottom (b). Note the top of the divider plate is hotter than the salt surface temperature in both cases

9.6. Heat Extraction System

The power block (salt pumps, heat exchanger/steam generator & power generation device) elements considered for the near-term nitrate salt CSPonD system will be those that can be commercially obtained. The power extraction system in future generation NaCl-KCl CSPonD designs have several constraints:

- *High-temperature salt*. Heat in CSPonD is stored in the heat capacity of the salt at temperatures up to 1000°C. Peak steam temperatures are ~600°C and limited by corrosion. The temperature of the salt to the steam system must be significantly below peak salt temperatures of 1000°C
- *High salt freezing temperatures*. The freezing temperature of NaCl-KCl is about 670°C. This implies that the steam cycle has the potential to freeze the salt.
- *Auxiliary heat loses*. The CSPonD cooling systems for internal reflective surfaces (e.g., a CB and the pond cover) and other components may be significant. If so, the

steam cycle should be designed to recover this heat to increase efficiency, e.g. in a cogeneration capacity.

- *Economics of scale*. There are large economics of scale associated with steam systems and significant increases of efficiency with scale. Conversely, each CSPonD receiver has an optimum field size, which maximizes collected power while still maintaining a small solar image and aperture size – reducing radiative losses. This raises the question of whether heat from multiple CSPonD systems should be fed to a single steam plant, or run as independent power generation units.

In the near term for a high temperature CSPonD system, a steam power cycle will be assumed with peak steam temperatures of 500 °C. In order to maintain constant hot side temperature input to the steam generator, the two-zone tank described above is to be used where hot salt is pumped to the steam generator where high pressure water is converted to high-pressure steam that is sent to a turbine to produce electricity. Cold salt is returned to the bottom of the tank. The pumps and steam generator system for our virtual “two tank” system have already been proven in Solar II and subsequent variations. Hence the system is basically “shovel ready”.

In the simplest form, steam generator coils could be in contact with the salt pond’s external walls, and the salt need not be pumped. Direct contact implies a varying input temperature which is difficult given the highest temperature of a chloride salt system. Hence the concept of a *heat clutch* is proposed where the steam generator coils are radiatively coupled to the salt tank, but the view factor is varied by adjustable louvers. This is just a concept at this time, and has not been researched further because at the present time for the nitrate salts, it is recommended to pump them through a steam generator as is done with current tower systems that use nitrate salts with a two tank system.

Alternatively, for the high temperature chloride salt option, where the “low” temperature of the salt is just above the desired 500 C steam temperature, two salt loops are used where hot salt can be blended with some cold salt recycled from the steam generators to create a uniform salt temperature entering the steam generators. Overhung centrifugal pumps take cold salt from the steam generators and feed it to a jet pump where the higher-pressure cold salt is used to boost the pressure of the high-temperature hot salt from the pond while mixing the two salts to the desired temperature before feeding the resulting salt to the steam generator.

Most of the salt handling and power-cycle technology required for the hot chloride salt option for CSPonD has been partly been developed for the molten salt reactor (MSR) [23]. The MSR was part of the Aircraft Nuclear Propulsion Program and later a power reactor program. Salt temperatures were over 800°C. The program built the Molten Salt Reactor Experiment: a ten-megawatt thermal reactor that operated for several years with a liquid-salt pump in the primary reactor system at 700°C, a primary salt to secondary salt intermediate heat exchanger, and the secondary heat transfer loop with a pump that dumped heat to an air-blast heat exchanger. High-temperature pumps in liquid salt were tested [24] in sizes up to 1500 gal/minute. Each pump used a nearly conventional bearing assembly to support a vertical shaft and an impeller suspended into the tank containing the high-temperature liquid salt. Drive motors and lubrication equipment were above the impeller and insulated from the hot salt. The pump seals were located between the impeller and motor in a cool environment with a small flow of inert gas toward the impeller to prevent salt build-up. The test loops showed high pump reliability in high-temperature salts that were also highly radioactive.

The MSR project also developed designs for a 1000-MW(e) power plant that included development of steam generators that coupled the salt-cooled reactor with the steam power cycle while preventing freezing of the salt in heat exchangers during start-up and shutdown. The total expenditures in today's dollars exceeded a billion dollars and hundreds of technical reports were written and are available. MSR plant thermal-to-electricity efficiencies were estimated at 43%. Salt coolants are also being investigated for use in fusion reactors and as intermediate heat transfer loops between gas-cooled reactors and chemical plants [23]. This includes studies on salts for heat transfer [25].

The CSPonD system may be deployed in arrays with the option of multiple CSPonD systems feeding a common steam turbine. There are large economics of scale associated with steam turbines; but, there are complications in long-distance heat transport and coupling multiple power sources. There are multiple coal plants, such as the Tennessee Valley Authority's Bull Run plant, where two boilers feed a common steam plant. More recent experience is the Chinese program to develop modular high-temperature nuclear reactors where it is planned that up to 8 modular reactors will feed high-temperature steam to a single turbine. A two-reactor station is under construction to demonstrate the reactor and combined steam system [24].

9.7. CSPonD Materials Durability & Compatibility

There is a large industrial experience base with molten salts used in the heat treatment of metals [26] where the salt bath is open to the atmosphere as metal components are moved in and out of the salt bath. The heat treating industry has developed standard methods to test the salt, uses additives to control salt chemistry, and replaces the salt if the impurity levels are too high. The rate of impurity build-up will be much lower for CSPonD than for a heat treating bath with its daily throughput of steel parts. Regardless, it is anticipated that impurities in suspension will have a significant effect on the attenuation properties of the salt and will therefore have to be closely monitored and controlled. There has been basic work associated with salt-cooled nuclear reactors to make measurements in-situ measurements in liquid salt systems using laser systems [27,28]. Changes in salt viscosity will also be more important for the CSPonD because the salt is part of a power cycle and may have to be pumped through heat exchangers.

If chloride salts are selected for CSPonD, these high-temperature salts generate small quantities of HCl when exposed to moisture at high temperatures. The quantities are far below any hazardous limits based on thermodynamic calculations and industrial experience. If however required, there are two control strategies: (1) salt additives (e.g. NaOH) to reduce the thermodynamic potential for HCl generation, and (2) nitrogen blanketing of the salt to minimize moisture input to the salt.

Figure 9-11: Open air NaCl-KCl Salt bath at 900oC for metal heat treating.
(Picture taken at Metallurgical Solutions, Inc in RI)

The chemical compatibility of NaCl-KCl with relevant concentrated solar power materials has also been checked using the thermodynamic database *FACTsage* [29] in the temperature range 700 to 1000°C, and NaCl-KCl is not expected to react with the constituents of typical structural materials (e.g., Fe, Cr, Ni, Mo, Mn) and refractory materials (e.g., alumina). These findings were anecdotally confirmed by discussions with engineers at the Metallurgical Solution Inc. heat treatment facility in Providence, Rhode Island. In their plant, molten NaCl-KCl does not attack submerged carbon steel, stainless steel or silica-alumina bricks at temperatures as high as 1100°C; also, no significant signs of salt oxidation are observed at these temperatures. (Figure 9-11) However, as mentioned in literature and as observed in our testing [28], quartz crucibles in contact with chloride salts tend to lose their optical clarity with time. This hazing is likely a diffusion related issue not a well-defined chemical reaction, and it was therefore not predicted by FACTsage. This is a primary reason why a quartz window for the aperture is not being considered.

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Chapter 10. The Heliostat system for a CSP-DSW plant

In this Chapter a more detailed discussion is presented over the operational requirements of the Heliostat system. A number of important engineering considerations are also presented, as well as the general parameters for the considered CSP-DSW plant. Since the Heliostats represent the most expensive component of a co-generation plant (in the range of 50% of total cost), it is imperative that the most appropriate and efficient system is adopted to maximise performance.

In the second part of this Chapter, a discussion and a modelling mechanism is presented about the placement of Heliostats on a hillside. A software tool has been developed by Prof. Mitsos' group at MIT through which the potential of a hillside is evaluated given a region's elevation data of adequate resolution. This tool is capable of selecting the most promising areas where a CSP plant can be built, accommodating various possibilities for the receiver system (CSPonD, Tower, or natural elevated receiver).

10.1. Concentrating Solar Radiation with Heliostats

The principle behind concentrated solar power (CSP) is that when light is focused, or concentrated, onto a small area, the temperature of the latter increases. This process implies the conversion of solar energy into heat, which can subsequently be either stored or immediately used by a heat engine: a device that converts thermal energy into mechanical output. This device obeys the laws of thermodynamics and its maximum theoretical efficiency is given by the Carnot efficiency as

$$\eta_{max} = 1 - \frac{T_{cold}}{T_{hot}}$$

where T_{hot} and T_{cold} are the input and outlet temperatures between which the heat engine operates. It is evident that a higher input temperature, achievable by higher concentration of solar radiation, will lead to a more efficient heat engine. The present Chapter focuses on harvesting and concentration of solar light.

Several technologies for concentrating solar energy exist such as parabolic troughs, linear Fresnel, parabolic dish and central receivers. In a previous report [1], the CSP-DSW group has concluded that the most suitable technology for Cyprus is the central receiver. In this concept, a large area of mirrors is used to concentrate light onto a centralized target, traditionally located atop a tower. The target absorbs the concentrated solar radiation and in the process its temperature is elevated.

Light harvesting: The heliostat

The mirrors used to harvest solar radiation are mounted on moveable frames, so as to track the motion of the sun throughout the duration of day and year, and reflect its light onto a fixed target. In order to do so, freedom of motion about two axis is required, and most often the elevation-azimuth combination is used. The device incorporating these characteristics is called a heliostat, and a couple of examples are shown in Figure 10-1.

A heliostat typically is comprised of the following components. First of all is the reflecting surface, which, depending on its size, can be made of a single mirror or multiple facets. The mirror is mounted onto a support frame that is connected to an axis, typically called a torque tube, about which it can rotate, yielding motion in the elevation direction. The torque tube is connected to a pedestal, anchoring the whole assembly to the ground, through another set of gears, allowing for motion in the azimuth direction. Motion is computer controlled by electrical motors driving the gear assemblies.

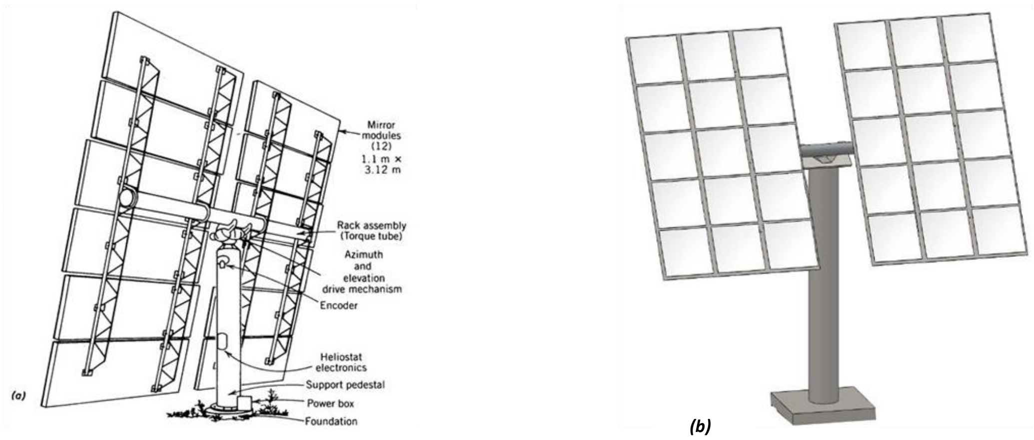


Figure 10-1: Schematics of heliostats with:

(a) showing the support structure from (W. Stine 2001) while

(b) shows the faceted construction of the reflective surface.

Heliostat mirror areas can vary significantly: eSolar, a commercial developer of CSP technology from the USA, deploys fields with 1.14 m^2 heliostats [2], whereas Abengoa Solar, a commercial company from Spain involved in energy generation from renewable sources, follows the "bigger is better" approach, using heliostats of 120 m^2 [3].

Model Name	***Manufacturer***	***number built***	***Area [m²]***	***cost [\$/m²]***	
				1/yr	*1000/yr*
Colon 70	*Abengoa*	*1*	*69.3*	*380*	*130*
Multi-Facet Stretched Membrane	*SAIC*	*4*	*177*	*805*	*168*
PSI 120	*Abengoa*	*1*	*122.1*	*475*	*150*
Sanlucar 90	*Abengoa*	*1*	*91*	*360*	*130*
Hellas 01	*GHER*	*2*	*28.2*		
ATS H100	*Advanced Thermal Systems*	*2*	*95*		*192*
ATS H150	*Advanced Thermal Systems*	*2*	*148*		*155*
AMS H150	*Babcock Borsig Power Environment*	*1*	*150*		

Table 10-1: Catalogue of solar heliostats, adapted from (Mancini 2000). Costs presented are in 1998 US dollars and are based on estimated production volume

Several companies have also proceeded to manufacture and test research heliostat units. Some of these efforts were compiled in a SolarPACES report (Mancini 2000), and are presented in Table 10-1. The trend of larger heliostats remains in the majority of the cases quoted.

It is important to note that the heliostat field represents a significant cost in any CSP plant, reaching up to 50% of the capital cost [5]. Table 10-1 also gives specific cost information for the production of a single unit, as well as the associated decrease in cost for a large manufacturing volume. The cost breakdown of the components of an individual heliostat is shown in Figure 10-2 [6].

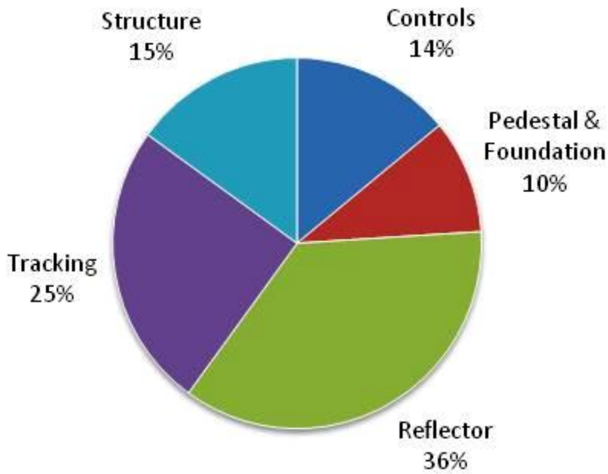


Figure 10-2: Heliostat component cost breakdown, adapted from (ECOSTAR: European Concentrated Solar Thermal Road-Mapping 2003).

There are two important factors to be considered when discussing the cost of CSP collector technologies in general and heliostats in particular. The first is that although some production units exist, the field is still young and there is much room for innovation. This is evident from the investment of commercial companies in a large number of experimental units, some of which were given in Table 10-1. The second factor is tied with the first: as the technology matures and total deployment of CSP field increases, the production volume will also increase. The economy of scale will drive down the cost of production for each unit, as reflected in the cost per m^2 of collector area. Predictions of cost trends per unit area for heliostats are presented in Figure 10-3, as estimated by DLR [7] and NREL [8].

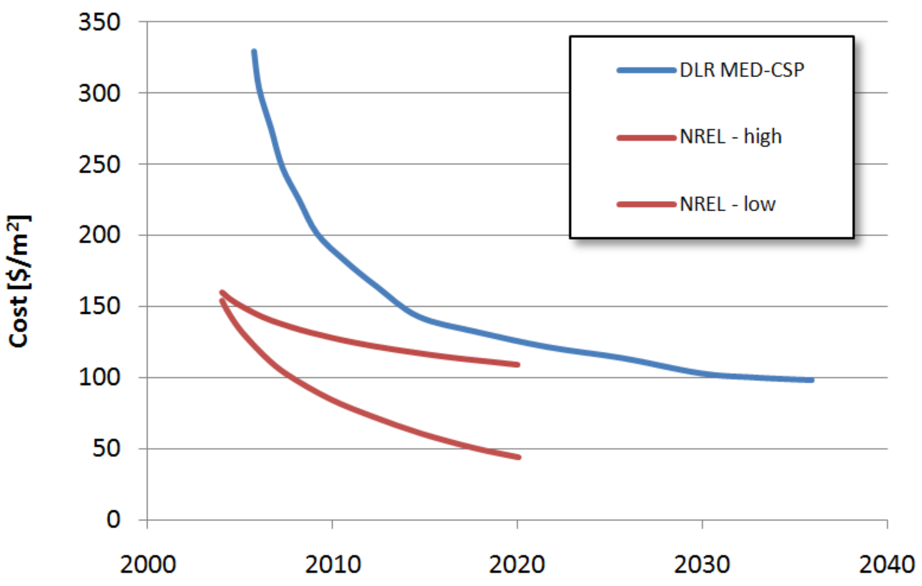


Figure 10-3: Specific cost of heliostat collection field, adapted from (DLR, German Aerospace Center 2005) and (NREL 2003).

10.1.2. Engineering Aspects

Surface canting

A correlation between concentration and achievable temperature on the receiver exists, and so, for high temperature applications, a high concentration factor is important. To first approximation, the most important factor governing the concentration factor, *C*, is the ratio between the reflecting and receiver surface area,

$$C = \frac{A_{reflecting}}{A_{receiver}}$$

It is clear that a small receiver area results in a high concentration ratio.

One way to achieve a small image area on the receiver is by giving appropriate curvature to the surface of the heliostat, called canting. Canting, therefore, refers to the relative orientation given to the individual facets the heliostat is comprised of. Two types of canting exist, on- and off-axis, depending on the relative location of the sun, mirror and target for optimal conditions. On-axis canting is when perfect focus is achieved when the sun, mirror and target are collinear. A parabola, with focal length the heliostat-target distance, is the shape that results in on-axis canting. In off-axis canting, the surface shape is optimized for a particular instant in time to give a focused image. Further concentration can be achieved by using focused instead of flat facets.

Tracking

As mentioned earlier, heliostats are required to track the apparent motion of the sun throughout the duration of the day and year. The solar path is presented in Figure 10-4 for a location near Pentakomo, Cyprus (Lat. 34.7° and Long. 33.2°). Here the azimuth angle is measured from South and zenith from the horizontal.

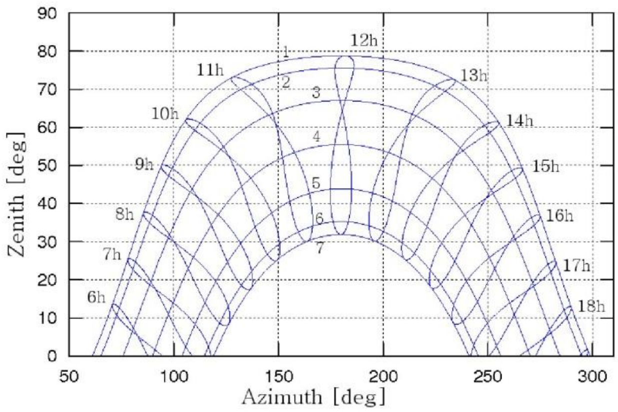


Figure 10-4: Solar paths as seen from Pentakomo (Lat. 34.7°, Long. 33.2°), 1) 22 June, 2) 22 May and 23 July, 3) 20 Apr. and 23 Aug., 4) 20 Mar and 23 Sep., 5) 21 Feb. and 23 Oct., 6) 19 Jan. and 22 Nov. and 7) 22 Dec.

With the position of the sun known at each instant in time and for a given heliostat location, the time dependent vector to the sun is ***S(t)***. Since the target is at a fixed location, the vector from the heliostat to the target, ***P***, is also known. Therefore, a tracking vector, ***T(t)***, for each heliostat is given as a function of time as

$$\boldsymbol{T}(t) = \boldsymbol{S}(t) + \boldsymbol{P}$$

A programmable logic controller (PLC) can be programmed to aim the heliostat at the predefined position based on the above equation, with only inputs being the locations of the heliostat and target, and the time. Such a tracking scheme is called *open loop* or *no-feedback*.

Another tracking scheme exists, utilizing sensors to obtain additional information regarding the position of the sun, the position of the reflection of the heliostat on the target, etc., to better aim the heliostat. Such tracking systems are called *feedback control*.

Another factor pertinent to the tracking system is the update frequency, or how often a signal is sent to the motors to re-align the heliostat. Since the sun's motion is continuous, continuous tracking is desired. This however requires accurate encoders and high gear-ratios, leading to increased cost of the heliostat.

Losses

A heliostat field is prone to several loss mechanisms, depending on the field layout, the relative position of the receiver to the field and the receiver size.

Cosine efficiency: The overall collection efficiency of a heliostat arises from the area that is reflected onto the target. This depends on both the sun's position and the location of the heliostat relative to the receiver. The effective reflection area of the heliostat is reduced by the cosine of half the angle between the sun, heliostat and target, due to the geometry of reflection. Therefore, minimizing this angle leads to higher heliostat efficiency, which is why receivers are typically placed atop towers.

Shading and blocking: Additional losses in reflecting area may arise depending on the particular field layout. For certain sun positions, one heliostat might cast a shadow upon the heliostat behind it, reducing the latter's effective reflective area. This is referred to as shadowing or shading. Alternatively, the path of the reflected light off one heliostat might intersect another heliostat, which is referred to as blocking. These losses are illustrated in Figure 10-5.

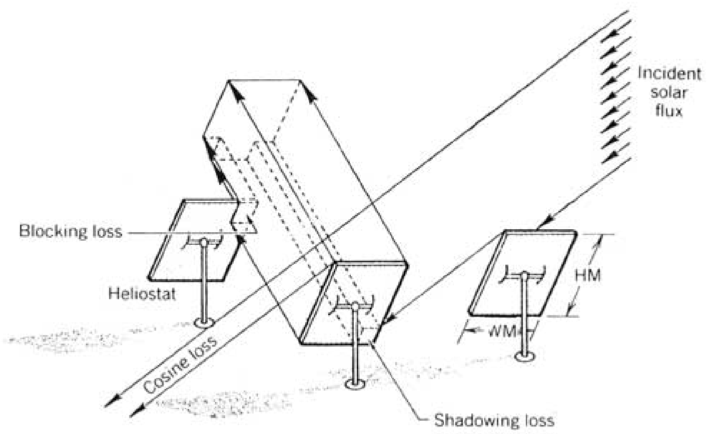


Figure 10-5: Shading and blocking losses of incoming solar radiation, from [9].

Spillage: Another parameter influencing the efficiency of the collected energy is the aperture size of the receiver. For example, if the aperture is smaller than the image formed by the heliostat, some of the reflected energy will be "spilled", or fall outside the receiver. This type of loss is referred to as spillage. It could also arise from the heliostat field not tracking the sun with sufficient accuracy.

Mirror Quality

Ordinary glass cannot be used for solar applications; instead low-iron glass is required. This is because iron absorbs light at 1100 nm and so the higher the iron content, the lower the transmittance through the glass [10].

10.1.3. Heliostats for the CSP-DSW

Although the primary function of a heliostat, i.e., to reflect solar irradiation onto a fixed target, remains unchanged, the designs that achieve this vary significantly. Along with the designs, the properties and characteristics of the device change as well. In the following section the desired features of a heliostat suitable for the particular conditions of Cyprus will be outlined.

Desired Features

From a morphological point of view, Cyprus has mainly a hilly terrain, and, being an island, is surrounded by sea. These two points immediately dictate some requirements for a heliostat design, namely that it should be adaptable to hilly terrain (typically heliostats are placed on flat or levelled land) and should be constructed of materials capable of surviving the harsh and corrosive elements present in seaside environments.

An additional feature of coastal environments is the high gusts encountered; typical measurements from Larnaca conclude that gusts up to 130 km/h (12 Beaufort or Category 1 hurricane) are encountered every 10 years [11], with even more severe gusts occurring less frequently. Although these are intermittent gusts rather than sustained winds, a requirement for a sturdy support structure becomes necessary.

Furthermore, from the introductory comments, it is clear that a focusing heliostat, which maintains the smallest possible image on the receiver throughout the year, is desired. This has implications on the surface canting and tracking accuracy of the device, setting stringent requirements for minimizing errors on both.

Due to the fact that the solar disc subtends a half-angle of about 5 mrad, the characteristic dimension of the image of a flat mirror will be larger than the mirror itself, and it will proportionately depend on the mirror-target distance. This fact highlights the importance of a short heliostat-target distance, i.e., short focal length. Additionally, it stresses the need for using focused elements, but also a medium sized reflective surface, to reduce as much as possible the image size, thus increasing concentration ratio.

In order to maintain reflectivity at high levels, the mirrors must be subjected to periodic washing. Therefore, a requirement for good mechanical resistance is also needed.

A summary of the required characteristics is given below

- Heliostat panels must be sufficiently rigid. Maximum deflections at any point on the reflecting surface must be minimal under maximum operating wind load conditions as compared to the position under no-wind conditions.
- Heliostat must have dual-axis tracking. The rotational mechanism should have a minimum step size of no more than 1 mrad in the azimuth and altitude directions and utilize appropriate gearing mechanisms to eliminate system backlash.
- Heliostat total reflective area is to be around 50 m^2. Mirror reflectivity is to be ≥ 90%. Mirrors should employ environmental seals for resistance to corrosive elements.

Based on the aforementioned factors, the recommendation is to proceed with a mid-sized heliostat, with a reflective area around 50 m^2. Dual axis motion is required with continuous motion being a desirable feature. Focused elements are to be used and an on-axis parabolic cant is to be given to the surface, to maximize the annual harvested energy while minimizing the image size. A design utilizing appropriate construction materials is to be selected, so that the heliostat can survive for prolonged periods on the harsh, coastal environment. For the 4MW facility, a total reflective area of 100,000 m^2 is estimated to be required. Assuming that the individual heliostat is 50 m^2, a total of 2,000 heliostats are required.

Heliostat serviceability and cleaning

Since heliostats operate outdoors, they are subject to the elements. Dust and dirt accumulate on the mirror surface, degrading the optical quality of the mirror, an effect known as soiling. Soiling is further accelerated in seaside environments due to the increased moisture and salt-particles in the atmosphere. Thankfully this process is reversible, and periodic cleaning restores the original reflectivity of the mirrors.

Estimates of soiling rates range from 0.2 – 0.7% per day. The ability, or lack thereof, of the heliostat to be stowed in a face-down position (inverted) strongly influences the amount of yearly washes required; an inverted heliostat requires between 1/2 and 1/3 the number of washes per year as compared to a non-inverted heliostat [5]. About 1 litre of water per m^2 of heliostat is required for cleaning.

As heliostats rely on mechanical means to track the sun, the gearboxes and motors will require periodic maintenance. The frequency and cost of the required maintenance is dependent on the particular design employed.

However, both cleaning and servicing requirements highlight the issue of access to the heliostats. Any field must have paths to allow a small motorized vehicle access each and every heliostat. This requirement must be taken into account during the heliostat field layout design.

Market Survey

Under the framework of the CSP-DSW collaboration, a market survey has been conducted, aimed at locating various vendors whose heliostat would meet the above requirements. In a related to the Study research activity, The Cyprus Institute was willing to procure a small number of heliostats in order to get familiarized with their operation, characterize performance, and research alternative tracking and surface configurations in its research facilities developed at Pentakomo area. These plans did not materialise due to various reasons.

Most commercial companies, have designed and are producing heliostats up to certain specifications that did not meet the CPS-DSW requirements without significant modifications. These companies were not willing to sell only a small number of units or allow modifications to their products. In addition, modifications or improvements, and particularly their implementation, necessarily gets entangled in intellectual property issues inducing long delays and creates complicated legal issues.

The second category of vendors was start-up companies, with premature or not fully tested products, which also had a significantly higher cost per unit, since they wished to recover their R&D expenditures. Further, they were unable to provide reliable warranted products.

10.2. Placement of Heliostats on a Hillside

A simplified model developed by Prof. Mitsos and his team at MIT, utilizing digital elevation data is presented for the selection and evaluation of potential sites for central receiver solar thermal plants. The intent of developing the model is for locating optimal sites for pond receivers and corresponding hillside heliostat fields, a site configuration introduced by Professor Alex Slocum and Daniel Codd of MIT[7]. However, the model can also be used for any terrain and receivers of any height, including traditional receiver towers. The advantages of utilizing hillsides include the elimination of significant costs associated with traditional tower systems (e.g., capital and maintenance). Additionally, terrain that is otherwise difficult to develop is optimal for concentrated solar applications. As a result, hillside heliostat fields further decrease capital cost relative to traditional CSP sites because they do not require flat land, a resource of limited availability and high demand.

With the use of digital elevation data, sites are evaluated by calculating the average annual field efficiency of a set of sampled locations within the extent of the heliostat field, the dimensions of which are defined as model parameters. Included in the calculation of site efficiency is cosine efficiency, i.e., the ratio of the projected heliostat area in the direction of beam insolation to the surface area, as well as shading and blocking losses due to variations in terrain. While any location can be evaluated, the resolution of data sufficient for use in this model is only publicly available for certain regions of the world, namely the United States. The resolution of the data used must be capable of capturing variations in terrain on

[7] A. Slocum and D. Codd. Solar energy concentrator system with energy storage. Provisional Patent Application APN: 61/243763, 18 Sep 2009.

the scale of heliostat separation distances in order to accurately calculate the factors that affect heliostat field efficiency.

Utilizing the elevation data available for the United States, two case studies are evaluated, both locations with high solar resources, White Sands, NM and China Lake, CA. In each, two receiver configurations are investigated: beam up, in which the receiver or secondary reflector is located at a higher elevation than the heliostats, and beam down, in which the receiver or pond is located at a lower elevation than the heliostats. In the case of a pond in the beam up configuration, a secondary reflector is required to redirect radiation into the pond. For receivers without a secondary reflector, each heliostat in the field must be elevated at least 5^o with respect to the receiver for direct absorption, also known as a beam-down configuration. In this layout, heliostats must be located at a higher elevation than the receiver, on a south-facing hillside for example, and beam directly into the pond. In each of the two case study locations, two scenarios are investigated, (i) allowing a secondary reflector at the receiver with an optical efficiency of 0.9, and (ii) sites that do not require a secondary reflector. A third site configuration is also possible, that is using a traditional receiver without the tower. In this scenario, the field efficiency would be the same as in case (i) but without the loss incurred due to the secondary reflector. Results from case studies show that optimal sites with a secondary reflector have efficiencies roughly 8% higher on average than optimal sites without a secondary reflector. The difference is due to an improved field cosine efficiency by utilizing the terrain at the receiver to effectively create a natural tower. This is accomplished by placing the receiver pond on a north facing hill at a higher elevation than the heliostat field.

10.2.1. Model

The model proposed consists of designating receiver locations on a grid layout of uniform spacing within a predefined region of interest. At each iteration, the heliostat field is sampled using digital elevation data to determine position relative to the receiver, from which the average annual efficiency is calculated for each location. Then, the total field efficiency corresponding to the receiver location is simply the average of the sampled field efficiencies.

SRTM Elevation Data

The digital elevation data used in this analysis is available publicly from the United States Geological Survey (USGS), the National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory (JPL), and the National Geospatial-Intelligence Agency (NGA). Specifically, the data set used for the U.S. case studies is from the Shuttle Radar Topography Mission (SRTM), with one arc-second resolution between elevation data points (SRTM1 v2.1 [12]), corresponding to roughly 30 meters on the topocentric plane. Due to the coarseness of the data, the analysis is based on a simplified model used for locating potential sites and approximating field efficiency. Data is also available from the same database for regions outside of the United States, but at the lower resolution of three arc-seconds per sample.

Calculation of Average Cosine Efficiency

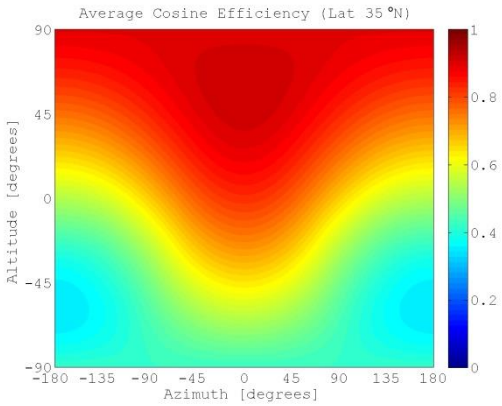
Calculating the average annual cosine efficiency is a computationally intensive process. Therefore, an efficient implementation is to generate a multi-dimensional table a priori. The tabulated cosine efficiencies are a function of azimuth, altitude, and latitude angles of the receiver with respect to the heliostat, where azimuth and altitude are defined in the Appendix B.1. Table 10-2 shows the range and resolution of each parameter.

For each tabulated value, the annual average cosine efficiency is the irradiation-weighted mean of the instantaneous cosine efficiency integrated over a year. The instantaneous beam irradiation is calculated using version one of the Meteorological Radiation Model (MRM v1) for direct beam irradiance under cloudless skies [13].

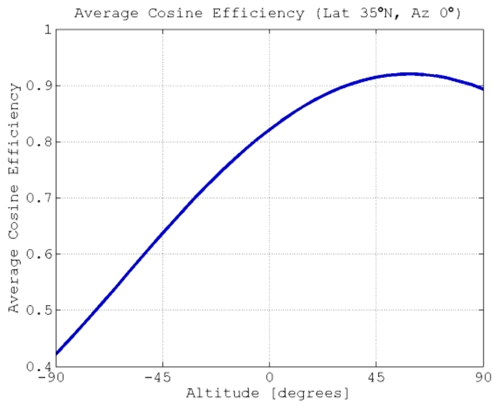
Variable	Minimum	Maximum	Resolution
Azimuth	-180	180	1
Altitude	-90	90	1
Latitude	25	50	1

Table 10-2: Cosine Efficiency Table - Range and Resolution (^{o})

Figure 10-6(a) shows the dependence of yearly average cosine efficiency on azimuth and altitude for a constant latitude of 35^o N (northern hemisphere). For the latitude selected, the maximum cosine efficiency occurs when the receiver is directly south of the heliostat and elevated roughly 60° from the horizontal plane. Figure 10-6(b) is the same data as in Figure 10-6(a), but with a constant azimuth of 0°, showing the effect of varying the altitude angle. For instance, the average annual cosine efficiency of a heliostat at 35° N latitude, 0° azimuth, and 60° altitude is 92%. Keeping everything else constant, a heliostat with an altitude of -20° has a cosine efficiency of 75%, a difference of 17%. While comparing two heliostats is not an accurate representation of an entire heliostat field, the difference in efficiencies of a field with a ground receiver versus a tower receiver can be significant due to projection losses.



a) Average Annual Cosine Efficiency as a Function of Azimuth and Altitude at 35° N Latitude



b) Average Annual Cosine Efficiency as a Function of Altitude at 35° N Latitude and 0° Azimuth

Figure 10-6: Average Annual Cosine Efficiency as a Function of Heliostat Position

Calculation of Shading by Southern Hillsides

Another factor of site evaluation is the potential shading of the heliostat field by southern hillsides. This occurs when the altitude of a hillside south of a heliostat (if in the north of the Tropic of Cancer), is greater than the altitude of the sun at any time such that their azimuth angles are the same. This scenario poses a significant problem because ideal locations for a hillside heliostat field are in mountainous terrain where there is a possibility that an adjacent hillside will shade parts or all of the heliostat field. However, checking a very large area in all directions south of each heliostat is computationally expensive. Therefore, prior to field cosine efficiency and blocking calculations, the area to the south of the heliostat field between the angles of -45^o and 45^o azimuth is checked for hillsides with an altitude greater than the minimum yearly solar altitude. This check is only done once in increments of five degrees and 100 meters in a two-kilometer radius for a single representative field location. Recognizing that some amount of shading may be acceptable, this representative location is at the center of the heliostat field, with an azimuth of 0^o and radius halfway between the closest and farthest heliostat. This way, while some shading may be acceptable, there will never be a case in which more than half of the heliostat field is ever shaded.

As for the implementation, the sun's minimum yearly altitude is tabulated a priori as a function of two parameters, azimuth and latitude. If a southern hillside has an altitude greater than the minimum yearly solar altitude, the field will be more than half shaded at least once a year. In this scenario, the corresponding receiver location is assigned an efficiency of zero, and is excluded from further calculations. Computationally, this approach is extremely fast compared to evaluating each individual heliostat and saves unnecessary time calculating the efficiency of a field that is significantly affected by shading.

Figure 10-7 shows the result of tabulating the minimum yearly solar altitude for two latitudes, 25^o N and 50^o N, encompassing the contiguous United States as shown in the Appendix B.1 [14,17,18]. For example, a hill with an azimuth of 0^o and an altitude of 25^o will shade a heliostat located at 50^o N latitude at least once per year, but never for a heliostat at 25^o N latitude.

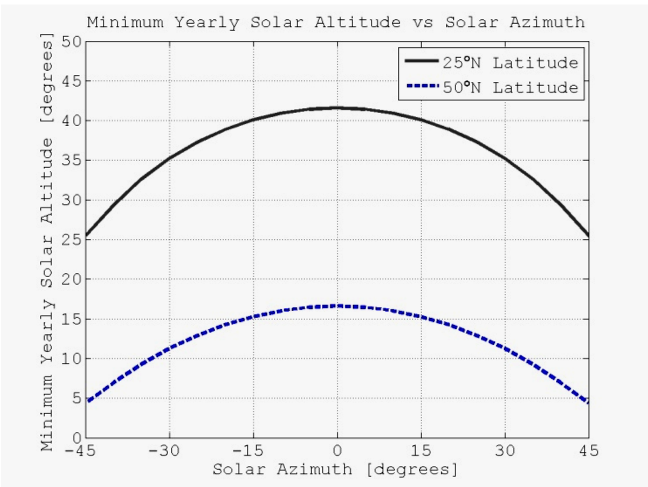


Figure 10-7: Minimum Yearly Solar Altitude vs Solar Azimuth

Site Evaluation Methodology

The methodology of site evaluation includes uniformly designating receiver locations, defining the corresponding heliostat field, represented by a set of elevation data points within the field extents, and then calculating the yearly cosine efficiency while taking into account blocking and shading by the earth. Blocking refers to intercepted irradiation between heliostat and receiver; and shading refers to intercepted irradiation prior to incidence at the heliostat.

Once the receiver location is set, the heliostat field is defined by minimum and maximum azimuth angles, as well as inner and outer radii (3D Euclidean distances). An example of a field with azimuth angles between -45^o and 45^o and radii between 150 and 500 meters, is shown in Figure 10-8. Each sampled field location is separated in increments of latitude and longitude corresponding with the resolution of the elevation data. The heliostat field is evaluated by looking up the tabulated cosine efficiency and checked for blocking at each location. The order in which points are selected is in increasing magnitude of the azimuth angle for constant latitude, and then progressively working farther from the receiver. The rationale for this procedure is that each successively sampled heliostat field location has a radius greater than all other previously evaluated locations for the same azimuth with respect to the receiver. In other words, this ensures that all heliostat field locations are evaluated in increasing radial distance for any given direction. If the azimuth angle of the field location being currently evaluated has the same azimuth angle of any previously evaluated locations, the altitude of the current location must be less than the previous. Therefore, only the minimum altitude angle must be stored for any given azimuth direction. If the current altitude is greater than the minimum altitude recorded, the current field location is blocked by one already evaluated and is assigned an efficiency of zero. If the current altitude is less than the minimum, then blocking does not occur and the efficiency of the location being evaluated is equal to the cosine efficiency. To account for coarse elevation data, two azimuth angles within five degrees of each other are compared for blocking. The total field efficiency is then calculated as the mean of all sampled heliostat field efficiencies. In Figure 10-8 the gray sample locations are ones which experience blocking and therefore have efficiencies of zero, while every other location is colored to represent the efficiency of the corresponding location.

After all receiver locations are evaluated, the program writes to file the latitude, longitude, and efficiency of each receiver. The output file is then analyzed with a geographic information system (GIS) software package, ArcMap v9.3 [14], and converted from vector data to a raster file, a method used for visualizing discrete data as a surface plot. For large areas, 100 km^2 or larger, the raster file is created by a kernel density calculation which represents the efficiency per unit area within a defined radius around each point (Data 2008). As shown in the case studies, the kernel density plots are good for locating regions of high efficiency receiver locations in a large area. Once an area is found to have high efficiency, a more detailed raster file is created by interpolating the efficiencies of individual receiver locations to identify the exact optimal location for a receiver. The resulting raster data is then written to a KML file, an image overlay for viewing in Google Earth [15]. The image overlay drapes the terrain with a color map in which receiver efficiency is the scale, red being high efficiency and blue as low efficiency. For kernel density plots, colors are indicators of relative efficiency magnitude per area, while in the higher resolution interpolation plot, the colors directly relate to the annual average field efficiency as denoted by the color scale.

In addition to the site selection model presented above, another complementary model worth mentioning exists for calculating an optimal heliostat layout for hillside technologies. More detailed than site selection, the heliostat placement model calculates the same factors that this model incorporates but on an individual heliostat basis, in three dimensions, and instantaneously as a function of heliostat position, orientation, and location of the sun, instead of tabulated a-priori. For example, in the site selection model, shading by southern hillsides is calculated for one representative field location. In the heliostat placement model, at any integration time step throughout the year, shading is calculated as the intersection of heliostat areas in the direction of normal insolation, requiring code for evaluating heliostat orientation and the sun's instantaneous position. Having a detailed model that evaluates the factors that affect heliostat field performance on an individual heliostat basis allows for a precise calculation of annual heliostat field performance and allows for optimization of heliostat layouts. While optimizing heliostat fields is not a novel concept, this model is unique in that it incorporates elevation data for hillside terrain instead of assuming a planar (two dimensional) layout which requires nominally flat land.

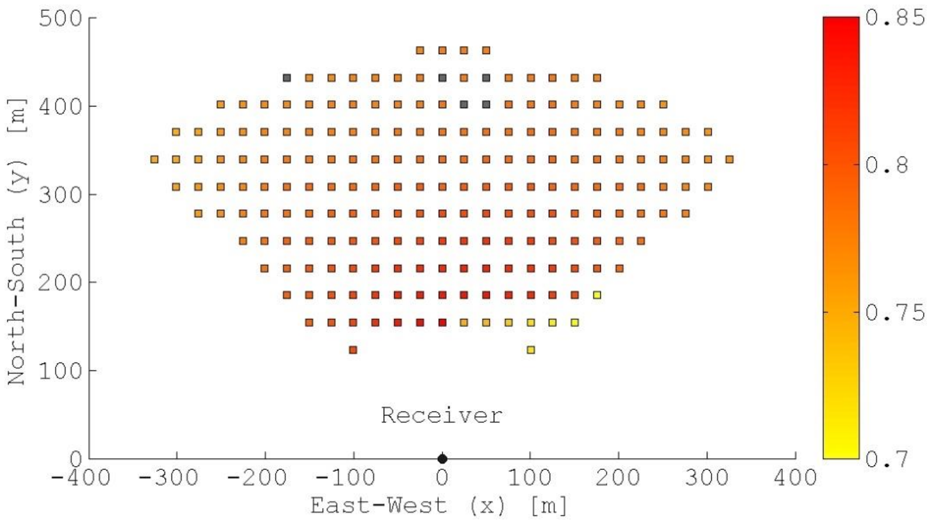


Figure 10-8: Example Heliostat Field Sampled Locations for Evaluating Site Efficiency

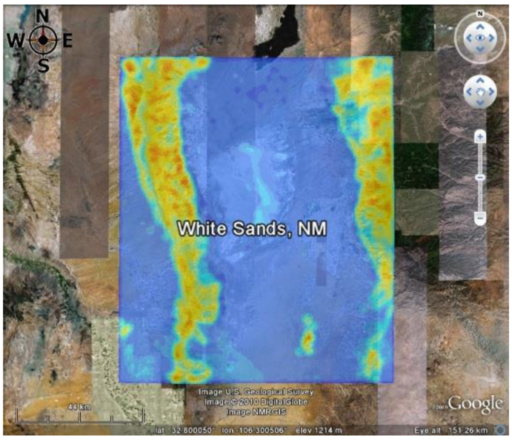
10.2.2. Case Studies

Three case studies are presented. The first two locations were selected per Professor Alex Slocum's suggestion, White Sands, NM and China Lake, CA, utilizing the resolution of elevation data available for the United States. In both, the areas are roughly 10,000 km^2 with pond receivers evaluated every 60 meters, and include roughly 2.8 million receivers per case study. The heliostat fields are defined by minimum and maximum azimuth angles of -45^o and 45^o and the minimum and maximum heliostat distance from receiver is 150 and 500 meters. The heliostat fields are sampled every 30 meters for a total number of samples per field of approximately 200. For each case study, one result is included to illustrate an optimal location for a pond receiver for each of two scenarios, (i) allowing a secondary reflector at the receiver with an optical efficiency of 0.9, and (ii) sites that do not require a secondary reflector.

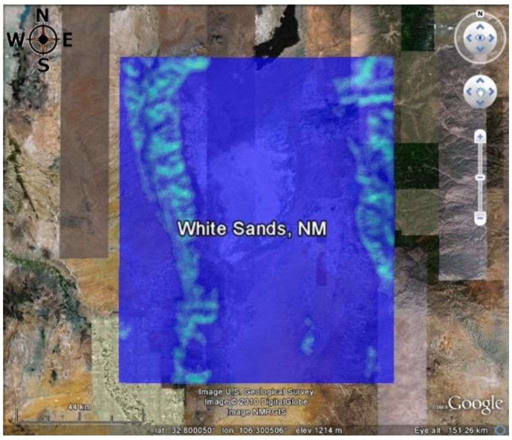
The third case study is a site in Cyprus where elevation data was provided for locating optimal sites for constructing power plants of different sizes, a 10 kW thermal demonstration plant and a 4 MW electric plant. Included in the Cyprus case study is a presentation of land potential, i.e., in addition to locating single optimal sites, answering the question of how much potential does the land have for future development of ground receiver concentrated solar technologies.

White Sands, NM

The first case study, White Sands, NM, is located at 32,8° N latitude and 106,3° W longitude. The analysis is completed for two scenarios, the first with an optional secondary reflector at the receiver, and the second without. Figure 10-9 shows both configurations for the entire area of the case study, highlighting regions with densities of receiver locations corresponding to high annual average field efficiencies in red and regions of poor efficiency in blue. As expected, hillsides provide the highest efficiency receiver locations in both cases. The plots also indicate that the field efficiency of sites with a secondary reflector are on average higher than those without despite the reflection loss.



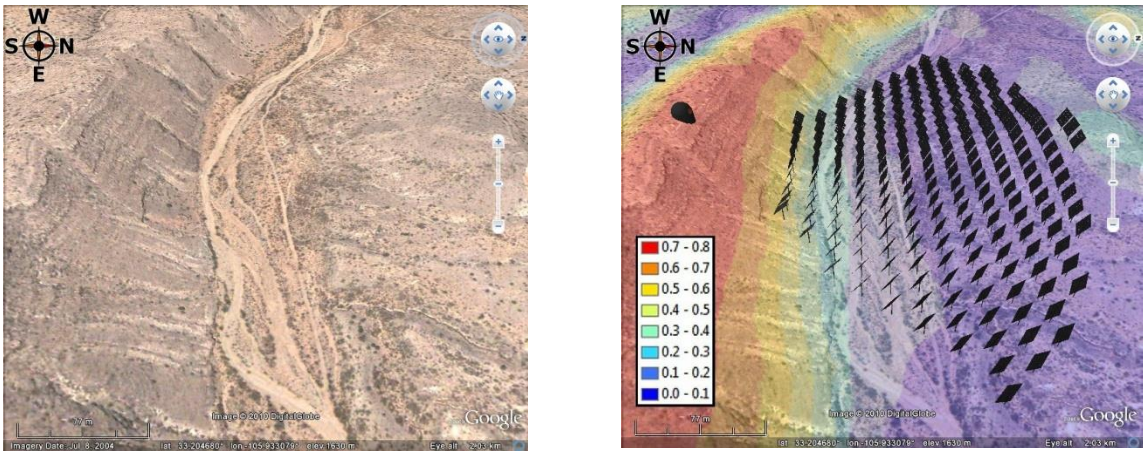
a) Sites With Secondary Reflector



b) Sites without Secondary Reflector

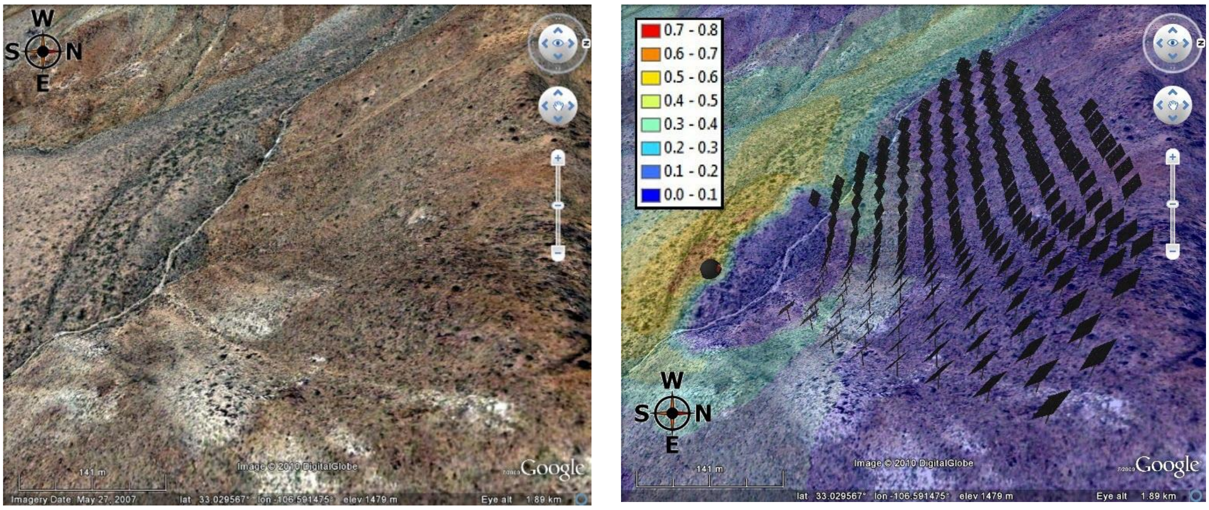
Figure 10-9: Density Overlay Indicating Areas of High Efficiency Pond Receiver Sites in White Sands, NM

Next, one of the highest efficiency results from each of the areas displayed in Figure 10-9(a) and Figure 10-9(b) are shown in Figure 10-10 and Figure 10-11, respectively. In these sites, the heliostat fields are north (right) of the receiver, represented in the image for visualization of the field extents only, not an actual heliostat layout. The field efficiency of the site with the secondary reflector is calculated to be 77% and the site without is 70%, a difference of 7% despite the 10% loss associated with the secondary reflector.



a) Terrain label *b) Field Efficiency Overlay*[8]

Figure 10-10: Potential Site for Pond Receiver With Secondary Reflector in White Sands, NM



a) Terrain *b) Field Efficiency Overlay*

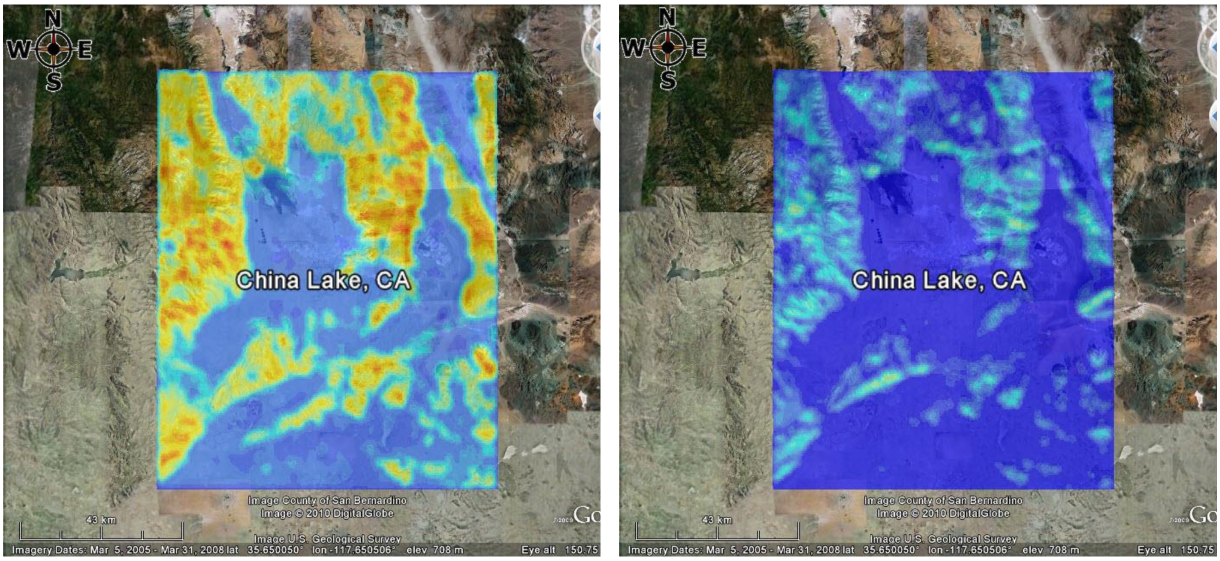
Figure 10-11: Potential Site for Pond Receiver Without Secondary Reflector in White Sands, NM

China Lake, CA

The second case study, China Lake, CA, is located at 36.65° N latitude and 117.65° W longitude. Figure 10-12(a) and Figure 10-12(b) illustrate regions of high efficiency receiver locations for both receiver configurations, with and without the optional secondary reflector at the receiver. One of the highest efficiency results from the areas displayed in Figure 10-12(a) and Figure 10-12(b) are shown in Figure 10-13 and Figure 10-14, respectively.

[8] Icons illustrate receiver location and sampled locations from elevation data, not an actual heliostat layout.

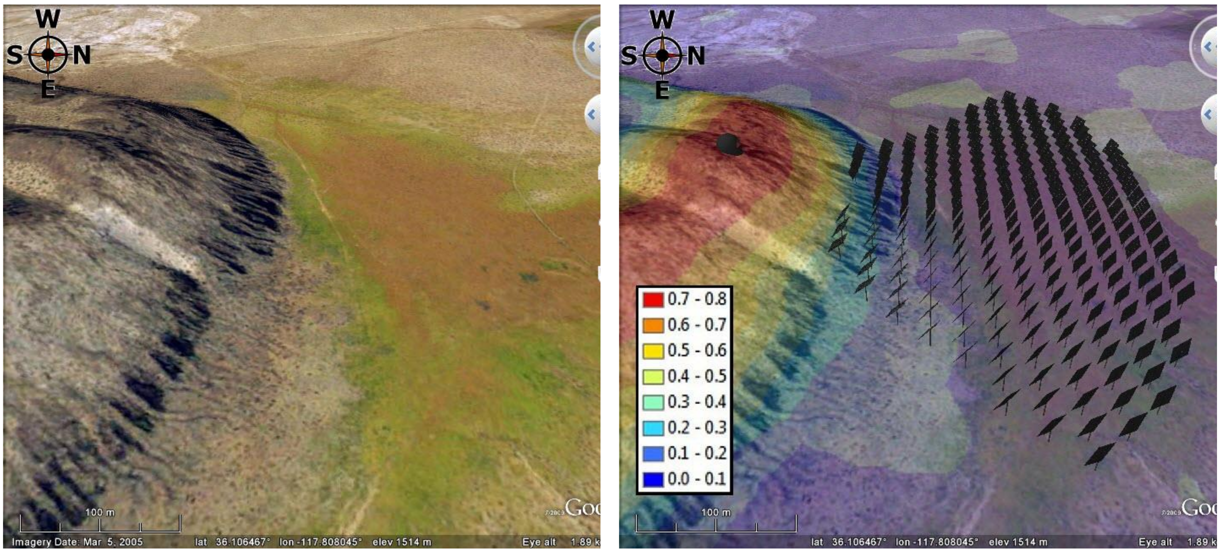
Similar to the previous case study, the optimal site utilizing a secondary reflector has a field efficiency of 77%, significantly higher than the site without, having an efficiency 68%.



a) Efficiency of Sites With Secondary Reflector

b) Efficiency of Sites Without Secondary

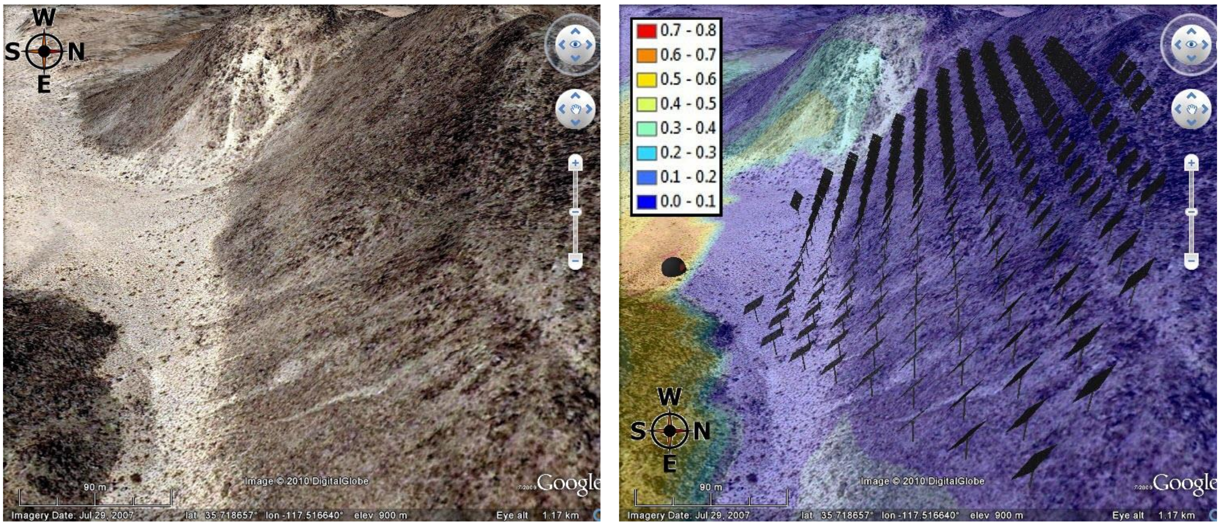
Figure 10-12: Density Overlay Indicating Areas of High Efficiency Pond Receiver Sites in China Lake, CA



a) Terrain

b) Field Efficiency Overlay[1]

Figure 10-13: Potential Site for Pond Receiver With Secondary Reflector in China Lake, CA



a) Terrain *b) Field Efficiency Overlay*[1]

Figure 10-14: Potential Site for Pond Receiver Without Secondary Reflector in China Lake, CA}

Cyprus Site Potential

In addition to common digital elevation file formats in which elevation is expressed as a function of latitude and longitude, the site selection model is also capable of using local elevation measurements taken on site. This feature is particularly useful for regions where publicly available data is not available at a resolution sufficient for use in this model. For Cyprus, publicly available elevation data is available at three arc-seconds per sample, one-third the resolution available for the United States. As a result, the heliostat field would be evaluated in 90 meters increments between sample locations, a resolution too coarse to get accurate information about variations in terrain at the scale of heliostat separation distances. Therefore, instead of using the public satellite data, local elevation measurements taken on site are used. The following case studies demonstrate the ability of the model to locate optimal pond sites and predict the potential of the CSPonD configuration in areas where elevation data was measured on site.

Another important aspect of site selection, in addition to finding an optimal site location, is calculating the potential of an area to the development of a particular solar thermal application, i.e., the suitability of the site configuration to the terrain of a proposed region. In the case studies presented below, two locations in Pentakomo, Cyprus are evaluated for two different size CSPonD sites. In both, the publicly available elevation data is very coarse, roughly 90 meters between samples. Therefore, the model is used to analyze the extents of only the land shown, corresponding to surveyed measurements on site, as opposed to satellite data. The first plot of land, as shown in Figure 10-16, is designated for a demonstration plant of roughly 10 kW heat transfer rate to the pond. The reason why only the direct-absorption pond configuration is considered is because both locations are south-facing with primarily monotonically increasing elevation in the north (positive y) direction; therefore, configurations which beam up to a receiver or secondary reflector at a higher elevation are not applicable in the following case studies. The second case study is a much larger area of land proposed for the development of a 4 MWe plant, shown in Figure 10-19. Both case study locations and areas are shown together in Figure 10-15. The 4 MWe plant is proposed to be built within the area outlined with the thick, dark border. The 10 kWt demonstration plant is planned for construction in the small black-hatched area.

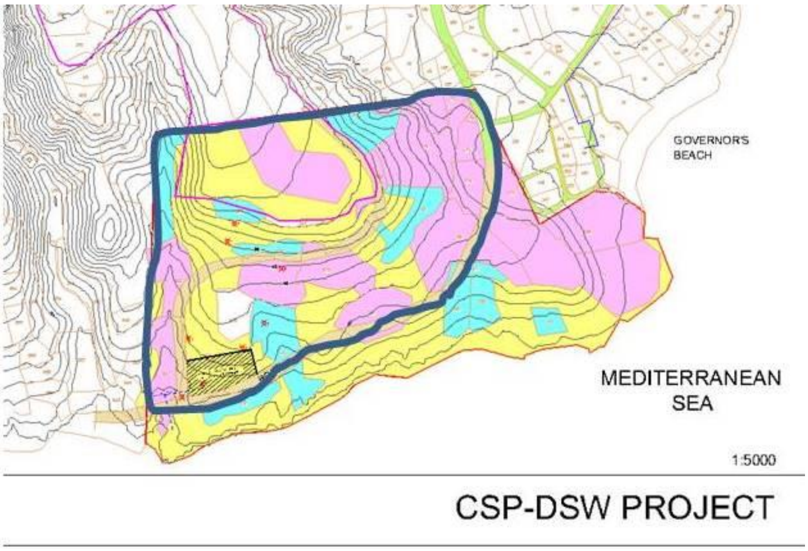


Figure 10-15: Pentakomo Site for Proposed Pond Receiver CSP(Institude 2009)

For the first case study, the 10 kWt demonstration site, the model is used to evaluate a field with minimum and maximum azimuth angle of -45^{o} and 45^{o} and minimum and maximum radii of 10 and 20 meters, respectively. These dimensions are chosen to represent an area with a heliostat coverage, i.e., the ratio of heliostat surface area to land area, of 20 percent. The results are shown in Figure 10-16, illustrating the efficiency of placing a pond receiver at the position indicated on the axes. Additionally a contour plot of the elevation data provided with 0.8 meter contours shows the terrain.

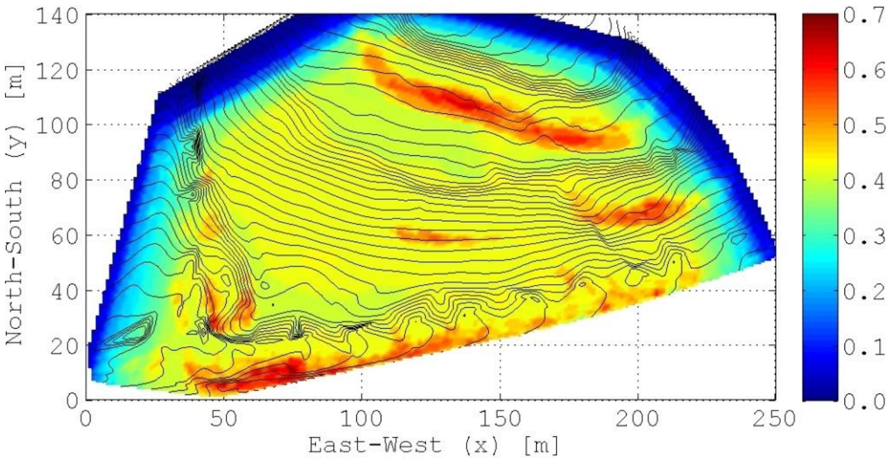


Figure 10-16: Elevation Contours of 10 kWt Demonstration Site with Efficiency Overlay

In order to calculate the potential of the total area, the number of distinct sites in which a 10 kWt demonstration plant could be built are indicated in Figure 10-17, as illustrated by the boxed regions. At each site, the annual average field efficiency is written for those above 40%. Of the 13 sites shown, the maximum field efficiency is 67%.

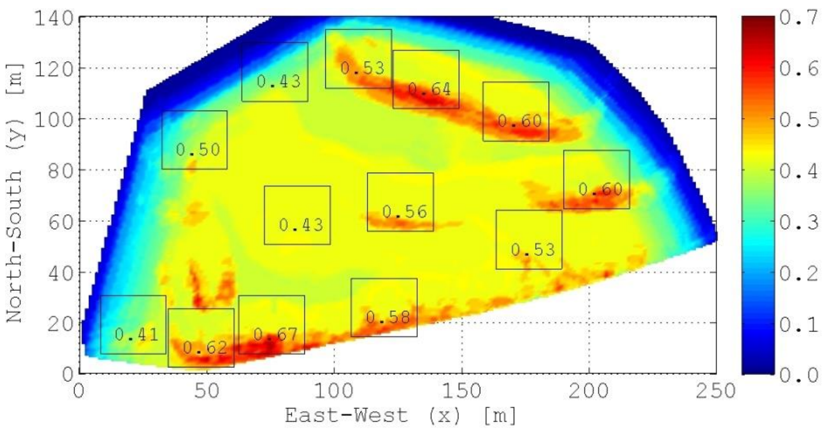


Figure 10-17: Pentakomo 10 kWt CSPonD Land Potential Evaluation

Additionally, if multiple demonstration plants of different sizes are to be built in the area shown in Figure 10-16, understanding how efficiency changes with the size of the heliostat field is crucial, a dependence specific to the terrain. The size of the hills needs to be suitable for the desired power. Therefore, the above analysis is repeated for different heliostat field sizes, represented by the amount of available direct normal insolation. The amount of power the pond receives is then calculated as the product of field efficiency and direct normal insolation. The results for various field sizes within the demonstration terrain yield pond-in power from 7 kWt to 240 kWt. The most significant result is the sharp decrease in field efficiency with increasing field size. For example, for a demonstration plant of 7 kWt heat transfer to pond, the maximum field efficiency is 68%, but for 30 kWt, the field efficiency drops to 61%. At 51 kWt, the field efficiency is 51%, and the trend of decreasing field efficiency continues. Due to the relatively small hillsides, this land is suitable for very small demonstration plants, and large plants pay a heavy penalty.

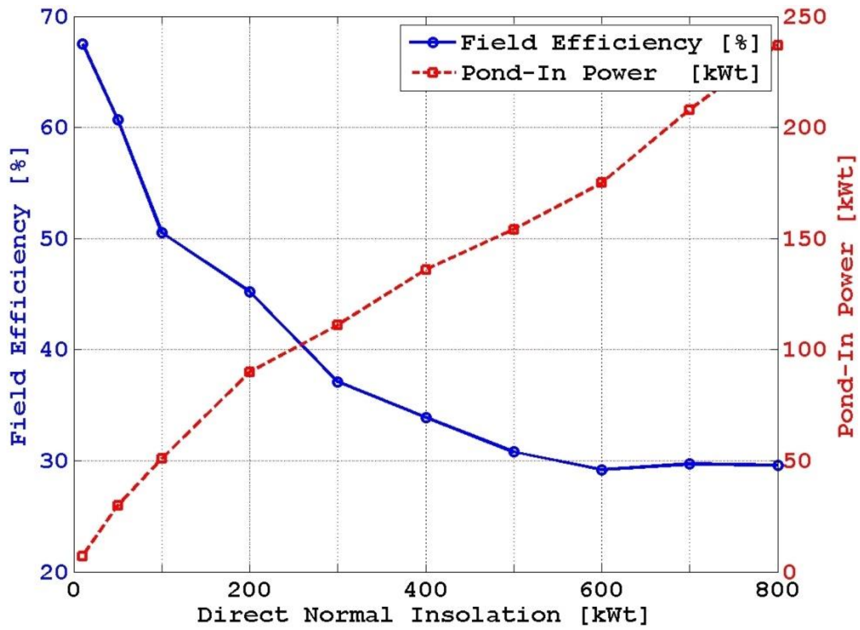


Figure 10-18: Field Efficiency vs Direct Normal Insolation

The above analysis is repeated below for a plant with a nominal rating of 4 MWe at an adjacent location, shown in Figure 10-19, illustrated with 16 meter contours. Again the contours are primarily monotonically increasing in the north (positive y) direction. Therefore, the CSPonD configuration remains the most suitable. The heliostat field is approximated to have a minimum and maximum azimuth angle of -60^{o} and 60^{o} and minimum and maximum radii of 100 and 500 meters, respectively. Similar to the 10 kWt sites, optimal locations for a receiver are south of hillsides with a steep slope in the north-south direction such that minimal blocking occurs.

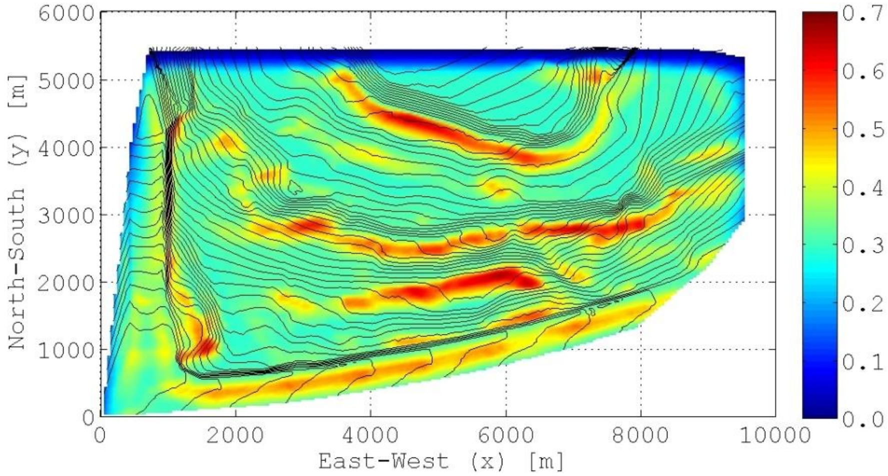


Figure 10-19: Elevation Contours with Site Efficiency Overlay}

Again, the criteria for evaluating the land potential are distinct sites (i.e., not overlapping) and have annual average field efficiency of at least 40%. Figure 10-20 shows the 25 sites meeting the criteria, with a maximum site efficiency of 67%. The reason why this area of land can accommodate larger heliostat fields and maintain an efficiency higher than the small plot of land is because the steepest hillsides are substantially larger, so fewer sampled locations are blocked.

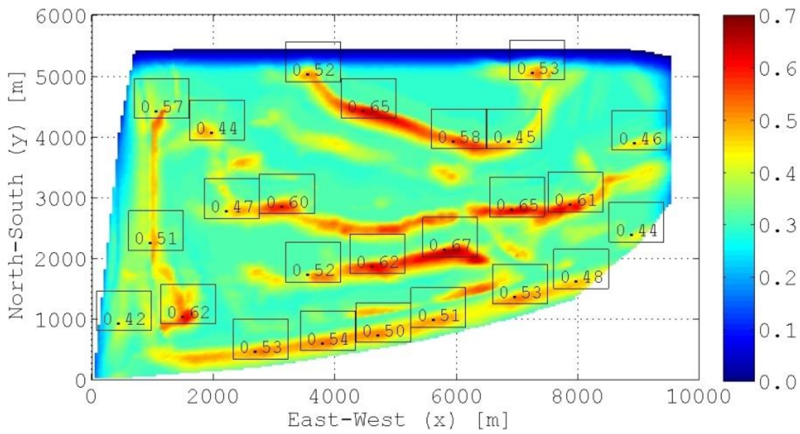


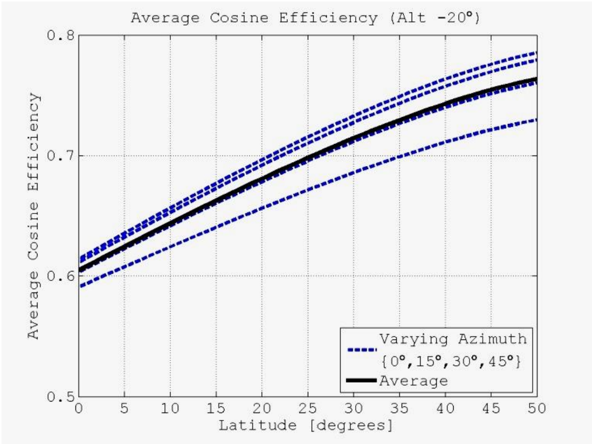
Figure 10-20: Cyprus 4 MWe CSPonD Land Potential Evaluation

The results presented in both elevation data sets are meant to serve as an initial approximation of land potential and site efficiency. Assumptions are made about the heliostat field dimensions. Future work includes calculating the relationship between heliostat field size and field efficiency for the large site. Additionally, with more elevation data, alternative sites and a comprehensive analysis of Cyprus' potential for hillside concentrated solar power can be evaluated.

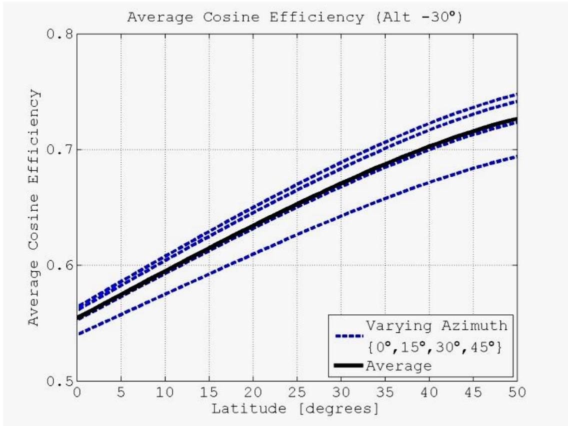
10.2.3. Results

The most significant result of the case studies presented is the field location relative to the receiver. In the most efficient receiver locations, the field is located at an elevation lower than the receiver, utilizing the terrain at the receiver as a natural tower. Even after accounting for a 10% loss associated with a secondary reflector (necessary for some technologies), the difference between two optimal sites in each case study is roughly 8%. By returning to the generic example of heliostat position relative to receiver, located at the end of Section Calculation of Average Cosine Efficiency and including a 10% loss to the efficiency of the heliostat with an altitude of 60^o, the difference in efficiencies is reduced from 17% to 8%. This result is similar to that in the United States case studies. While these results are expected to hold for Cyprus, the areas that are analyzed in the Pentakomo case study are only suitable for beaming down to a receiver at lower elevation. However, with the availability of elevation data for Cyprus at a resolution similar to that of the United States, the same trends as those found in the United States case studies should also be evident in Cyprus.

Further results of the analysis are location trends. To illustrate why a pond receiver without a secondary reflector would not be suitable for locations near the equator, Figure 10-21 plots the effect of varying latitude on field cosine efficiency. In each plot, Figure 10-21(a) and Figure 10-21(b), various heliostat locations are evaluated for a hillside of constant altitude relative to the receiver, with the average of these representative points plotted as the solid line. For field altitudes of -20^o and -30^o, the trend is an increasing field efficiency with increasing latitude. For instance, Cyprus has a latitude of approximately 35^o N. The efficiency of the field is expected to be approximately 13% higher than the same field located at the equator.



a) -20° Altitude



b) -30° Altitude

Figure 10-21: Average Annual Cosine Efficiency vs Latitude

(Decreasing Efficiency for Increasing Azimuth)

The caveat to the trend of increasing field efficiency with increasing latitude is the effect of shading, which is more prevalent with increasing latitude for areas of similar terrain. This is caused by the sun's lower altitude, as shown in Figure 10-7, increasing the chance that a southern hillside will shade the heliostat field. Another drawback of latitude locations in the distribution of solar resources. For instance, in the case of the United States, solar resources are most available in the Southwest, as illustrated by Figure 10-22. The combination of these conflicting trends will become evident after the entire United States is analyzed with this model.

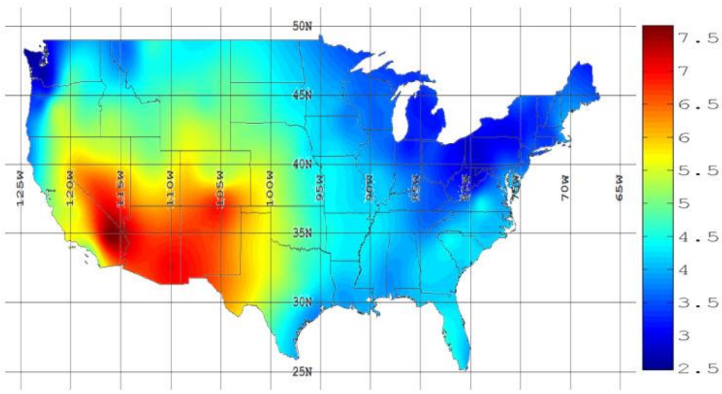


Figure 10-22: US Solar Resource Map $\left[\frac{\text{kWh}}{\text{m}^2\text{-day}}\right]$ *(Data 2008)(World (Latitude and Longitude Grids, 2000) 2000)(USA (States - Generalized, 2006) 2006)*

10.2.4. Conclusions

Presented is a model used for central receiver system site selection and evaluation. As a result of developing and using the model, the following conclusions are made. First, latitude and cosine efficiency are positively correlated for pond receiver systems without a secondary reflector. When the pond is located at the ground level, the angle of incidence of solar irradiation at the heliostat decreases with increasing latitude. Second, the effect of shading is more prevalent at higher latitudes. As a corollary to the previous result, because the sun's topocentric altitude decreases with increasing latitude, the chance of shading by hillsides south of the heliostat field increases. Finally, the optimal receiver locations for pond receiver systems are elevated with respect to the receiver field, utilizing the terrain at the receiver to create a natural tower.

One area for improvement in the post processing of the analysis includes mapping regions based on the availability and practicality of placing heliostat fields at the sites evaluated. Examples include rocky terrain, a road passing through the heliostat field, or unavailable land that has already been developed or designated for another purpose. In each of these scenarios, determining the optimal placement of a central receiver system would include more information than solely elevation data.

The advantage of defining consistent heliostat field dimensions for all evaluated sites is the computation time of the program. However, the drawback to this implementation is that the heliostat field dimensions are not going to be optimal in general. In other words, without calculating the optimal field dimensions, the evaluated site efficiencies are going to be a function of the model inputs. Therefore, caution must be used in the application of the model.

Finally, while the first two case studies presented are roughly 10,000 km^2, future work includes mapping the total potential for pond central receiver power plants for the entire United States, about 8,000,000 km^2. Additional locations outside of the United States may be considered, however the resolution of elevation data currently available may not be sufficient. Even at three arc-seconds per data point, one-third the resolution currently used for United States sites, the number of sampled field locations would be one-ninth the number currently used and not enough to produce meaningful and accurate results. Should elevation data become available for Cyprus at a resolution made available for the Pentakomo case study, similar analyses can be repeated on a larger scale.

10.3. Chapter References

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Chapter 11. Desalination system for a CSP-DSW plant

11.1. Cyprus CSP-DSW - RO vs. MED

According to the briefing by the International Desalination Association at its World Congress in Dubai, the global water production capacity of desalination plants on 8 November 2009 was 59.9 million m^3/day (22nd GWI/IDA Worldwide Desalting Plant Inventory). There are now 14,451 desalination plants online, plus 244 known to be under contract or in construction, which will contribute an additional capacity of 9.1 million m^3/day. Among these plants, a significant and growing portion are gas power dual-purpose plants with either RO or thermal desalination components (MED or MSF) utilizing energy recovery, but there are no such plants utilizing solar energy. As is the case with adopting any new hybrid technology, the reasons are both historical and techno-economical. The reader interested in both historical and technical insights regarding seawater desalination methods using renewable energy sources is advised to consult the comprehensive manuscript by Kalogirou [1].

The technological barriers with utilizing solar energy to drive seawater desalination are the inefficiency of photovoltaic systems and the lack of viable solutions for large-scale thermal storage for the so-called solar-thermal systems. CSP coupled to a high-temperature thermal storage, as envisioned in the Cyprus CSP-DSW project, aims to obviate the difficulties with the latter. By using concentrated solar power and a thermal storage system, we can consider that we have a large high-temperature source from which we can extract heat to drive a thermal plant. This is equivalent to a fossil-fuel problem with the fuel being the sun. The first consideration in the design of a new plant is its thermodynamic efficiency. As we saw in the previous sections, single-purpose thermal desalination (MSF or MED) plants have lower efficiency than RO plants. The popular assumption has been that only fossil fuel rich-countries can afford to build thermal desalination plants, hence the higher built capacity of such plants in these countries representing approximately half of the global desalination capacity. As these MSF plants began to be retrofitted with MED units (which achieves higher efficiency, cf. Darwish et al. [2]), the previous assumption was replaced by the realization that a dual-purpose power/water plant leads to 10-20% improvement to energy efficiency. If the primary fuel is sunlight or there is low temperature heat to be harvested, it seems reasonable to replace the large condenser in wet-cooled power plants with a thermal desalination plant both from thermodynamics (see below) and economic perspective. More importantly, it has been proven that when MED plants are driven by low temperature heat derived from solar-thermal power generation, the total water cost is lower than that from a stand-alone RO plant driven by solar energy, cf. Al-Hallaj et al. [3].

The second consideration in the design of a new plant is economics and operational efficiency. The relevant question here is which desalination process produces water at the lowest cost in a dual-purpose CSP-DSW plant, RO or MED? Thermal plants improve as the size increases, while RO is scale-independent. As the CSP-DSW is a dual-purpose plant, water cost should be compared to the cost of electricity. The question posed above can be answered after the plant size and water/power ratio are fixed. The former is somewhat constrained by the budgeted capital cost of the Cyprus CSP-DSW plant, which suggests that a 4-10 MWe turbine should be considered, cf. Poullikkas & Rouvas [4]. The latter cannot be fixed because the fresh water supply on a small island like Cyprus fluctuates with the (lately erratic) environmental conditions, and the cost of electricity is tied to (increasing) fossil fuel prices. Simply put, if there is a fresh water crisis but oil (therefore electricity) is cheap, then an RO plant is optimum because this would maximize the production of fresh water and hence the profit from its sale. If water is cheap but oil is expensive, then the optimum solution is MED (although it also requires some electricity), since then the profit from selling the electricity produced by the plant would offset the loss of power generation capacity suffered by extracting steam from the turbine to drive the MED system. Despite the recent torrential rains (too much rain water and in the wrong place), the current fresh water supply on Cyprus remains taxed, and water remains expensive. But also the cost of electricity is high in Cyprus and it is not expected to decrease relative to other necessities. In situations with varying power and water demand curves, a common practice is to consider a hybrid approach. When the electricity demand is low, RO water production will increase because electricity cannot be stored (while water can), with the added benefit of increasing Q_p, which improves the overall efficiency. During periods of peak grid demand, the RO water production will decrease, and with improved MED design, so will the MED water production. Finally, blending of MED and RO output allows the hybrid plant to achieve potable water specifications. MED output is extremely low in TDS and requires re-mineralization that can be accomplished by blending it with RO permeate with higher TDS, which is more economical to achieve with the high TDS feed water of the Cyprus coastline. So, economics and operational efficiency consideration imply that we might need to consider a hybrid RO/MED CSP-DSW plant for Cyprus.

Before we turn our attention to discuss RO versus MED for the Cyprus CSP-DSW plant design, it is important to review other relevant single-purpose and dual-purpose plants (see Appendix C.1). Conventional dual-purpose hybrid (RO/thermal desalination) plants are a reality, with the largest hybrid plant of this category operating in Fujairah (United Arab Emirates). The power production side of the plant consists of 4 gas turbines with associated heat recovery steam generators, and 2 steam turbines. The water production side employs 5 MSF units and 1 RO Plant with 2 stages. The total production capacity of the Fujairah 1 plant is about 450,000 m^3/day water and 660 MW power, which is about two orders of magnitude larger than the Cyprus CSP-DSW plant. The DLR AQUA-CSP study [5] and a related study for Oman (Gastli et al. [6]) consider a hypothetical medium size CSP-DSW plant delivering 21 MW net electrical power to the grid and a water capacity of 24,000 m^3/day. (This is comparable in size with the anticipated Cyprus plant.) We may note in passing that the water/power ratio in both plants is ~ 1 m^3/kWh. On the other side of the spectrum, the Plataforma Solar de Almeria AQUASOL project in Spain [7] is a solar-driven MED system designed for 24-hour operation with improved energy recovery and exergetic loss reduction but it requires substantial supplemental energy. The AQUASOL thermal power (Q_p=190 kW) and water production (3 m^3/hr) are two orders of magnitude smaller than those anticipated for the Cyprus CSP-DSW system.

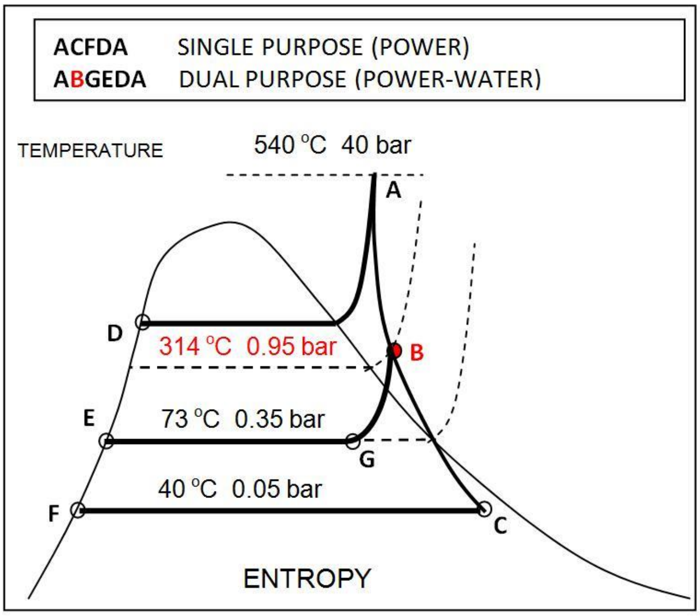

Figure 11-1: Single and dual purpose plant cycle, temperature vs. entropy of working fluid (steam).

11.2. Thermodynamics and Design Considerations of CSP-DSW

In both processes (RO or MED), the net thermal energy input (which is the difference between the heat from hot, Q_H, and cold reservoirs, Q_C) is used to raise the chemical potential of the seawater feed by separating the salt from it (chemical potential of brine + chemical potential of product – chemical potential of feed > 0). For RO, the global energy flux is Q_H→Power Plant→RO→Q_C while for MED, the flux is Q_P→MED→Q_C. Recall that Q_P, the process thermal power, is the thermal input to the MED system. From 1st law analysis and if $Q_H = Q_P$, the (reversible) energy requirement is absolutely the same for RO and MED as a stand-alone process (otherwise one can build a perpetual mobile run with sea water). The differences appear in 2nd law analysis, and in the context of CSP-DSW, in the choice of the power plant and process configurations. Real power cycles are not as sensitive to the cooling temperature as the Carnot process. The analysis of Poullikkas & Rouvas [4] indicates that there is a small decrease of the thermodynamic efficiency of the power cycle as steam is extracted from the last stages of the turbine. This last advantage makes thermal methods, in general, and MED in particular, a promising candidate for combined power and desalination cycles like in CSP-DSW.

The discussion can be better framed if we repeat the definition of the two cases considered earlier:

Case 1**:** *Consider a dual-purpose CSP-DSW plant based on an RO system with performance mimicking that of the Larnaca seawater desalination plant. The net electrical output of the turbine is 3.769 MWe. Let us define additionally a reference distilled water output of 209.8* m3/hr. Producing this by RO will require *209.8* m3/hr × 4 kWh/m3 *= 0.839 MWe, thus allowing the dual-purpose plant to deliver approximately 2.929 MWe to the power grid. Finally, let us adopt a selling price of 0.26 €/kWh for electricity and 0.92 €/m^3 for water.*

Case 2: *A parallel-feed MED-TVC system with 20 effects is considered. Seawater enters all effects with 25 C and 40,000 ppm salinity, and steam extracted at 0.5 bar with mass flux 3.5 kg/s (the maximum rate that process steam can be extracted from the turbine) is first heated by 1.3 MWth of heat harvested from the CSPond lid, enters the TVC, and then the first MED effect. The system can be abstracted by the 3-effect system of Figure 4 if effects 2-19 are replaced by effect 2. The net power output from the power block drops to 3.071 MWe. From that amount, we have to subtract the power required to drive the MED auxiliaries, which we estimate at 0.8 kWe/m^3. This means that the net power available from the turbine (coupled to system 5) to the electrical grid is 2.903 MWe.*

Let us return to the reference dual-purpose plant with the nominal 4 MWe turbine. A condensation turbine operating with a Rankine power cycle (represented by ABCFDA on Figure 11-1) can deliver 3.769 MWe with 32.3 % power generation efficiency. The same turbine on extraction mode and 0.5 bar process pressure, can deliver ~3 MW electrical power and 3.5 kg/s=13.6 m3/hr process steam for thermal desalination. Note that by extracting 91% of the steam, the generation efficiency decreases only to 23.9%, while the cooling water is reduced to 16.3 kg/s from 203.7 kg/s in the power-only mode, indicating that a power plant condenser 12.5 times smaller is now sufficient. The dual-purpose cycle is marked by ABB'GEDA in Figure 11-1. In contrast to the single-purpose cycle (ABCFDA) where the steam generator attached to the thermal storage system is the sole thermal input (branch DA in Figure 11-1), the dual-purpose cycle affords additional means of thermal input in the form of heat harvested from the solar collection system and provided to the (motive) steam (branch BB' in Figure 11-1), which enters the thermo-compressor system of the MED. This increases the efficiency of the MED system and the overall efficiency of the steam cycle.

Coupling the power cycle with RO (Case 1) can provide 0.830 MWe for desalination, which would produce 209.8 m3/hr fresh water. At the same time, we are discarding the enthalpy difference between the states C and F in Figure 11-1, which corresponds a little less than 8.4 MW (accounting for parasitic losses) to the latent heat of the steam transferred to the cooling water of the condenser. If we adopt Case 2, coupling the power cycle with MED-TVC instead would produce the same amount of fresh water as RO. With MED, we are exploiting the majority of the heat that would be rejected into the sea with RO, thus raising the thermodynamic efficiency of the steam cycle to 93.6%. The results are summarized in Table 11-1.

	Case 1: RO	Case 2: MED
Electrical power to grid (kW)	***2,929***	***2,903***
Steam cycle efficiency (-)	***32.3 %***	***93.6%***
Water production (m^3/hr)	***209.8***	***209.8***
Total Income (€/hr)	***954.5***	***947.8***
Inputs, list of DSW components	***839 kWe, 700 m^2 of RO membrane***	***3.5 kg/s extracted steam, 1.3 MWth harvested heat, 168 kWe, 20 MED effects, TVC system***

Table 11-1: Comparison between CSP-DSW with RO and MED

To decide as to whether Case 1 or Case 2 is better hinges on which variable we choose as an objective function. In the CSP-DSW system treatment in Chapter 8, an analysis of various desalination options has been carried out based on MED systems that have been reported in the literature. There the most appropriate choices for the desalination system, based on the optimization of two set Objective Functions: Obj_1: Maximum Income and Obj_2: Maximum Weighted-Average Energetic Function. The results of the optimisation process were presented in Chapter 8. Due to time constraints, it was not possible to incorporate the advanced MED-TVC system in the optimisation process.

Nevertheless, we can use the same objective functions on a basic-level analysis to compare the RO with the MED-TVC system of cases 1 and 2.

If we adopt the values of 0.26 €/kWh for selling electrical power to the grid and 0.92 €/m3 for selling water, then the Obj1 (the income from selling the electricity and water of each plant) is given in Table 11-1. The last row includes the list of components for desalination, with the estimate for RO membranes obtained from the permeate flux and the ideal permeability value of 284 kg/hr/m2 mentioned in Chapter 4. The RO system in Case 1 produces almost the same income as Case 2. So, the decision on which is preferable hinges on the *net cost of water*. The latter depends on capital and operational costs, which are scale-dependent.

One can also adopt a simplified version of Obj_2 for a direct comparison on the basis of Energetics:

Simplified Objective Function 2 = Electrical Power (net) + 4 kWh/m3 × Distillate Production	
Case 1: (RO)	*2929 kWe + 4 kWh/m3 × 209.8 m3/hr = 3769 kW*
Case 2: (MED)	*3071 kWe + 4 kWh/m3 × 209.8 m3/hr - 0.8 kWe/m3× 209.8 m3/hr = 3743 kW*

Table 11-2: Energetics comparison between CSP-DSW with RO and MED

As indicated in Table 11-2, the high water production CSP-DSW system coupled with MED-TVC is comparable with the CSP-DSW RO system based on energetic requirements. The above results are significant. They indicate that MED with a TVC system can compare *with RO on energetic and on income basis, even on small dual-purpose plants like the one considered here.* With the better integration of the MED system with the power production system, through the harvesting of latent heat from the storage system, MED gains an advantage. This advantage is further strengthened by the fact that the assumed weighted constant of 4 kWh/m^3, which is used as the levelling equivalent of RO's electricity consumption, does not include the energy requirements for RO pre-treatment and membrane cleaning, and is therefore rather conservative. On the other hand, the process of using harvested heat to upgrade the motive steam driving the TVC system eliminates the need for steam vacuum systems for the MED and this lowers the auxiliary energy needs. In fact, through the careful selection of compact heat exchangers, the electrical power required to drive the MED auxiliaries has been lowered to 0.8 kWe/m^3. Ideally, CSP with a hybrid RO/MED system is preferable for reasons of operational flexibility. The optimization of the ratio RO/MED requires non-trivial computations unless the plant configuration and RO/MED system size is fixed. If it is not, determining the optimum configuration will require the inclusion of capital and operational cost models, which constitutes a formidable optimization problem.

11.3. System design of an improved CSP-DSW with MED-TVC

In this section we present a possible design schematic of the integrated CSP-DSW plant with an MED-TVC system augmented with turbine/MED by-pass features and automatic controls. This is an alternative to the conceptual system presented in Chapter 8. The plant configuration is given in Figure 11-2. This design makes an efficient use of the heat harvested from the CSPonD lid to upgrade the low pressure steam extracted from the turbine so it can better drive the TVC, instead of preheating the seawater prior to desalination. This is accomplished by a secondary loop, which transfers heat from the CSPonD to the low pressure (0.5 bar) steam (prior to entering TVC) via the heat exchanger marked by HX 1. A second heat exchanger (HX 2) is used to preheat the seawater and condense the second (0.05 bar) steam extracted from the turbine. A third heat exchanger (HX 3) transfers additional heat to the seawater from the brine prior to discharging it to the sea. The MED also features another condenser (HX 4), which extracts heat from the water vapor generated at the last effect of the MED and transfers it to the seawater prior to its anti-scaling treatment (de-carbonation and acidification), which is required before it enters the MED effects.

In addition to the heat harvesting system from the CSPonD, there are two extra features that endow the system with extra flexibility:

(1) A steam by-pass around the turbine, by utilizing a pressure reducing valve and a de-superheater device. The bypass is activated when the turbine is shut down or its flow is low. The quantity of high pressure steam flowing to the turbine is controlled by the turbine back pressure and the maximum brine temperature. The by-pass control also includes control of the water injection to the steam de-superheater.

(2) A seawater by-pass around the MED effects and the use of MED condenser (HX 4) as a dump condenser for the steam extracted from the turbine. This is possible because the seawater flow through the MED condenser under normal operation is comparable to that required to cool the turbine. Instead of feeding it to the TVC system, the steam from the turbine is fed to HX 4. Depending on the thermal storage operation characteristics, HX 1 can be also by-passed (and the heat harvesting system de-activated) by using valves.

The process configuration and valve system allows the plant to operate continuously as a single-purpose plant, when either the turbine or the MED require maintenance or replacement. Other innovations included in our design are the employment of compact parallel plate falling film heat exchangers (typically supplied by companies like Alfa Laval) and the design of the individual effects in the MED system so as to exploit buoyancy forces for the establishment of efficient vapor flow both inside each effect and between effects. As Figure 11-4 shows, the MED effects can be stacked in a compact configuration so as to minimize thermal losses and decrease pressure drop. We have used computational fluid mechanical simulations to size the effect cavity and especially the space around the heat exchanger so vapour venting through the vacuum and outlet ports is unimpeded.

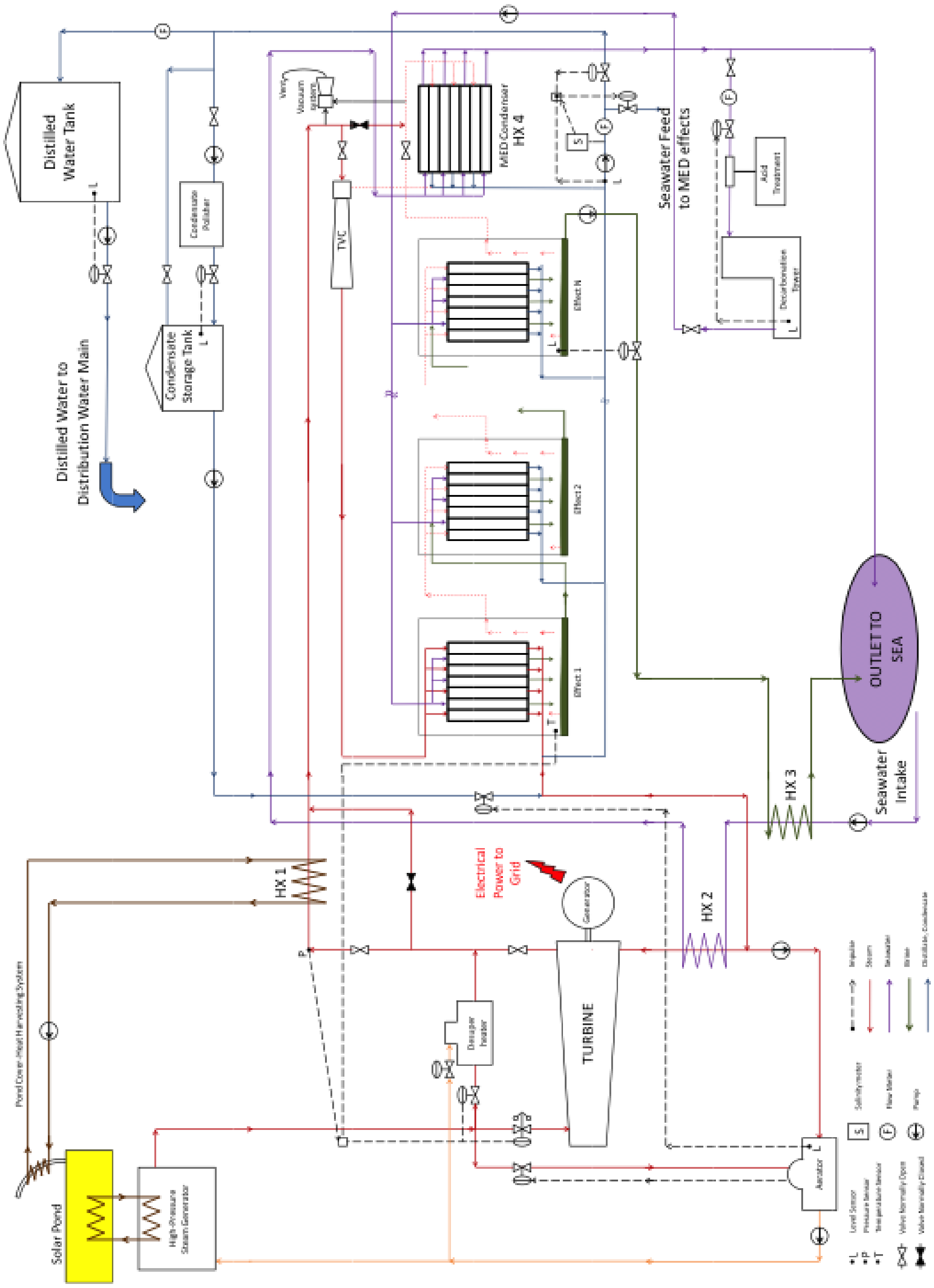

Figure 11-2: Plant Configuration with advanced MED design

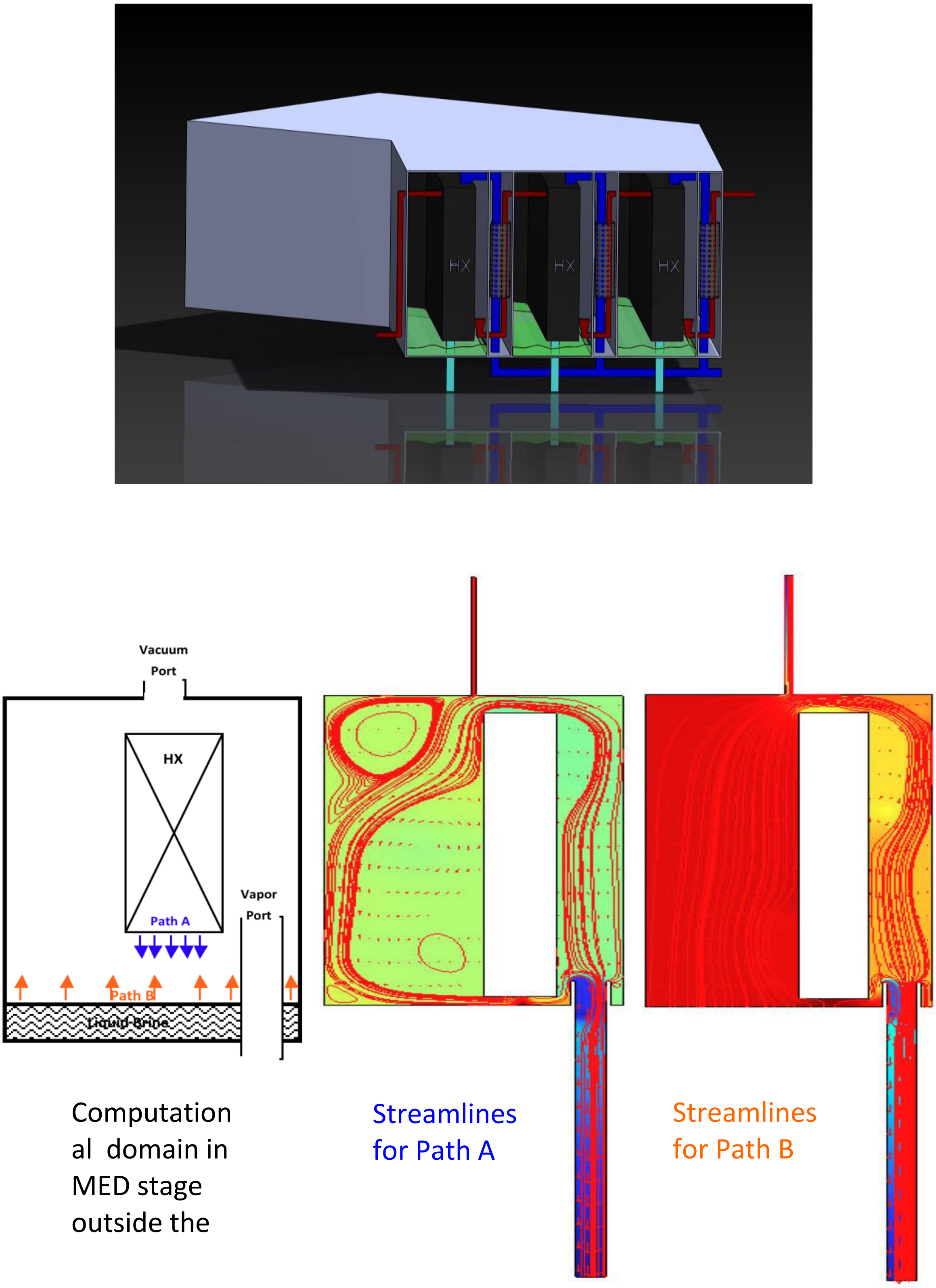

Figure 11-3: Upper panel: modular MED system with compact parallel plate falling film heat exchangers (HX). The steam path is coloured red, the distillate light blue, the seawater feed dark blue, and the brine green. Lower panels: Computational fluid mechanics model of single MED stage

11.4. Conclusion

In addition to the search for new materials to decrease the cost of water purification, novel system integration schemes are required [8]. Given a fixed thermal energy source (e.g. CSP with large thermal storage) and a Rankine-cycle power plant, performing seawater desalination via a hybrid RO/MED system is a better option (in terms of thermodynamic and operational efficiency, as well as economics) than using the electricity from the power plant to drive a Reverse Osmosis (RO) plant. RO has a number of advantages for seawater desalination:

(i) scalable,

(ii) low capital cost

(iii) coupling with power production is straightforward since it requires all energy input to be in the form of electricity.

Multiple Effect Distillation (MED) also has a number of advantages:

(i) Very low electrical consumption (less than 1 kWh/m^3) compared to other thermal processes such as Multi Stage Flash Distillation (MSF) or membrane processes (RO)[9];

(ii) Steady production of high purity distillate at water recovery ratios of over 80%, without complicated pre-treatment of seawater and irrespective of variations of sea water conditions;

(iii) Low temperature operation (< 90°C) to avoid corrosion and scaling, (iv) ideal for coupling with harvested heat or assuming the role of the condenser for power plants. Determining the optimum balance between RO and MED requires the solution of a complex optimization problem in a domain delineated by fresh water and power grid economics, as well as capital and operational cost of the plant;

A proper integration of power production and thermal desalination can improve the overall efficiency of the dual-purpose plant. The standard MED system incorporates steam, typically extracted from the turbine of the power subsystem, to drive the distillate production in the first effect. The heat of the distillate is reused in the subsequent effects to increase the yield of product water. The input steam can also power a thermo-compressor (used for improving the GOR) and a seawater pre-heater. We have incorporated additional thermal inputs to MED by harvesting waste heat from the CSP system to upgrade the motive steam for the thermo-compressor. Despite the fact that such MED systems can reach baroque complexity, thermal desalination plants are very robust and owing to the low temperatures used in MED and new heat exchanger materials technology, it has become possible to extend plant life to 40 years.

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Chapter 12. Financial Modelling

12.1. Introduction

In this Chapter the financial performance of a CSP-DSW pilot plant is examined. The financial analysis is carried out based on a discounted cash flow (DCF) model. In this analysis, four different desalination configuration options are examined for the CSP-DSW project. As mentioned in the previous chapters the choice of the desalination component is a complex matter, therefore it was decided that a simultaneous treatment of various options was needed.

The expected financial costs for Equipment, Operation and Maintenance (O&M), replacements and others, were estimated based on the designs presented in this report. The expected performance in terms of annual electricity and water production were the basis for calculating financial revenues.

The results show that the financial viability of a CSP-DSW pilot plant depends heavily on the subsidised price for electricity. Given the Feed-In Tariff (FIT) in Cyprus for electricity from CSP facilities, the CSP-DSW pilot plant is financially viable and attractive for all four configurations. A sensitivity analysis on various parameters has also been performed and the results are recorded in the last section.

Interesting results have also been obtained by the omission of the FIT. Subsidising electricity from Renewable Energy Sources (RES) in Cyprus and not the production of desalinated seawater using RES, introduces a severe market distortion, significantly compromising co-generation schemes and completely de-incentivising desalination from renewables.

12.2. Methodology

The CSP-DSW pilot plant under consideration will mainly generate revenue by selling electricity and desalinated water but also benefit from “clean energy” schemes such as the Global Greenhouse Gas (GHG) emission reduction. The annual cash flow streams were estimated for the financial efficiency analysis based on the DCF technique. The analysis was carried out using spreadsheet software. In the analysis estimated direct financial costs with estimated direct financial revenues are compared. All future cash flows are estimated and discounted to obtain their Present Values (PV). The sum of all future cash flows, both incoming and outgoing, comprises the Net Present Value (NPV), which is taken as the value or price of the respective cash flow. As it is well known, if the NPV value derived through the DCF analysis is higher than the current cost of the investment, the endeavour should be considered financially feasible.

Upon the definition of all project costs, revenues and benefits, the model calculates a variety of financial indicators, including:

- Net Present Value (NPV)
- Internal Rate of Return (IRR)
- Benefit cost ratio (also known as profitability index)
- Revenue cost ratio

12.3. Assumptions and considerations

12.3.1. Overall financial environment

For costs and revenue values an annual discount rate of 6% and an inflation rate of 2% that extends over 20 year project horizon, were considered. The debt interest rate was assumed to be 6%, equal to the discount rate for the analysis. The established Feed-In Tariff system for power plants based on CSP technology in Cyprus has been used. A 10% income tax was considered on the gross profit of the project [1]. In the analysis, an amount equivalent to 0.05% of initial capital requirement was allocated for insurance. The construction time (gestation period) was assumed to be 2 years while the total lifetime of the project is assumed to be 20 years. Finally, the currency conversion rate assumption was taken as 1 Euro is equivalent to 1.43 $ (USD).

12.3.2. Price for electricity and water

The current established FIT in Cyprus for electricity production through CSP is 0.26 €/kWh [2]. This is a special FIT established in Cyprus for the promotion of electricity production through renewable sources and depends on the renewable source. Electricity from photovoltaic systems is purchased at a price of 0.34-0.36 €/kWh [3]

Desalinated water on the other hand has no FIT and no specific purchase price from the water grid. The various desalination plants currently operating in Cyprus have individual agreements with the water grid operator (the Water Development Department), for water sales. For the purposes of this analysis the selling price of 0.92 €/m^3 is assumed [4].

For both electricity generation and water desalination an operational availability of 85% over the project's lifetime is assumed. In addition, it is assumed that the plant will be able to generate only 50%, 60% and 70% of the designed capacity in the first three years of operation.

12.3.3. Benefit from the Clean Development Mechanism (CDM)

Cyprus is one of the non-annex I countries to the United Nations Framework Convention on Climate Change (UNFCCC) and therefore eligible for benefits under the Clean Development Mechanism (CDM). The GHG emission factor for the baseline emissions by the Cypriot electricity network that is used herein is 0.8 Ton/MWh [2]. The monetary benefit from the CDM is assumed to be 14 Euros per Ton of CO_2 saved from the clean electricity production. However, this clean energy related revenue is tentative and subject to the established carbon market and international political conditions. It is for this reason the analysis was conducted with both accounting and ignoring the probable revenue stream from the CDM.

12.3.4. CSP-DSW Design options

The basic design of the CSP-DSW is the one presented in Chapter 8. The plant consists of Solar harvesting Heliostat field, able to deliver just over 2000 GJ/day to the receiver. The configuration used is based on the CSPonD concept developed by MIT, in which the Receiver and Storage unit are incorporated into a single entity and thermal storage is achieved by directing the solar radiation into a container of nitrate salt. The salt is kept at a molten state and acts as storage, streamlining the solar energy input for its use with a conventional Rankine power generation cycle. The steam turbine of the power block has a 4 MWe nominal capacity and is of the extraction type. This allows for extracting steam at different pressure-temperature points for the use with an MED desalination module.

For the desalination, four different options were the considered:

Case (A): A small, 8 effect MED unit with a daily capacity of 1002 m^3 of water as presented in Chapter 8.

Case (B): A hybrid solution employing a small 8 effect MED unit with a daily water production capacity of 1002 m^3 and a small RO unit with a daily capacity of 1500 m^3 as presented in Chapter 8.

Case (C): An RO system with advanced water production capacity of 5035 m^3 per day as presented in Chapter 4 (case 1)

Case (D): An advanced MED unit with 20 effects able to produce also 5035 m^3 per day as presented in Chapter 4 (case 2).

Depending on the desalination case considered, different amounts of electricity and water production are considered for the financial analysis. The estimated values of daily electricity and water production are given in Table 12-1. It should be noted that in cases (C) and (D) the desalination capacity is significantly higher than the first two cases. It should also be noted that these systems are designed to be on equal production footing, thus allowing for a direct financial comparison between the MED and RO technologies at the given scale.

	Case (A)	***Case (B)***	***Case (C)***	***Case (D)***
Net Electricity to grid	*83,040*	*78,240*	*70,296*	*69,672*

(kWh/day)				
Net Water to sell (m3/day)	*1,002*	*2,502*	*5,035*	*5,035*

Table 12-1: Key features of the four different designs of CSP-DSW plant for whicha DFC analysis has been performed

In the following section the detailed analysis for the case (A) is being presented. The key performance factors for all four cases are also derived and presented in parallel.

12.3.5. Financial revenues estimates

Financial revenues are estimates of the complete revenues that are expected during the operation of the pilot plant. They consist of income from the selling electricity and desalinated water to the electricity and water grid respectively, and from the GHG emission reduction benefit.

The CSP-DSW plant for case (A) is designed to deliver in excess of 30.3 GWh of electricity per year. Therefore, with a considered 85% operational availability, from the 4th year till the 20th year the annual electricity production will be in excess of 25.7 GWh which corresponds to over 9.5 million Euros per annum revenue.

Similarly for the desalinated water sales, the designed MED output capacity being 1002 m^3 per day, 310,870 m^3 is the annual yield from 4th year corresponds to revenue of 408.9 thousand Euros per annum.

The annual GHG emission reduction is about 20,610 tons from the 4th year. Assuming a benefit from the GHG emission reduction of 14 Euros per Ton, the annual revenue from the CDM mechanism would be in excess of 412.2 thousand Euros.

In comparison Case (D), which has much higher capacity for water production is able to deliver 5035 m^3 of water per day, and from the 4^{th} year the annual production is thus 1.56 million m^3, with an associated revenue of 1.43 million Euros. Due to the high production, electricity production receives a penalty and therefore only 21.6 GWh are produced on an annual basis after the 4^{th} year with a corresponding revenue of 5.6 million Euros. The revenue from the CDM would in this case be 0.24 million Euros. The annual revenue break up for Cases (A) and (D) is shown in Figure 12-1.

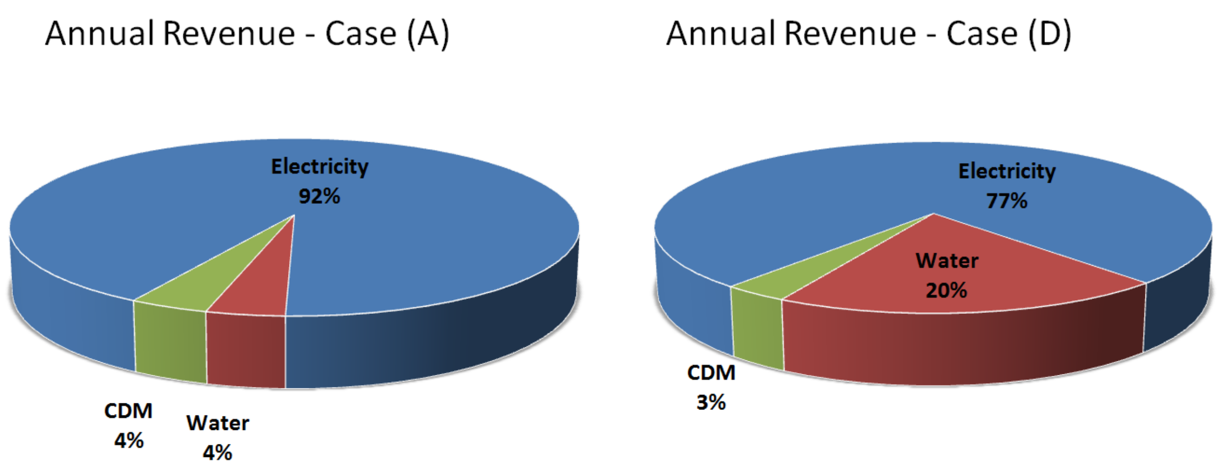


Figure 12-1: Annual revenue break up for the Cases (A) and (D)

The yearly revenue streams for all of the cases are summarized in Table 12-2.

Annual Revenue stream	*Case (A)*	*Case (B)*	*Case (C)*	*Case (D)*
Electricity (Euros/yr)	*9,578,742*	*6,311,229*	*5,670,426*	*5,620,091*
Water (Euros / yr)	*408,981*	*714,145*	*1,437,140*	*1,437,140*
CDM (Euros / yr)	*412,210*	*271,596*	*244,020*	*241,854*

Table 12-2: Yearly revenue stream break up for four cases

This table shows clearly the heavy penalty of “escaped” electricity production, in favour of water production in the revenue streams. This penalty is induced by the FIT for electricity and will be discussed in detail in a following section. It is already evident that the FIT policy in effect discourages co-generation plants.

12.3.6. Elements cost estimates

Financial costs are estimates of expenditures related to the project. Initial capital costs, operation and maintenance (O&M) costs (including personnel salaries), equipment replacement costs are some of the main cost elements that enter into the model. The capital (construction) cost data presented are derived from various vendor quotations, experience, and institutional cost data files. The operating costs are derived, in part, from actual Power and MED plants in service, supplemented by performance estimates. The cost estimates information should not be used for procurement negotiations; they are meant only for the DCF and cost benefit analysis. The data should be used only to compare alternative schemes at a planning level, or for research purposes. The implied level of accuracy of the data presented in this section is subject to an uncertainty of about 20%, as it is customary for high-tech projects at this stage of the analysis.

The major cost elements and their cost data are listed below:

A. Heliostat System

- *Capital cost:* A total of 15 Million Euros for 100,000 m^2 mirror area, at a price of 150 €/m^2
- *Annual O&M cost:* 5% of the capital cost
- *Replacement cost*: 15% of initial capital cost
- Lifetime before replacement or major overhauling in addition to the annual maintenance: 10 years for mirror replacement

B. Receiver and Storage

- *Capital cost:* 1.1Million Euros
- *Annual O&M cost*: 5% of the capital cost
- *Replacement cost*: 35% of the capital
- Lifetime before replacement or major overhauling in addition to the annual maintenance : 15 years

C. Power Block including steam generator

- *Capital cost*: 5.4 Million Euros
- *Annual O&M cost*: 1% of the capital cost
- *Lifetime*: 20 years
- *Replacement cost*: 100% of the capital

D. Desalination unit - design option (A)

- *Capital cost*: 770,000 Euros
- *Annual O&M cost*: 30,000 Euros per year
- *Replacement cost*: 100% of the capital
- Lifetime before replacement or major overhauling in addition to the annual maintenance : 20 years

For the rest three cases the costs are summarized in the Table 12-3.

Costs	Case (A)	Case (B)	Case (C)	Case (D)
Initial Capital (mil. €)	0.77	1.9	3.9	3.9
Annual O&M (k. €)	30	94	215	138

Table 12-3: Capital and O&M cost requirements

E. Other capital costs

- Utilities: 1.5 Million Euros
- Site works: 1.5 Million Euros
- Piping: 1.5 Million Euros
- Salt: 0.46 Million Euros
- Land: A heliostat field area of 100,000 m2 along with the power plant and the desalination plant and extra space for future capacity expansion was considered in the analysis. The land price was assumed to be 10 Euros per square meter for a high inclination land area. It is assumed that closer to the coast and with a lower inclination, land prices will increase dramatically. A total 214,000 m^2 of land area will be required for the plant which would cost about 2.1 Million Euros. For further studies the price of land needs to be more precisely defined, especially if such studies are location specific. Especially for the case of Cyprus, land prices are extremely sensitive to location. Unless a specific area is appraised, no general rules apply for land values. The price quoted in this analysis is clearly on the low side.

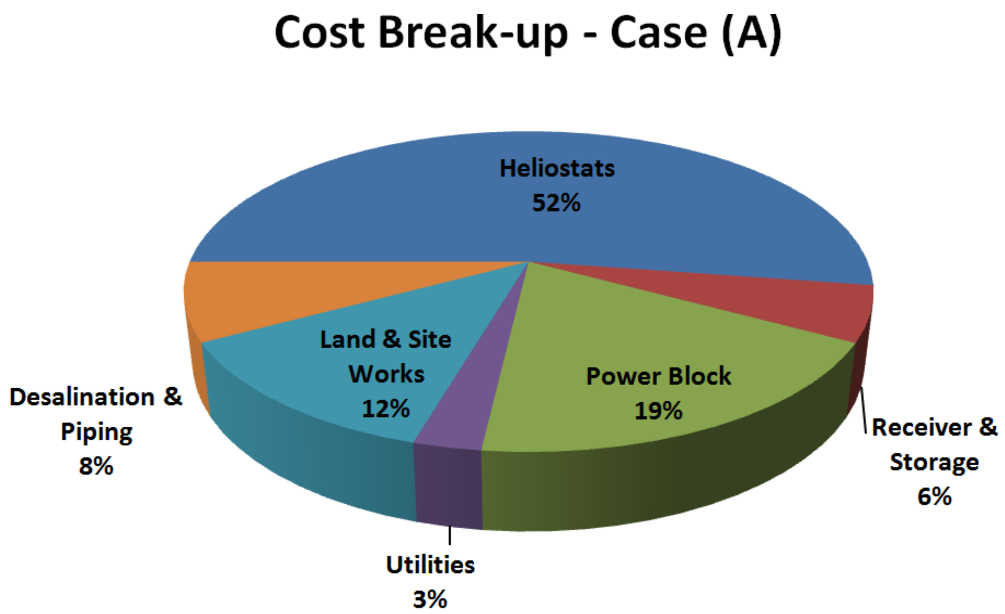
F. Personnel cost

The following table shows the personnel and salary requirements for the CSP-DSW pilot plant:

	No. Of People	Per Head Monthly Cost (k €)	Total Yearly Cost (k €)
Heliostat	*5*	*1.7*	*105*
Receiver and Storage	*2*	*1.7*	*42*
Power Block	*15*	*1.7*	*314*
Desalination	*3*	*1.7*	*63*
Supervisors & Administration	*5*	*2.4*	*146*
Total	***30***	*-*	***671***

The total personnel cost will be 671,000 Euros per year in 2010. In the analysis, an annual salary increase of 1% in addition to the annual inflation rate is considered.

The total initial capital cost need is about 25.4 Million Euros, whereas the annual O&M cost (including salaries) is estimated to be about 1.4 Million Euros for the base year 2010. It can be seen from the Figure 12-2 that the heliostat field constitutes over 50% of the entire initial capital investment. Figure 12-3 shows that the annualized values of the capital and the O&M costs from the heliostat field are the dominant source of all component costs.



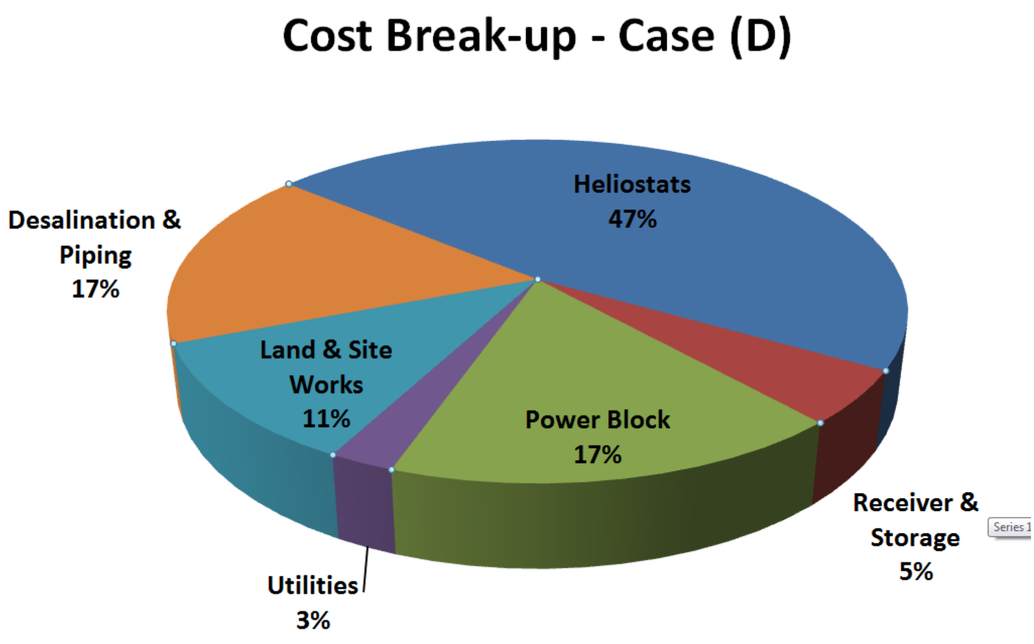


Figure 12-2: Initial capital cost break up for Cases (A) and (D)

It should be mentioned that the CSP-DSW concept is unique in respect to the Solar Harvesting and Thermal storage components. It has not been tested outside of laboratory conditions and therefore a conservative approach has been taken in the financial analysis by assuming high O&M costs. A provision for contingency funds has not been considered in the analysis.

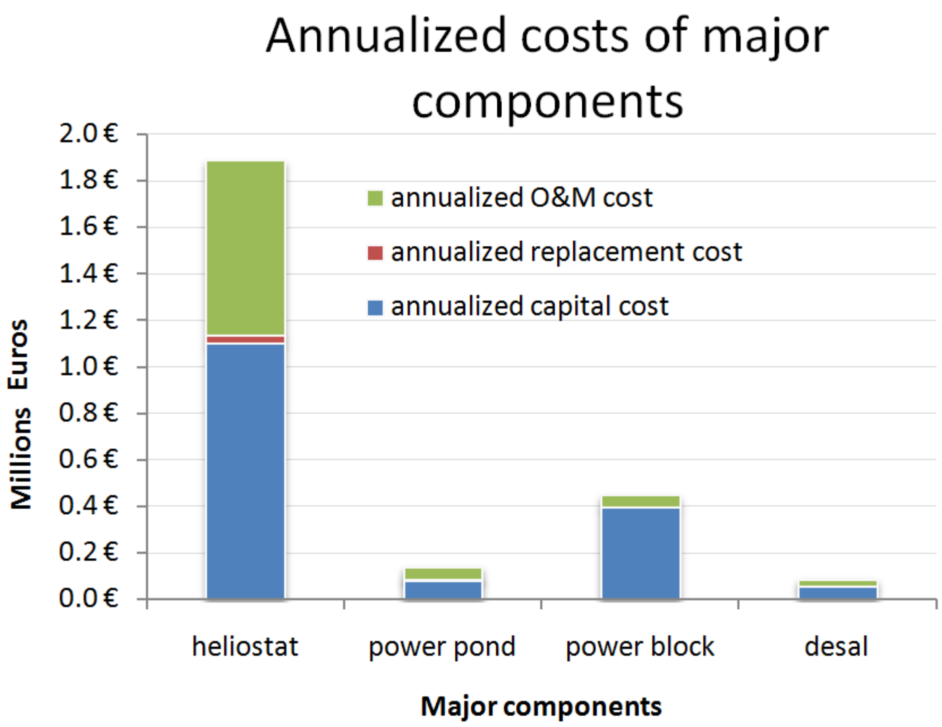


Figure 12-3: Annualized costs of major components for Case (A)

12.4. Financial Analysis Results

In this section a comparison of costs, income and benefits quantified in terms of actual money spent or received within the project's lifetime is conducted. The financial analysis results are described for clarity in detail for the case (A), while results are presented for all four cases appear in parallel.

12.4.1. Financial analysis results for Case (A)

The analysis results show that the plant will create a net positive cash flow of about 19 Million Euros in present money value, without the GHG emission reduction benefit. The production of electricity and the water remain constant from the 4th until the 20th year of operation. The selling tariffs for electricity and water are also fixed over the project's lifetime, whereas the operation and maintenance costs are subject to inflation and annual salary increases. Thus, the net cash flow gradually decreases as can be seen in the Figure 12-4. The Internal Rate of Return (IRR) of the investment will be about 13.26%. The project would generate 3.19 Euros as revenue per 1 Euro of investment. The benefit–cost ratio is 0.706 i.e. the project would return 0.706 Euros as net positive cash flow for each Euro invested over the life time of the project (20 years). The payback duration will be 7.9 years as can be seen in Figure 12-5. The threshold capacity, i.e. the operational availability at which the plant would operate on a break-even basis, provides a financial viability measures and in this case is calculated at 54.46% (compared to the assumed 85%).

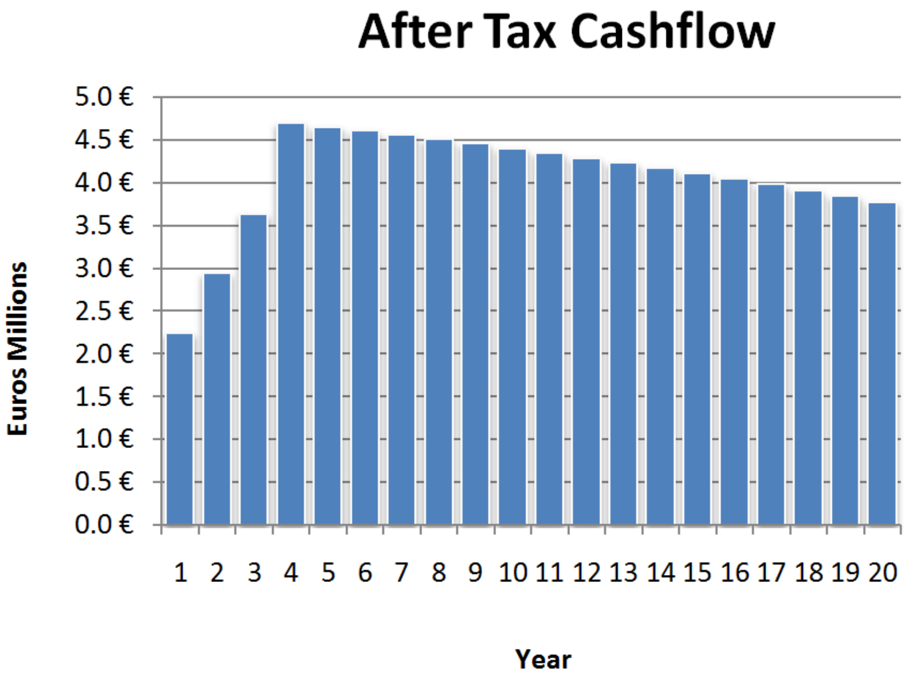


Figure 12-4: After tax cash flow for Case (A) without the GHG emission reduction benefit

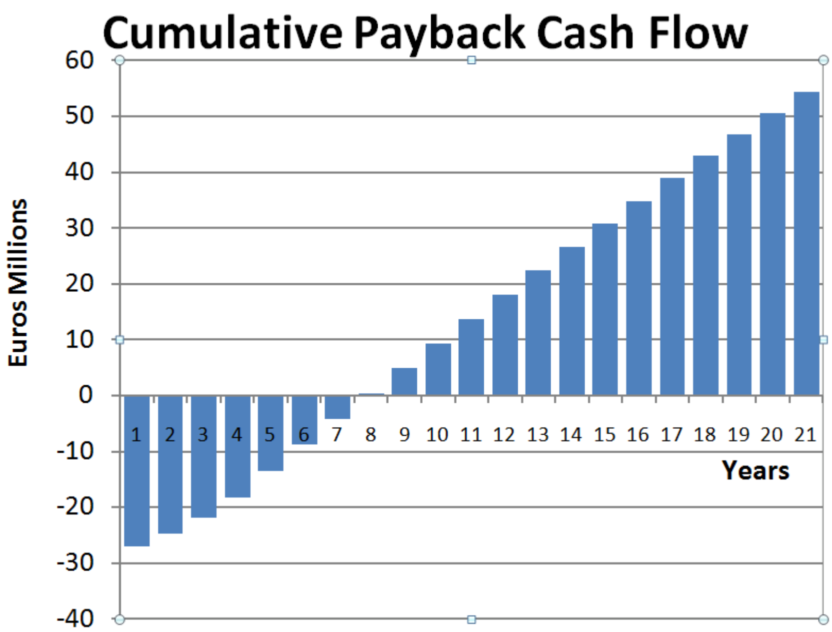


Figure 12-5: Cumulative payback cash flow for Case (A) without GHG emission reduction benefit

If the additional revenue from the Clean Development Mechanism is considered, then the financial performance of the project improves:

- NPV of after tax cash flow: 21 Million Euros
- IRR: 14.18%
- Benefit cost ratio: 0.809
- Revenue cost ratio: 3.32
- Simple non-discounted payback: 7.6 years

12.4.2. Results for the remaining cases

Similar analyses were conducted for the remaining three design options. The key financial performance results of all cases are summarized in Table 12-4.

It is noted that all four design options are satisfying the general rule that appropriately risked projects with a positive NPV could be accepted. However, as an investment, if there is a choice among many mutually exclusive alternatives, the one yielding the highest NPV presents the most attractive option, provided they present the same risk.

	Case (A)	Case (B)	Case (C)	Case (D)

NPV of net cash flow (mil.€)	*19.1*	*17.4*	*14.7*	*15.1*
IRR (%)	*13.26*	*12.47*	*11.20*	*11.35*
Benefit Cost ratio	*0.706*	*0.619*	*0.486*	*0.502*
Revenue Cost ratio	*3.19*	*3.08*	*2.91*	*3.02*
Payback (yrs)	*7.9*	*8.2*	*8.8*	*8.7*
Capacity Threshold (%)	*54.5*	*55.4*	*57.3*	*56.1*
Expected Electricity kWh/kW	*6,441*	*6,068*	*5,452*	*5,404*
Initial capital (Million Euros)	*27.0*	*28.1*	*30.1*	*30.1*

Table 12-4: Financial performance key indicators for all Cases excluding benefit from GHG emission reduction

Thus Case (A) seems to be financially the most attractive case. Case (A) yields in fact the best results in all examined indictors amongst the four examined cases. This again as commented earlier is the result of the FIT for electricity production. Case (A) produces the most amount of electricity and the least amount of water.

The annual net and the cumulative net cash flow streams for all four cases are shown in the Figure 12-6 and Figure 12-7 respectively. From both graphs it is observed that all cases present similar results although Case (A)'s financial superiority can be clearly seen.

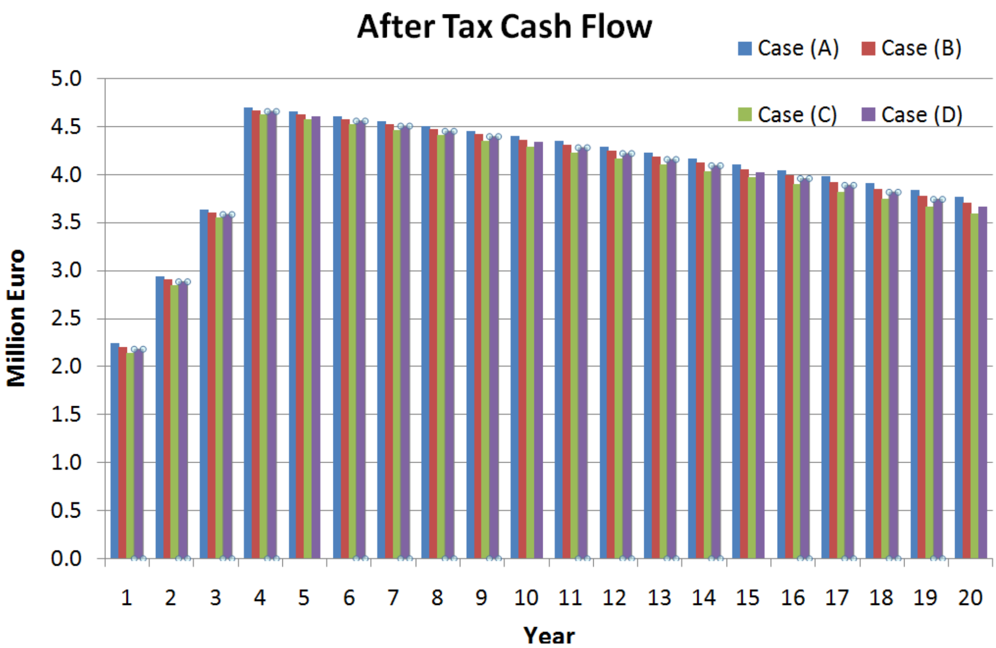


Figure 12-6: After tax cash flow for all Cases

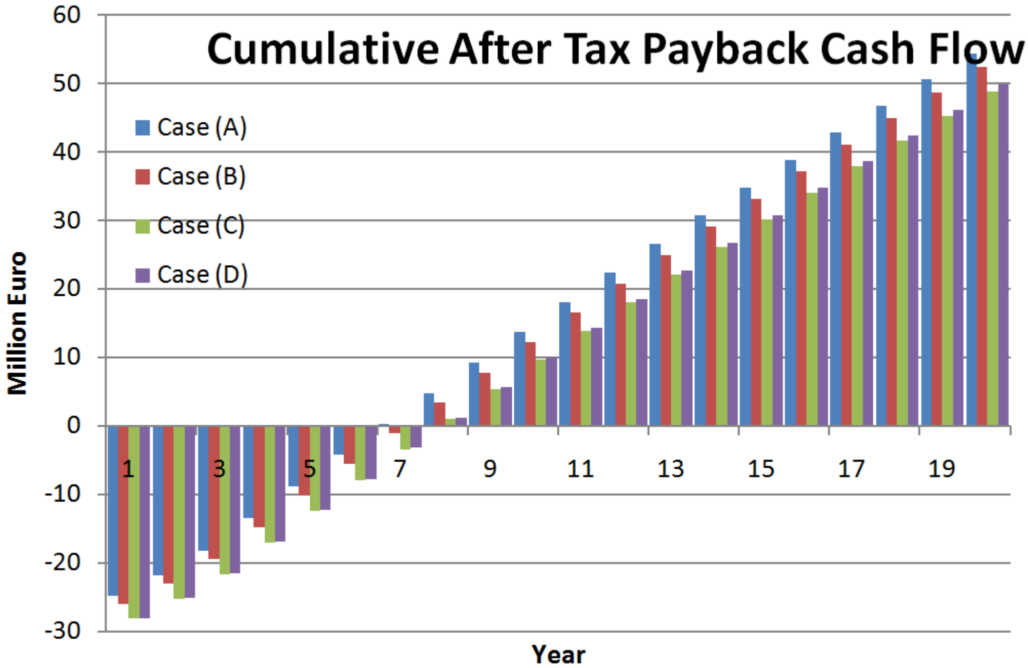


Figure 12-7: Cumulative after tax payback cash flow for all Cases

12.4.3. Financial Performance in a non-FIT environment

We now consider the same plant of Case (A) operating in the same conditions but without the subsidised electricity selling price of 0.26 Euro. Instead the normal electricity purchase price in Cyprus from conventional sources of 0.10 Euro is considered. This of course needs to be understood as subject to oil price fluctuations. In such case, without FITs, the investment is not financially viable. The NPV is negative at -20 Million Euros. It should be noted that for each individual year the net cash flow is always positive. However, the return from the business is less than the assumed borrowing rate of 6%, making the overall investment non-feasible. One can easily calculate the threshold electricity tariff that is needed to make the business break-even over the entire life span at 0.183 €/kWh.

The analysis has been conducted for all four cases and the key financial results of this are shown in Table 12-5.

	Case (A)	*Case (B)*	*Case (C)*	*Case (D)*

NPV (Million Euros)	*-20.5*	*-19.8*	*-18.8*	*-18.1*
Threshold tariff for break-even (€ Cent/kWh)	*18.30*	*18.53*	*19.01*	*18.71*

Table 12-5: Financial performance with 10 Cent/kWh tariff

Table 12-5, shows a remarkable result. Although the absence of a FIT for electricity is responsible for all cases being financially non-viable, Case (D) is the significantly better than the rest. This signifies that in a non-FIT environment, where electricity and water production are treated on an equal footing the co-generation scheme is preferable. Water production does not incur a penalty through lost electricity and therefore shows the potential of dual purpose plants. The fact that case (D), betters case (C), means also that for those two configurations, water production through MED is financially preferable to water production through RO. Cases (C) and (D) have been chosen in such a way so as to have the exact same water production and almost the same electricity output, therefore a direct comparison of the two technologies can be made on a financial level. In order for the benefits of co-generation and of the harnessing of the latent heat to appear, electricity and water production through RES must be treated equally by the market.

12.4.4. Electricity only plant

It is a matter of interest to estimate the performance of an electricity only plant which is utilizing the similar sub-components as the co-generation unit with the omission of the desalination unit. The considered turbine with 4MWe nominal capacity can deliver a maximum of 3.77 MW of electrical power to the grid as was mentioned in Chapter 8. The projected financial performance indicators of this plant are listed in Table 12-6.

Indicators	
Maximum Power Output (MW)	*3.77*
NPV of net cash flow (Million Euros)	*23.6*
IRR (%)	*15*
Benefit Cost ratio	*0.901*
Revenue Cost ratio	*3.47*
Payback (yrs)	*7.3*

LCOE (Cent/kWh)	*18.12*
Threshold C.F. for break even. (%)	*50.3*
Threshold tariff for break-even (Cent/kWh)	*17.25*
Expected electricity (kWh/kW)	*7,018*
Initial capital (Million Euros)	*26.2*

Table 12-6: Key financial performance of electricity only plant

It should be mentioned here that a pure electricity only plant should have a slightly more efficient power block with respect to the considered CSP-DSW power block. The Power only plant is more financially attractive from a financial point of view from a dual purpose plant, as is pointed out in the analysis in Chapter 8.

12.4.5. Levelized cost of production in the co-generation plant

While the net cash flow and financial performance of the entire co-generation plant are relatively simple to estimate, determining the cost of electricity and water in a dual purpose plant is very complex process. Although there are several methods which have been proposed in the literature, there exists no commonly agreed method for such determination. Research papers by El-Nashar A.M. [1], Saeed M.N.[2], and Hamed O.A. et al [3] show that cost allocation between power and water for a co-generation plant is a non-settled issue. From the number of methods that have been recommended for cost analysis, some are based on rigorous accounting procedures in which the cost is determined via the energy-exergy streams, while others are based on direct cost accounting, which allocates all cost components between water and electricity according to certain rules such as exergy pro-rating, power loss due to extraction of steam to the desalination unit or cost allocation based on functional considerations.

We opted for a method in which the cost of water and electricity is calculated by the escaped revenue method. In this approach, the difference of possible revenue streams between an electricity only plant and the cogeneration plant was thought to have occurred because of introducing the desalination facility into the electricity only system. Therefore the cost of water is linked to the difference of revenue from the electricity production of the:

$$LCOW = \frac{Revenue_e - Revenue_{cg}}{Production_W}$$

where $Revenue_e$ is the revenue from electricity of the single purpose plant, $Revenue_{cg}$ is the revenue from electricity of the dual purpose plant, and $Production_W$ is the water production during the plants whole lifetime. The Levelized Cost of Electricity (LCOE) for the dual purpose plant, is calculated after the LCOW is subtracted from the total levelized costs of the plant. The calculated levelized costs of Water and Electricity are given in Table 12-7.

	Case (A)	*Case (B)*	*Case (C)*	*Case (D)*
LCOE (Cent/kWh)	*17.85*	*18.14*	*18.82*	*18.31*
LCOW (Cent/m3)	*193*	*127*	*104*	*107*

Table 12-7: Levelized Cost of Electricity and Water

12.5. Sensitivity analysis

Although most assumptions used in the DCF analysis have been made with a moderate approach the analysis contains factors which are difficult to predict and estimate. A sensitivity analysis is conducted to identify key variables and assess risks in various scenarios. Through this exercise a reasonable assessment of the technology and the uncertainties about the financial assumptions can be made.

In all of the following cases (unless otherwise specified) the interest rate considered is 6%, the investment was based on 100% equity and any benefits from CDM is excluded. In all cases the current FIT system applicable in Cyprus is considered.

12.5.1. Capital Cost sensitivity

The plant's financial performance decreases when the capital cost rises as expected. In Figure 12-8 the percentage variation of the NPV of net cash flow is shown against the change in capital cost. It is evident from Figure 12-8 that all the cases exhibit approximately the same sensitivity which is substantial. Similarly, the effect of deviations in the capital cost on IRR is shown in Figure 12-9.

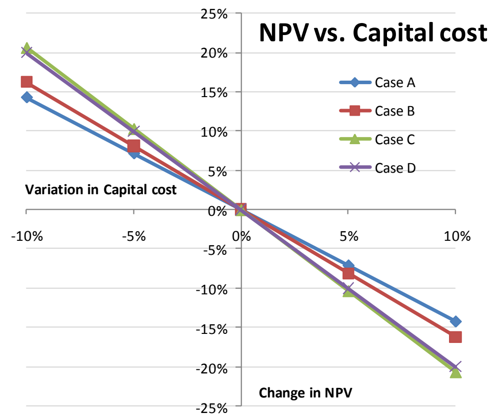


Figure 12-8: Sensitivity of NPV on Capital cost

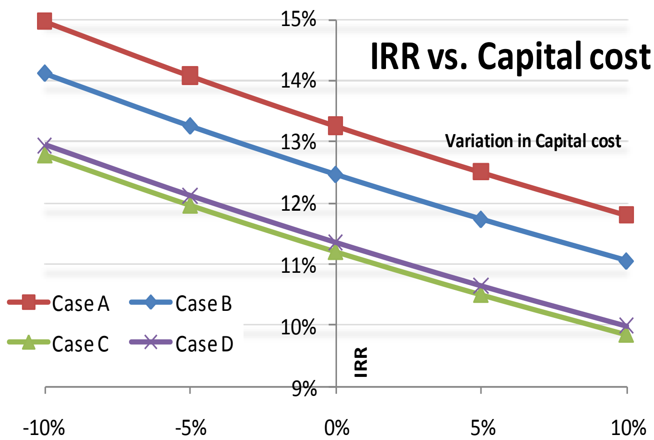


Figure 12-9: Sensitivity of IRR on Capital cost

12.5.2. Operation and Maintenance Cost sensitivity

O&M costs present a significant variable of the financial performance of the considered CSP-DSW pilot plant. The sensitivity of the project on the O&M cost was calculated and the results are presented in the following figures. As can be seen in the Figure 12-10 the NPV of Case (A) is the least sensitive on the O&M cost variation, whereas Case (C) is the most sensitive one.

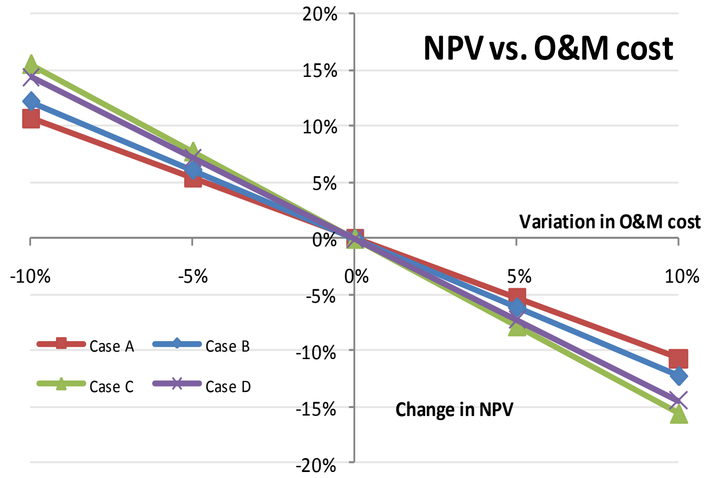


Figure 12-10: Sensitivity of NPV on O&M cost

This is to be expected. O&M costs are common for most cases apart from the desalination modality. Case (C) includes an RO system which requires both constant maintenance and replacement of the membranes. The small MED unit of Case (A) is the least demanding, therefore is the least sensitive.

In Figure 12-11 shows the effect of O&M variation on the projects IRR.

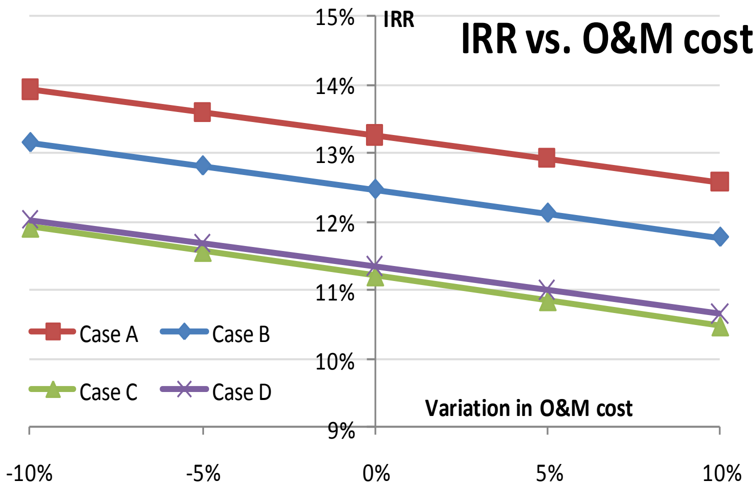


Figure 12-11: Sensitivity of IRR on O&M cost

12.5.3. Loan interest rate sensitivity

Instead of the fixed 6% rate of interest which was assumed so far, in this section the effect of the interest rate's variation on the project performance was estimated. In order for this sensitivity analysis to be meaningful the assumption of 100% equity is also abandoned for an 80%-20% debt-equity ratio. It The loan repayment duration is taken to be 20 years, the same as the project's lifetime. During the construction period of two years, the rate of interest is assumed to be the same. Figure 12-12 and Figure 12-13 show the effect of the interest rate's variation on NPV and IRR.

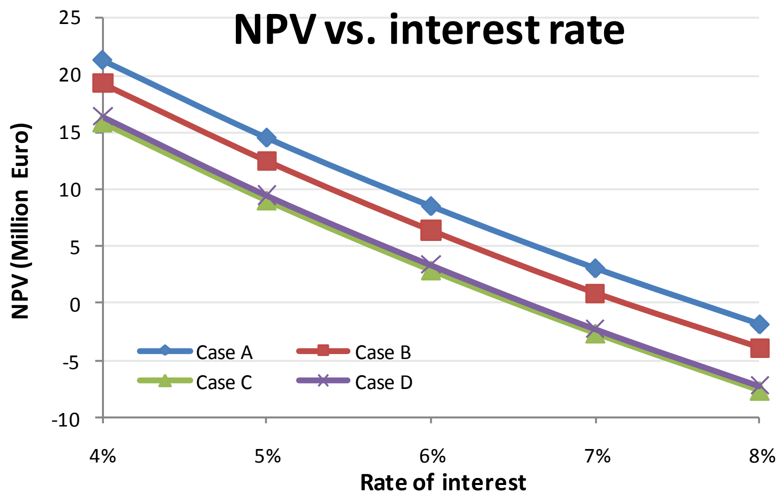


Figure 12-12: Sensitivity of NPV on Rate of Interest

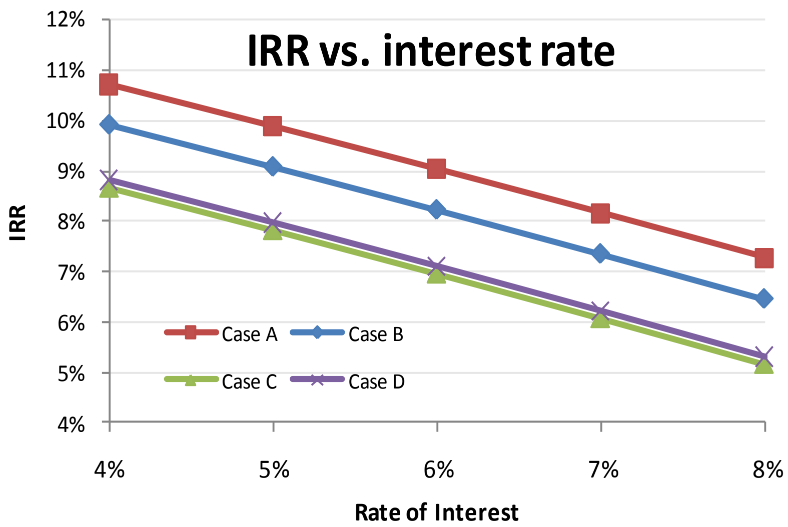


Figure 12-13: Sensitivity of IRR on Rate of Interest

The CSP-DSW plant in quite sensitive to the interest rate. An increase to a rate of 8% leads to a negative NPV for all four cases. Of course this is an extremity. Even the assumed rate of 6%, although a common practice for business financing in Cyprus, can be considered very conservative. Recent funding schemes by entities such as the European Investment Bank have introduced special interest rates for projects based on RES, making such investments much more attractive.

It is observed that a very strong dependence on the profitability/viability of the project is observed which highlights the possible significance of a policy of guaranteed low-interest loans for the encouragement of CSP and CSP-DSW plants.

12.5.4. Effect of the change in Debt-Equity ratio

In this sensitivity analysis four debt-equity ratios are considered. The case of 0 ratio corresponds to 100% equity; 0.5 corresponds to 50% of the initial capital investment derived from debt; 0.8 corresponds to 80% debt; and 1 corresponds to a full capital investment from debt. The rate of interest is fixed at 6%.

It is obvious from the figures that with respect to the total investment point of view, the project becomes more financially attractive if the debt portion remains small. Case (A) is financially viable even with a full capital investment from debt, although barely profitable. The introduction of special interest rates for such projects can provide a significant motive for the installation of single and dual purpose plants from RES.

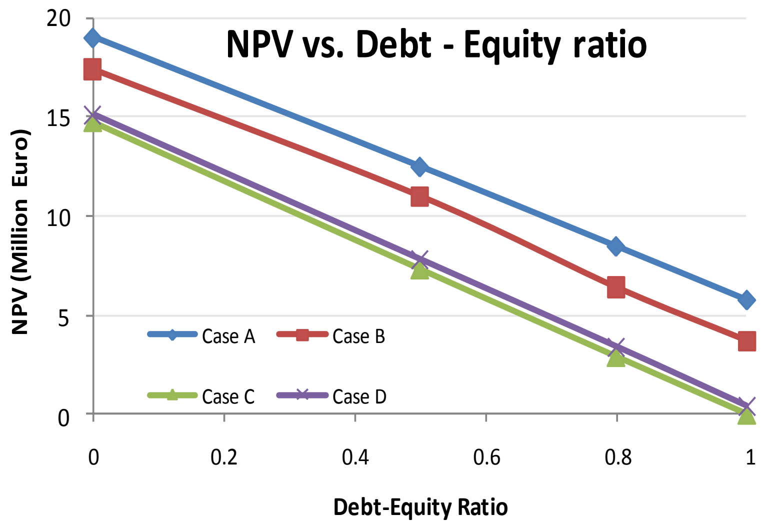


Figure 12-14: Sensitivity of NPV on Debt-Equity Ratio

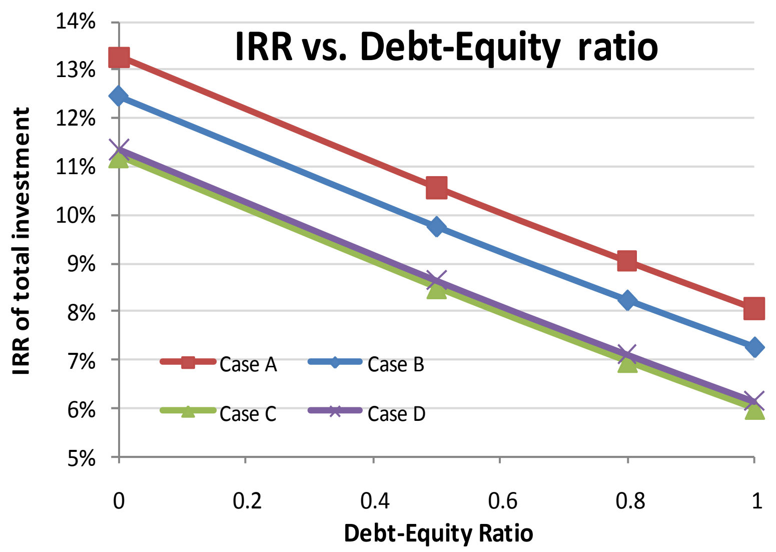


Figure 12-15: Sensitivity of IRR on Debt-Equity Ratio

12.6. Conclusions

The CSP-DSW co-generation technology in all four cases examined is a profitable endeavour with the current feed-in tariff for electricity which stands right now at 0.26 €/kWh. All cases produce a positive NPV on after tax net cash flow in the normal boundary conditions set in the beginning. Therefore, from a commercial point of view CSP-DSW project is certainly worthwhile to pursue. The most profitable scheme is ***Case (A)***, with the lowest production of water and the highest amount of electricity sold to the grid. This is because as mentioned earlier water production induces a heavy penalty by reducing electricity production which is in turn sold at a very attractive tariff.

Without a feed-in tariff all cases produce a loss; they are not financially viable a conclusion which comes as no surprise. This is expected as CSP technologies, especially at such small scale, are not yet competitive with conventional power production methods.

In the absence of a feed-in tariff for electricity, the best option (even though all are non-profitable) is ***Case (D)***, the large capacity MED system. This shows that for the CSP-DSW design, MED is financially the preferred choice over RO, while on an equal production footing. The absence of a feed-in tariff removes the imbalance between water and electricity production from renewables. It therefore shows that for co-generation schemes to work, it is imperative that water production from RES must also be subsidised.

In the current FIT system in Cyprus, electricity purchase rate is fixed over the project's life while O&M costs and salary are both subject to regular increases. This makes the net positive cash flow gradually decreasing. A solution to reduce this effect which as a deterrent in such investments, is the linkage of the FIT system with the inflation rate. This has been one of the reasons that companies are hesitant to invest in fixed FIT environments. An even more rational system would see that a time-variable FIT for renewables is adopted to regulate the production from renewables during the day [9].

The net cash flow and other financial indicators provide a realistic assessment of the CSP-DSW technology. However the comparison of the CSP-DSW solution with single purpose plants using the levelized costs of electricity and water is not simple. The determination of electricity and water cost in dual purpose plants is not a straightforward exercise and there exists no universally agreed method for such costing although a number of methods have been proposed in the literature.

The levelized cost of electricity in an electricity only CSP plant (such as that considered in Section 12.4.4.) was estimated to be 18.12 cent Euro/kWh whereas the commercial retail price survey result for April, 2010 in Europe for solar PV is calculated to be 19.33 cent Euro/kWh for a grid connected plant which does not have energy storage capacity [4]. The cost of 18.12 cent Euro/kWh was calculated for a 4MWe plant which is not optimal for such purposes. A rough estimate of an optimized 50 MWe plant, indicates that the cost will be reduced to below 13 cent Euro/kWh. The CSP-DSW technology shows great potential to get even lower electricity generation, but also desalination costs in the future as the technology further develops and reached maturity.

However, the technology is still in the development phase and as such the associated technology financial risks are significant. A dedicated risk analysis is needed in the near future. The Cyprus Institute will further explore the current dataset produced through this financial model and pursue further analysis of the performance of the CSP co-generation scheme in research, which goes beyond the scope of this study.

12.7. Chapter References

[1] Cyprus Inland Revenue Department, Ministry of Finance, www.mof.gov.cy

[2] Poullikkas, A. Economic analysis of power generation from parabolic trough solar thermal plants for the Mediterranean region-A case study for the island of Cyprus. *Renewable and Sustainable Energy Reviews*, 13(9):2474 - 2484, 2009.

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[7] Hamed O.A., Al-Washmi H. A., Al-Otaibi H.A., 2006. Thermoeconomic analysis of a power/water cogeneration plant. Energy. 31 (2006) 2699-2709

[8] www.solarbuzz.com

[9] Ghobeity,A and Mitsos, A. Optimal use of solar thermal energy for combined power generation and water desalination. *Proceedings of the Distributed Renewable*

Energy Sources in the Mediterranean region (DISTRES) Conference, December 11-12, 2009, Nicosia, Cyprus.

Chapter 13. Site Considerations

13.1. Site Selection Characteristics

The site selection characteristics for a CSP-DSW plant must ensure the optimal and cost effective operations of all of the components of the plant: the solar field (including collection and storage), the power production block and the desalination block. When assessing a potential site, the following factors must be taken into consideration:

- Annual mean direct beam solar radiation must be maximised – since direct solar radiation is the "fuel" of the CSP-DSW plant it must be ensured that it is maximised. Due to the size of Cyprus the direct solar radiation across the island is approximately the same, however, when maximising the direct solar radiation factors like shading due to land morphology and direction (e.g. facing north, or east, etc.) which a site is facing are of paramount importance. Collected solar radiation is maximized in cases with flat land due to lower cosine losses and serviceability of the heliostat field is most easily facilitated, however, the reality is that such locations are not very common in Cyprus and the civil costs associated with flattening out a plot are extremely high. Maximising direct solar radiation therefore becomes an exercise of setting up a site (i.e. structuring the solar field) or choosing a site in such a way so that the maximum amount of solar radiation can be collected. However detailed examination of south-facing sloping (hilly) terrain such as that found in Larnaca, Limassol and Paphos districts offer attractive alternatives to flat terrain: comparable radiation, less shading but increased serviceability costs.
- Proximity to water and more specifically proximity to the sea as sea water will be used both for desalination and cooling of the power block. Transportation of water to and away from the plant is an extremely costly process (the capital costs

associated with transporting water can exceed €20/m^3/km) which can significantly add to the capital, maintenance and operational costs of the plant – the costs for transporting water depend on land morphology, distance and horizontal elevation; the latter can prove to be an extremely costly process due the cost of pumping to elevate water. It is therefore of paramount importance that locations as close to the sea as possible are selected.

- Site altitude and weather conditions both macro- and micro-level should not have high incidences of atmospheric water, smoke, fogs, haze, and airborne particulates (dust, tilled farm land, evaporation pond residues, etc.). Periodic rain can assist in keeping the heliostats clean. Particulates that stick to the mirrors will greatly reduce the reflectivity of the mirrors and as a result will diminish the amount of solar radiation that can be collected.
- The site must not be prone to high winds or wind amplification due to terrain features – high winds do not only carry particulates which can stick to the mirrors and reduce their reflectivity, but can also cause the breaking of mirrors on the heliostats.
- Land area should be sufficiently large to accommodate the heliostat field (and potential future expansions if possible), and provide a clear safety zone for heliostat and plant operations e.g., glint, cooling tower fog.
- Close proximity to power grid and water network tie-in points with the latter being more important as the costs of water transport are much higher (see previous points) than the costs of electricity transport (approximately €20,000/km).
- Not in the vicinity of local airports, particularly airport low-altitude approach paths.
- Relatively low seismic risk.

The above considerations indicate that the site can have a major impact on the capital, maintenance and operational costs of the CSP-DSW plant. When assessing potential sites it is important that each of the above factors are taken into consideration in order to ensure that electricity and water are produced for the CSP-DSW plant at an optimal cost.

13.2. Potential Sites

Throughout the duration of the project, several locations were reviewed in order to assess their potential as sites where a CSP-DSW plant could be built. All locations were assessed according to the criteria set in the previous section, always taking into consideration any potential environmental and social impact that such a plant can have in the area. Out of all the locations reviewed, the following were shortlisted:

(a) The area south of the Technological Park at Pentakomo (Figure 13-1 and Appendix D.1)

(b) The area surrounding Vassilicos Power Plant (Figure 13-2 and Appendix D.2)

(c) The area surrounding Moni Power Plant (Figure 13-3 and Appendix D.3)

(d) The area surrounding Dhekelia Power Plant (Figure 13-4 and Appendix D.4)

Figure 13-1: Areal view of Pentakomo site

Figure 13-2: Areal view of Vassiliko site

Figure 13-3: Areal view of Moni site

Figure 13-4: Areal view of Dhekelia site

All of the above locations are in close proximity both to the sea and to the power grid and water network, all of which are factors that minimise site set up costs as water and electricity can be cost effectively transferred to and from the site. In terms of land morphology, the locations are not optimal –never is in general in a coastal island environment and in particular that of the Cyprus Republic, however, optimal use of the land can be achieved by carefully selecting the location of the heliostats and the setup of the solar field. In addition, since all of the locations are either close to or next to existing industrial infrastructure and in specific power stations (even Pentakomo is approx. 3km from Vassilikos Power plant), this will minimise any environmental or social impact that the construction of a CSP-DSW plant can have to in the area; furthermore, it will make it easier to obtain the necessary permits in order to construct and operate such a plant (see next section).

Although no specific land has yet to be allocated by the relevant authorities for the construction of a CSP-DSW plant in the areas close to the power stations, the Planning Bureau and the Ministry of the Interior have already provisionally and conditionally allocated an area of 6 hectares in Pentakomo as a potential site (see map in Figure 13-5) for the construction of such a plant. The area belongs mostly to the Government – it is therefore easier to obtain it than other. On the other extreme, the land in Dhekelia is within the British Sovereign Bases area and it may present complicated political problems in order to secure the land.

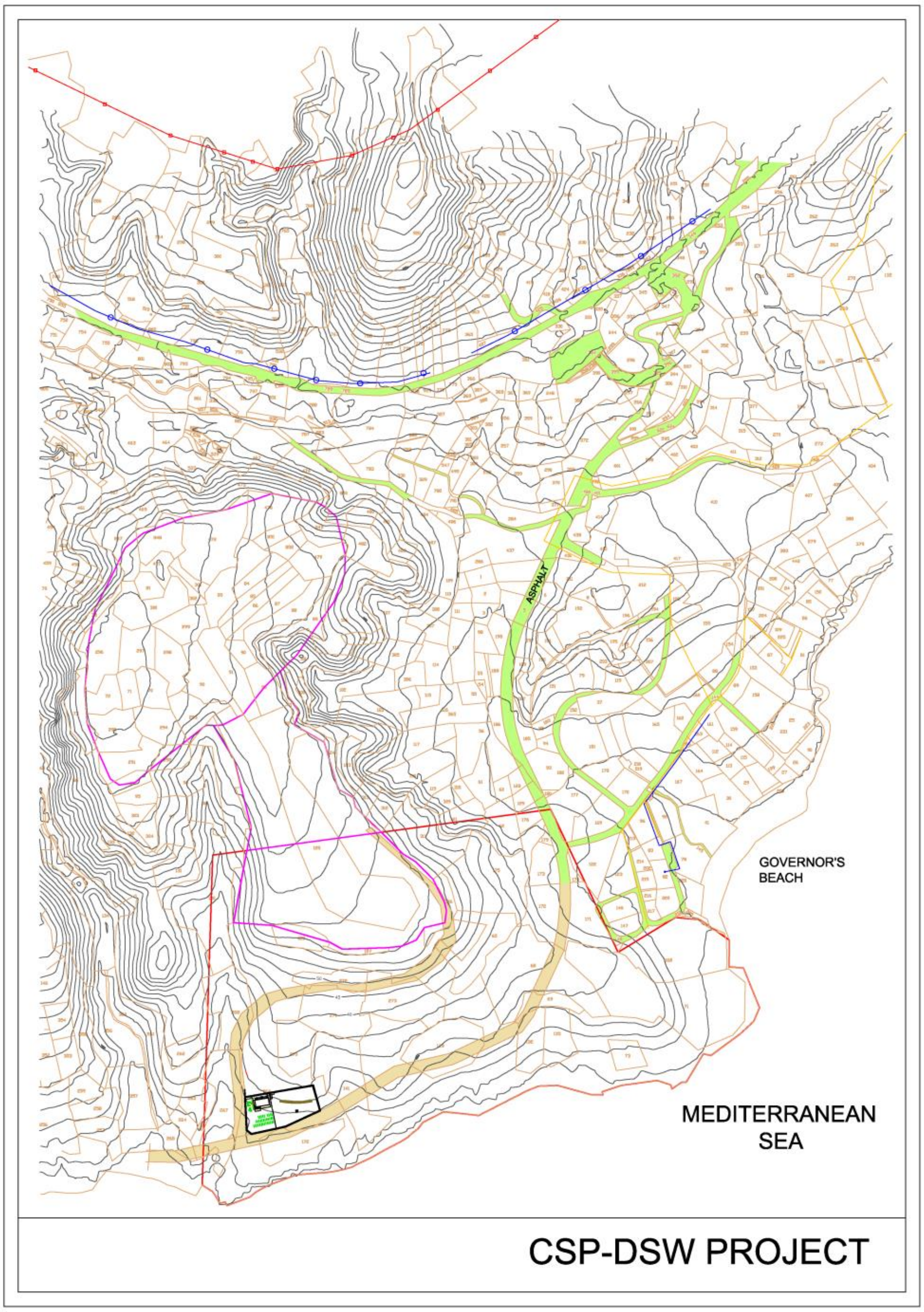


Figure 13-5: Map of the Pentakomo area. The Red line indicates an area which was identified as suitable of hosting a facility (up to 5 MW).

It is south-facing and hilly therefore elaborate surveying is needed to identify the size of the facility it can support. From the information we have, it appears it can support a facility up to 4 MW, the design objective of the proposed conceptual design.

13.3. Licences/Permits Required to Construct and Operate a CSP-DSW Plant

In order to be able to construct and operate a CSP-DSW plant, the relevant permits must be obtained by the responsible government authorities. Permits must be obtained from

- The Department of Housing and planning (DHP) – This department is responsible for granting the relevant permits for the construction of any buildings
- The Cyprus Energy Regulatory Authority (CERA) – This authority is responsible for regulating Cyprus's energy market. Anyone wishing to construct an energy producing plant must first obtain the relevant licence from CERA
- The Department of Land and Surveys (DLS) – This department is responsible for obtaining all relevant permissions and allocating any government owned land for the construction of a CSP-DSW plant.
- The Water Development Department (WDD) – This department is responsible for regulating and monitoring Cyprus's water resources. If any desalinated water produced by the CSP-DSW plant will be distributed to the water network then the relevant permission by the WDD must be obtained.

The steps to obtain all relevant permits/licences/permissions for the construction and operation of a CSP-DSW plant can be summarized as follows:

1. The DLS must first officially allocate a proposed plot for the construction of a CSP-DSW plant. In order to achieve this, an official letter accompanied by plot plans and numbers of the proposed plot must be sent to DLS outlining the use of the plot and the operation of the CSP-DSW unit.

2. A preliminary review must be conducted by the DHP in order to confirm that the allocated plot is in a zone where the construction of a CSP-DSW plant is permitted. The DLS might, even in this preliminary stage, ask for
    a. An environmental study to be reviewed by the Environment Service
    b. Permissions from the Civil or Military Aviation.
3. An application must be submitted to CERA for "Exemption from Licence for Units producing less than 5MW from Renewable Energy Sources" [1]. This exemption is required in order to be able to operate a <5MW plant and distribute the power produced to the electricity network [2]. As part of this application the following will be required:
    a. Business Plan
    b. Operation Plan including names of responsible people with relevant qualifications
    c. Development Plan
    d. Technical description of unit
    e. Techno-economic Feasibility study
4. An application must be submitted to WDD for distribution of the desalinated water produced from the CSP-DSW plant to the water network. There is no standardised application procedure for this, so the application must be submitted in the form of an official letter to the WDD, who will in turn request any further relevant information, e.g. quantity, proposed tariff, etc. The WDD will in turn decide if it wishes to purchase the water produced, at what tariff it wishes to do so and where the tie CSP-DSW unit can tie in to the water network [3].
5. Following acquisition of the licences/permits from CERA and WDD an official application must be submitted to the DHP for the acquisition of the appropriate building permit.

The steps outlined above are by no means exhaustive; they do however provide the general guidelines on how the relevant permits for the construction of a CSP-DSW plant. Due to the complexity of the unit and the fact that there are no precedents for such specific units, any body/authority applying for such permit might be requested to provide information or follow additional procedures that are not outlined above.

13.4. Recommendation

Based on the overall design study a number of important parameters have been specified which could further guide the identification of potential sites for the construction of a pilot CSP-DSW plant. Four specific sites have been identified as satisfying the above mentioned considerations. It is recommended that the potential problems that may arise in obtaining title and beneficial occupancy be explored by the competent authority of the Republic before a detailed and costly investigation is pursued. Following that a more detailed technical investigation and optimization study be conducted using the detailed software tool developed at MIT (by Prof. Mitsos team) to finalize the choice. At the present stage, we judge the Pentakomo site as the most promising choice, one that needs to be explored further. It must be pointed out that for the actual placement of Heliostats on the selected field, finer topographical data will be needed.

13.5. Chapter References

[1] Appendix D.5. Application for Exemption from Licence for Units producing less than 5MW from Renewable Energy Sources www.cera.org.cy

[2] Appendix D.6. Electricity Transmission Network www.tso.org.cy

[3] Appendix D.7. Major Water Works www.moa.gov.cy/wdd

Chapter 14. Conclusions and Recommendations

This Report presents the findings of the Research and Development Study for the Concentrated Solar Power- Desalinization of Sea Water (CSP-DSW) pursued by the Cyprus Institute for the benefit of the Cyprus Government. The study has been led by the Cyprus Institute. Principally collaborating institutes and organisations include the Massachusetts Institute of Technology (MIT), the University of Illinois at Urbana Champaign (UIUC) and the Electricity Authority of Cyprus (EAC). In addition various relevant Cypriot authorities have contributed to the research part of the project: the Water Development Depart (WDD), the Cyprus Energy Regulatory Authority (CERA) and the Cyprus Meteorological Service (CMS). Special acknowledgments are also due to the Department of Control, the Cyprus Land Survey, the Ministry of Commerce, Industry and Tourism, the Ministry of Communication and Works, the Ministry of Interior, the Ministry of Education, and the Cyprus Planning Bureau. The project was co-funded by the EU Cohesion Fund.

The study was conducted between January 2009 and May 2010, while preparatory work begun in September 2009. A large part of the study included research in a number of different fields, which helped illuminate a number of technical issues.

In the preceding Chapters the following have been presented:

1. The current state of technological developments concerning the production of electricity using CSP, and the available desalination technologies. Detailed cataloguing of alternative technologies and an assessment of their maturity level and advantages and disadvantages vis-à-vis their employment for a CSP-DSW commercial (industrial) plant.

2. Characteristics of suitable locations and land requirements for the construction of a pilot plant in Cyprus.
3. An innovative design for a Pilot plant, that is suited to the needs and conditions of Cyprus, with proposals for its various subsystems: Solar harvesting, Energy Storage, and Power and Water production units, the main operational parameters, capacity of electricity and water production, and an operational plan of the proposed pilot plant.
4. An Economic Assessment of the proposed technology through a Discounted Cash Flow (DCF) business model.

In this final Chapter of this Report the final conclusions of the Study are presented. In addition the final recommendation of the CSP-DSW Study's Principal Investigator, Prof. C. N. Papanicolas are recorded concerning the construction of CSP-DSW demonstration unit in Cyprus, as per the intention of the Cypriot Government.

14.1. Conclusions

A thorough review of the commercially available Concentrated Solar Power (CSP) technologies was conducted. The four primary types of CSP technology, Parabolic Troughs, Fresnel Systems, Central Receivers (Heliostat arrays) and Parabolic Dishes were considered. It is concluded that Fresnel Systems and Parabolic Dishes (especially when coupled to Stirling Engines) hold promise for the future but at the moment have not reached a stage of maturity for implementation. Concentrating Systems employing a Stirling Engine on a fixed location (and not coupled to the Dish) would be especially efficient for co-generation schemes with the engine directly coupled to a desalination system.

In contrast, Parabolic Troughs and to a lesser degree Heliostat-Central Receiver systems comprise relatively safe technological solutions, which are ready for pilot plant implementation. It is also concluded that the Heliostat-Central Receiver configuration offers the greatest potential in terms of power cycle efficiency in conjunction with thermal storage at high temperatures (which is essential for 24 hour operation, a principal technological goal of our design objectives). This configuration is receiving increasing research attention in both Europe and the USA through the various announced research funding initiatives.

Cyprus is isolated from any continental power grid from which to draw power when intermittent renewable sources (e.g. wind or photovoltaic) cannot produce power (due to lack of wind, or during evening hours and cloudy weather), which necessitates the employment of renewable sources that allow for energy storage. The island is also small in size so intermittency and fluctuations present themselves acutely, without the benefit of geographical averaging. Unfortunately, a number of renewable sources of energy that have this desired characteristic (e.g. hydro, geothermal, biomass) are not available in any sufficient quantity in Cyprus. Concentrated Solar Power (CSP) is the only technology available to Cyprus that meets this requirement. Given that solar power is the most abundantly available renewable source in Cyprus and that it can be concentrated to produce high-quality heat for CSP, it is imperative that any plan for a Pilot Plant incorporates energy (thermal) storage so that the Plant can operate on a 24-hour basis. ***We conclude that among the technologically proven options for CSP, the Heliostat – Central Receiver offers the most promising solution both for Electricity production but especially so for co-generation of Electricity and Desalinated water.***

The two principal and proven methods for desalination using renewable resources were considered: membrane-based methods, principally Reverse Osmosis (RO), and thermal desalination methods, principally Multiple Effect Distillation (MED). The technological constraints that determine the energetic requirements of each class separately were examined, with the aim of determining the most energetically favourable option for the development of the co-generation plant on the island. MED and RO, as reported in a number of studies and research manuscripts, are very close in competition, both on energetic and economic basis and therefore both present a credible solution for isolated desalination. One needs to perform a rigorous analysis based on economics for selecting the most efficient and financially sound solution for each case. ***MED however for co-generation has the advantage that it allows for tighter integration and use of low-temperature heat from the power production and the Solar Collection and Storage systems***. It is to be noted that while MED is currently identified as the leading choice, a hybrid solution employing both MED and RO technologies should also be considered to allow operational flexibility.

The hybrid solution however requires also a long-term analysis to examine its economic and operational viability.

A comprehensive review of the available power generation technologies was conducted in the preceding months and an evaluation of the emerging trends has been performed. It is concluded that at the current stage of development, only Rankine Cycle (steam turbine) engines should be considered for a pilot plant. However, these engines are highly efficient and very reliable for high power ratings (in excesses of 30 MW), while renewable sources such as CSP in island environments are in need of smaller more efficient engines in the 1 to 10 MW range. Promising new technologies, that are better adapted to CSP, especially variants of the classical Stirling Engine, are actively being pursued by a number of private companies and institutions. ***It is our judgement that at the moment, apart from Rankine Steam Turbines, all other power generation concepts are not mature for implementation even for the cases of pilot plants and it is inconceivable to consider them for industrial application; Steam turbines should be the technology of choice for the Pilot plant.***

As we have amply documented in the body of this report, CSP is a technology that is on the verge of becoming mature for industrial employment. However, local geographical conditions are important and do play an important role in our considerations. CSP plants require substantial amounts of water to operate (primarily for cooling). The CSP-DSW concept incorporating thermal desalination (MED) overcomes this drawback by turning this into an advantage (by incorporating desalination). Nevertheless, like all solar technologies CSP requires substantial amounts of land, which is expensive in island and coastal regions, especially given the desired near-sea proximity.

14.2. Technological Choices for a pilot CSP-DSW Co-generation Plant

Taking into consideration the general CSP-DSW concept and operating parameters and based on the research activities throughout the duration of this project, a proposal for the requirements of a suitable Pilot Plant for Cyprus has been presented in Chapters 8 through 13. The conceptual design of the co-generation Plant has received considerable attention by our research team and a preliminary optimization step for certain fixed plant configurations corresponding to available technologies has been completed. The particular technologies for the main components of the CSP-DSW are also presented. The technological choices made are such as to present a design optimised for an island environment and in particular Cyprus. As such, it should be viewed as an optimal design for the intermediate and long term.

14.2.1. Solar Harvesting and Storage

A Heliostat - Central Receiver technology for the Concentrated Solar Power modality is proposed. It should also incorporate thermal storage at high temperatures for 24-hour operation.

Although the Central Receiver system has been demonstrated in various cases, it has not been proven reliable in base-load operation yet without power generation assisted by fossil fuel (typically natural gas). A research challenge is identified in the energy storage system, which constitutes a critical part of our design goal. The molten-salt storage concept is currently the most successful large-scale solution, however it suffers from technical problems and high capital and O&M costs. In addition, the technical complexity of a Power Tower, and specifically its Receiver module and salt pumping system for capturing and exchanging heat, add costs and technical complexity to a design which has not proven to be economically viable yet, in particular at small scales such as the CSP-DSW pilot plant envisioned.

In this framework it was decided to explore an innovative variation of the conventional Central Receiver System, based on the concept of Concentrated Solar Power on Demand (CSPonD) developed by Prof. Slocum and his colleagues at MIT. In the proposed design, the Receiver and the Storage unit are integrated into one entity which is located on the bottom of a hillside, while the heliostats are placed on the hillside thus eliminating the need for flat land or the construction of a Tower. The optical losses associated with the "cosine effect" due to the concentrating point lying on ground level, are weighted against the economic and technical simplicity of the concept, and by the smaller seasonal variation in the received radiation. The latter constitutes a benefit of the specific design as the heliostat field is utilised better during the summer months. For the CSP-DSW application investigated, this design is technically simpler and economically more attractive, whilst using in principle the same heat extraction method currently employed by CSP with storage plants. With small changes to its design and storage medium (from nitrate to chloride salts), it has the potential to increase its working temperature up to 1000^o C and therefore to be coupled to the more efficient Brayton cycle gas turbines (e.g. supercritical CO_2 power cycle) which are viewed as one of the most promising emerging technologies. However, the CSPonD concept has only been demonstrated in laboratory-scale experiments. The results are promising, but real-scale testing is required. The Cyprus Institute in collaboration with MIT plans to test and experiment on the viability of this method on a real-scale experiment in its facilities to analyse and prove the validity of the concept at real operating conditions.

Commercially available Heliostats have not been operated or designed for operation in coastal environments. Special considerations are needed for the deployment of the high-wind and corrosive conditions by the sea. In addition special consideration is needed for their deployment at hillsides. The Engineering and Planning should insist on components suitable to weather and environmental conditions of coastal environments. The currently available designs and commercially available options, limited as they are, can provide the required harvesting light but it is unlikely they will be durable for the given environment. The same observation holds for parabolic troughs.

14.2.2. Power Generation

As a primary option for power generation the commercially available Rankine (steam turbine) engines, which are proven and widely used in steam generating plants, are recommended.

The power generation scheme to be employed is a standard Rankine Cycle steam turbine with a nominal capacity of 4 MWe. The turbine will be an extraction turbine, which is compatible with the co-generation scheme as it allows steam extraction for desalination at various pressure-temperature conditions. Steam Extraction however bares a very hefty penalty: it redirects high quality steam to desalination, thus hampering the electricity production, which in the case of Cyprus is heavily penalised due to the skewed tariff system for water and electricity (see below). This is a crucial discovery of the present study: Steam turbines have for the past decades been developed to be most efficient for large scale production, therefore they underperform at the lower limit which stands at 4 MWe. In contrast exploitation of renewable energy demands smaller than larger scales with wider geographical distribution. There is therefore a significant gap in efficient power production methods designed for renewables, something which is widely acknowledged and is the driving force in the development of Stirling engines. This consideration applies *a fortiori* for CSP-DSW co-generation as further geographical constraints come into play. However the renewed interest in RES has induced a vigorous activity in the development of more efficient and smaller engines for electricity production which are expected to reach maturity in the next five years.

14.2.3. Desalination

Multiple Effect Distillation (MED) is the proposed technology for desalination provided an MED system at this scale can be designed with high GOR and low electricity requirement. Given the choice of the thermal energy source (CSP) and a Rankine-cycle power plant, performing seawater desalination via MED is a better option than Reverse Osmosis (RO) within the CSP-DSW scheme. A hybrid solution where both technologies are employed should be further examined.

For the desalination system, it became apparent that the choice between MED and RO simply added in tandem to the power production cycle was not as straightforward, as they both offer comparable performance. In the comprehensive review AQUA-CSP by the German Aerospace Agency (DLR), this fact is acknowledged and highlighted with the note that without a specific design and conditions, it is impossible to select either method as more appropriate for the CSP co-generation scheme. Within the CSP-DSW study, a detailed analysis as to the preferred desalination method (RO vs. MED) has been made.

Following the analysis by Prof. Mitsos and his colleagues at MIT who optimized for a weighted function of electricity and water production, with no constraint considered for minimum allowable water production, it is concluded that MED energy requirements are higher than typical RO energy requirements. These results are valid for the 4 MWe steam cycle used and considering a typical (conservative) from the literature MED unit with 8 effects and a low GOR. In a different study also included in this report, Prof. Georgiadis and his colleagues at the University of Illinois have also designed and analyzed an advanced MED system employing a Thermal Vapour Compressor, which harvests heat from the storage system to enhance the desalination process and which is shown to be competitive with RO on energetic basis and more favourable on economics basis within the CSP-DSW system. This MED system also incorporates the ability to by-pass the turbine or the MED system for added flexibility. The advanced MED design has not been incorporated into the integration and optimization calculations of Prof. Mitsos. This however remains a task for the relevant team as a research topic to be pursued. Based on the above studies and given that the harvesting of escaped thermal energy is expected to yield higher benefit from MED, we recommend that either an MED or a hybrid MED-RO configuration be pursued.

14.2.4. Financial Analysis

The financial analysis that has been conducted examined various scenarios based on different economic and engineering choices. From early on it was observed that the application of a feed-in tariff in Cyprus for electricity produced from renewables, introduces an imbalance for co-generation schemes. It was therefore decided to examine the CSP-DSW system with four different configurations of desalination systems under two different conditions, with and without a feed-in tariff for electricity. The four different options examined are represented in the following four cases:

Case (A): A small, 8 effect MED unit with a daily capacity of 1002 m^3 of water as presented in Chapter 8.

Case (B): A hybrid solution employing a small 8 effect MED unit with a daily water production capacity of 1002 m^3 and a small RO unit with a daily capacity of 1500 m^3 as presented in Chapter 8)

Case (C): An RO system with advanced water production capacity of 5035 m^3 per day as presented in Chapter 4 (case 1)

Case (D): An advanced MED unit (GOR =16.65) with 20 effects able to produce also 5035 m^3 per day as presented in Chapter 4 (case 2).

The main conclusions of the financial analysis are the following:

- The CSP-DSW co-generation technology in all four cases is a profitable endeavour with the current feed-in tariff for electricity which stands right now at 0.26 €/kWh. The most profitable scheme is ***Case (A)***, with the lowest production of water and the highest amount of electricity sold to the grid. This is because producing water induces a heavy financial penalty by reducing electricity production, which is in turn sold at a premium tariff.
- Without a feed-in tariff all cases produce a loss, i.e., they are not financially viable or competitive. This is expected as CSP technologies, especially at such small scale, are not yet competitive with conventional power production methods, a fact well-documented and universally accepted.
- In the absence of a feed-in tariff for electricity, the best option (even though all are non-profitable) is ***Case (D)***, the large capacity MED system. The implication for the CSP-DSW design, is that MED is financially a preferred choice than RO, while on an equal production footing, and if heat is harvested and used for thermal desalination. The absence of a feed-in tariff removes the imbalance between water and electricity production from renewables. It therefore shows that for co-generation schemes to work, it is imperative that water production from renewable sources must also be subsidised. In Chapter 12, a relation between the tariffs and the economic viability of the CSP-DSW scheme is presented.

The Cyprus Institute is further exploring the current dataset and pursue further analysis of the performance of the CSP co-generation scheme in a research project that is independent to the present study.

14.2.5. Location

In terms of choice of location, a number of options have been explored. It was concluded that the requirement that not only contiguous flat land but also hilly south facing terrain could be gainfully utilized. This is a major finding of the study that has already changed the “conventional wisdom” of the field layout. Particular specific sites or areas that fit these criteria have been presented in Chapter 13 and include:

(a) The area south of the Technological Park at Pentakomo

(b) The area surrounding Vassilicos Power Plant

(c) The area surrounding Moni Power Plant

(d) The area surrounding Dhekelia Power Plant

These locations all have the desired characteristics for the placement of a CSP-DSW pilot plant as explained in the relevant chapter.

It is recommended that the potential problems that may arise in obtaining title and beneficial occupancy be explored by the competent authority of the Republic before a detailed and costly investigation is pursued. Following that a more detailed technical investigation and optimization study be conducted to finalize the choice using the detailed software tool developed at MIT (by Prof. Mitsos team) which can evaluate the solar potential of various sites and for various CSP configurations given elevation data of sufficient resolution. To the best of our knowledge no such data with the desired resolution exist at the moment for Cyprus for a detailed analysis including heliostat placement, but could be obtained by topographic surveys. The Cyprus Institute obtained such data through a private surveyor for the land that would host its Solar Laboratory facilities in Pentakomo. The area surveyed was much smaller but of sufficient resolution enough for such an analysis. At the present stage, we judge the Pentakomo site as the most promising choice, one that needs to be explored further.

14.3. Pilot Plant Capacity

A detailed investigation of the desired pilot plant capacity revealed a number of conflicting requirements and considerations. The following considerations need to and have been taken into account:

1. Morphology of terrain: Sloping southwards (hilly) near the sea. Hillsides are beneficial both as a more cost-effective solution due to the price of the land and as suitable for the CPSonD concept (which is simpler than the conventional tower).

2. Size of Solar field: 10 hectares of suitable land are required for 1.5 MWe capacity. Land requirements for the remaining installation is negligible.

3. Electricity production: given the current commercially available power generation turbines, steam turbines becomes highly inefficient below 4.0 MWe, therefore 4 MWe is the chosen nominal capacity. It is noted that at this limit the efficiency of power production is not the optimal.

4. Desalination Production: with current conditions (i.e. feed-in tariffs for electricity only at 0.26€/kWh), a small MED unit is proposed with a production capacity of 1000m^3 per day as the most profitable investment. However should a tariff for “green” water be introduced, an MED unit of at least 5000 m^3 per day production is recommended. The hybrid MED-RO configuration is favorable from an operations point of view due to the flexibility it introduces, however a long-term (seasonal) optimization and economic analysis is needed to examine its viability.

14.4. Recommendations

The thorough examination of all relevant parameters that pertain to the design of a CSP-DSW co-generation plant, as amply documented in the body of this report, leads to the following findings and recommendations concerning the desirability and feasibility of constructing a pilot CSP-DSW plant:

I. The concept of co-generation of electricity and Desalinated Sea Water using Concentrated Solar Power is sound both from an engineering point of view and from an economic and policy point of view. The advantages of CSP-DSW are realized when the power and desalination cycles are integrated thermally and optimized together.

II. Among the various options examined for the particular application in the physical, economic and technological constraints of the island, the Heliostat – Central Receiver technology is judged to be the most suitable. In Cyprus, it will be most beneficial if it is, and it should be, implemented in conjunction with a substantial storage capability so as to render the plant a “base load” facility operating on 24h/7d schedule. Variants of this technology such as a tower receiver or the MIT/CSPonD receiver both complemented with heat storage could provide the desired solution. Desalination employing Multi Effect Distillation possibly in hybrid mode with Reverse Osmosis for added flexibility is recommended.

III. Given the currently available turbine technology a minimum size of 4MWe is required. A capital investment approaching 25 Million Euros (excluding the cost of land) will be needed.

IV. We recommend the utilization of a south facing hilly terrain on the south coast of Cyprus as the preferred location to site such a plant. While the use of hilly terrain is a novelty, we recommend this option with confidence.

V. A detailed and sophisticated business model of the pilot plant whose conceptual design we have studied in detail reveals that such a plant, with the above mentioned parameters will be economically profitable.

VI. An investigation of the commercially available components reveals that key components (such as heliostats) are not optimized for the particular application and for deployment in Cyprus; components that are available have not been designed or tested for conditions of saline humid costal environment. We judge that this will introduce unnecessarily high risk of rapid aging and imparting unacceptable financial risk. Furthermore, not being able to predict their behaviour of these components prevents their integration into an optimized dual purpose plant. In situ testing of components should immediately begin to correct this technological risk.

VII. A number of “custom” solutions that need to be engineered for the particular application, such as the receiver and storage units, which are currently at the conceptual/experimental stage need to be further tested, preferably in the Cyprus coastal environment, to a sufficient degree to achieve a well-integrated CSP-DSW design and to present acceptable risk for an investment to a pilot plant.

The choices recommended and the detailed information provided in the main body of the report provide a sound basis for the commencement of research and engineering studies for a 4 MWe CSP-DSW demonstration plant, a size we propose as appropriate. As implied in points VI and VII above, we judge that a decision to proceed with the construction of such plant with components not tested and adapted to the Cyprus (or in general island environments) introduces high risk. The technological and financial risk will be substantially reduced if the pilot project is launched with a first phase (approx. three year duration) in which components will be tested, adopted and optimized before they are employed in large numbers in the pilot plant. It is of course a policy decision what constitutes an acceptable risk in a strategic developmental path and whether a speedy development offers opportunities that ameliorate the higher risk – this needs to be ascertained and decided by the policy makers of the Republic.

The viability of projects in Renewable Energy Sources is strongly related to economic incentives, an argument which is well understood and to which the Government of Cyprus subscribes, as it is manifested by its generous Feed-in Tariff policy for electricity production from Renewable Energy Sources. Based on our economic analysis, it is recommended that a Feed-in Tariff be introduced for water production from renewable energy sources so that the current market distortion is corrected, and more “green desalination” is encouraged. It is also recommended that Feed-in tariffs be annually adjusted according to inflation.

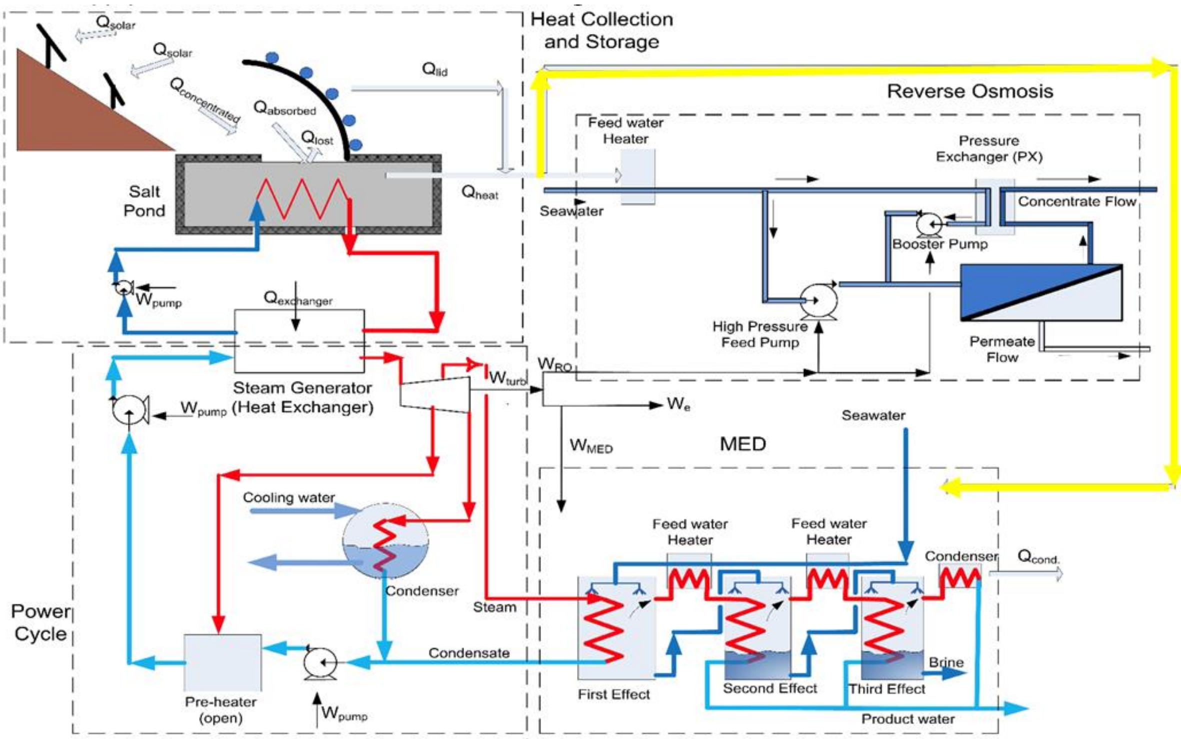
We conclude by re-stating the principal conclusion of the study:

> ***Concentrated Solar Power – Desalinated Sea Water (CSP-DSW) co-generation plants are technologically viable and economically sustainable in the Cyprus business climate and Renewable Energy Sources policy context. We recommend that the CSP-DSW demonstration pilot plan considered by the Cyprus Government be launched, along the lines of the conceptual design presented in the main body of the report. We strongly recommend the pursuit of testing and demonstration of critical subsystems at an experimental scale in order to assess the robustness and suitability of the technologies chosen in an island environment. We believe that is in the national interest that these tests - experiments be launched immediately. These experiment and tests are closer to a development phase and they may offer substantial opportunities for spawning competitive (internationally) high-tech enterprises thus catalyzing an important component in the development of green economy.***

Appendices

Appendix A.1. CSP-DSW Concept and Parameters

Process flow and table with 4 MW turbine operating conditions.



Turbine Size		4 MWe (Nominal)		
Process Pressure		–	**1 bar**	
Turbine Type		**COND**	**EXTR**	**B/PR**
Inlet pressure	bar	40	40	
Inlet temperature	°C	540	540	
Inlet steam flow	kg/s	4.17	4.17	
Process steam flow	kg/s	–	0.5 - 3.5	3.8
Return temperature	°C	134.8	134.7 - 134.7	134.7
Condenser CW flow	kg/s	203.7	176.9 - 16.29	–
Generation efficiency	%	32.29	31.09 - 23.87	22.50
Overall ST efficiency	%	–	41.70 - 93.58	99.33
Net ST heat consumption	MWth	12,4	12.4 - 12.4	12.4
Power	MWe	4,0	3.8 - 3.0	2.8
Net process (desal.) heat	MWth	–	1.2 - 8.6	9.5

Appendix A.2 Analysis of Sea Water in Cyprus

The feed water at the RO plant in Larnaca has a 1.5<SDI <3.5 (Koutsakos et al. 2007) [6]. Measurements of seawater intake TDS at the Vasilikos EAC are at the 41,000 ppm level (A. Poullikkas, private communication, 18 Dec. 2009). List included in the call for tenders from the Water Development Dept. of Cyprus.

ANALYSIS OF THE SEA WATER	
Conductivity	*63,000*
PH	*8.1 – 8.5*
Total solids	*45,000 ppm*
Total hardness as $CACO_3$	*7,500 ppm*
Temperature	*16-28°C*
ANIONS	
Chlorides	*23,000 ppm*
Sulfates	*4,000 ppm*
Carbonates	*9 ppm*
Bicarbonates	*150 ppm*
Nitrates	*2 ppm*
CATIONS	
Sodium	*13.000 ppm*
Potassium	*600 ppm*
Calcium	*500 ppm*
Magnesium	*1.600 ppm*
Boron	*5.0 – 6.5 ppm*

Appendix A.3. Energy requirements for seawater desalination.

The table below corresponds to a review of estimates for single-purpose plants (desalination only) (Semiat, 2008) [8].

TABLE 1. Different Energy Requirements for Industrial Desalination Techniques[a]

ref	technique	heat requirements (thermal) [(kW h)/m^3]	electricity requirements (pumping) [(kW h$_e$)/m^3]	combined energy demand [(kW h$_e$)/m^3]
	RO		4–6	4–6
7	MSF	40–120 (thermal)	2.5–5	21–58
	MED	30–120 (thermal)	2–2.5	15–58
8	MSF	25–114 (thermal)	4.8	not clear
5	MSF variations	34–102	2–2.2	17–47
9, 10	MED	4–5 (electricity)	1.5	5–6.5
	MED			6–12
11	MSF			10–16
	RO			3.8
12	RO			3–4

[a] Estimations for thermal units depend on the GOR achieved in the plant and on the steam temperature. The far-right column represents equivalent energies in terms of electrical energy for comparison.

TABLE 2. Energy Consumption for Distillation Techniques Based on Exiting Steam and Heat Losses at Different Temperatures[a]

temperature working range of exiting steam (°C)	electrical power potential in the power station (kW h$_e$)	boiling point elevation range(*13*) (°C)	energy consumption including pumping [(kW h$_e$)/m^3]	
			GOR = 10	GOR = 16
70–35, MED	17.0	0.98–0.34	4	
100–35, MED	30.7	1.18–0.34	5.6	5
120–35, MSF	38.9	1.31–0.34	8.4	6.9
MED energy losses			13	
MSF energy losses			17	

[a] BPE values of seawater are included. Energy values are calculated from steam tables.

Appendix A.4. List of major commercial suppliers of water treatment and purification technologies.

Adapted from Miller, Sandia Report (2003) [7].

Company	***Headquarters***
Alfa Laval	*Sweden*
American Engineering Services	*USA*
Anglian Water PLC	*United Kingdom*
Ansaldo SPA	*Italy*
Agua Design (Ionics)	*USA*
ASI	*USA*
Cayman Water Company, Ltd.	*British West Indies*
Culligan Water Technologies, Inc.	*USA*
Degremont SA (now Suez)	*France*
Dow Chemical Company (FilmTec)	*USA*
E.I. Dupont De Nemours and Company	*USA*
Entropie (Veolia)	*France*
Fluid Systems	*USA*
Ham RO Systems, Inc.	*USA*
Hydranautics, Inc.	*USA*
Hydropure,Inc.	*USA*
Ionics, Inc.	*USA*
Israel Desalination Engineers (IDE)	*USA*
Lyonnaise Des Eaux- Dumez (now Suez)	*France*
Mechanical Equipment Co.	*USA*
Memtec America	*USA*
Osmonics	*USA*
Suez (Ondeo)	*France*
Trisep Corp.	*USA*
United Water Resources (Suez)	*USA (France)*
US Filter (now owned by Vivendi)	*USA (France)*
US Water (Suez)	*USA (France)*
Vivendi Environment	*France*
Water Equipment Technology	*USA*
The Weir Group PLC	*Scotland*

Table 0-1: List of major commercial suppliers of water treatment and purification technologies

Appendix A.5. List of the "Desalination Players" according to Suez Environment (2008).

Names	Origin	Thermal	Membrane
Degremont – Suez Environnement Group	France		X
Veolia (special unit for thermical : Sidem)	France	X	X
Acciona	Spain		X
Befesa – Abengoa group	Spain		X
Inima – OHL group	Spain		X
Aqualia – FCC	Spain		X
Doosan	Korea	X	X
Fisia Italimpianti	Italy	X	
IDE Technologies	Israel	X	X
Hyflux	Singapore		X
Biwater	Great-Britain		X
VA Tech Wabag	Austria	X	X
Aqualyng AS	Norway		X
Aquatech	United States	X	X
Sasakura	Japan	X	
Alfa Laval	Sweden	X	

Table 0-2: List of the "Desalination Players" according to Suez Environnement (2008).

Appendix B.1. Coordinate System and Geographical Coordinate System for the USA

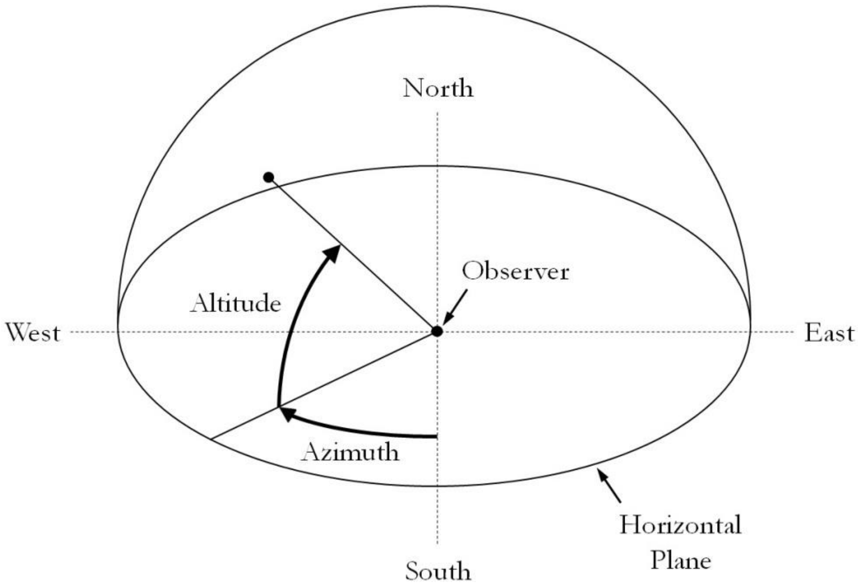


Figure 0-1: Horizontal Coordinate System

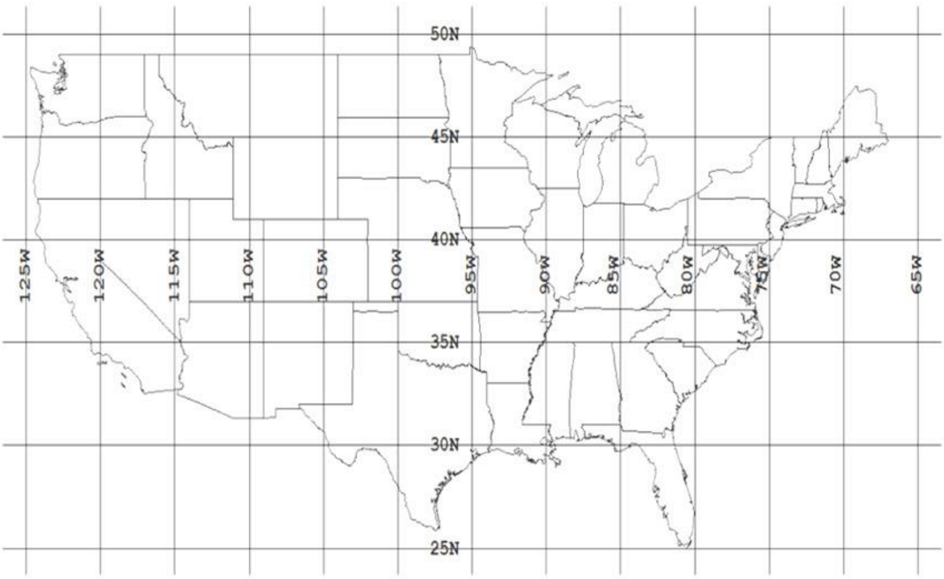


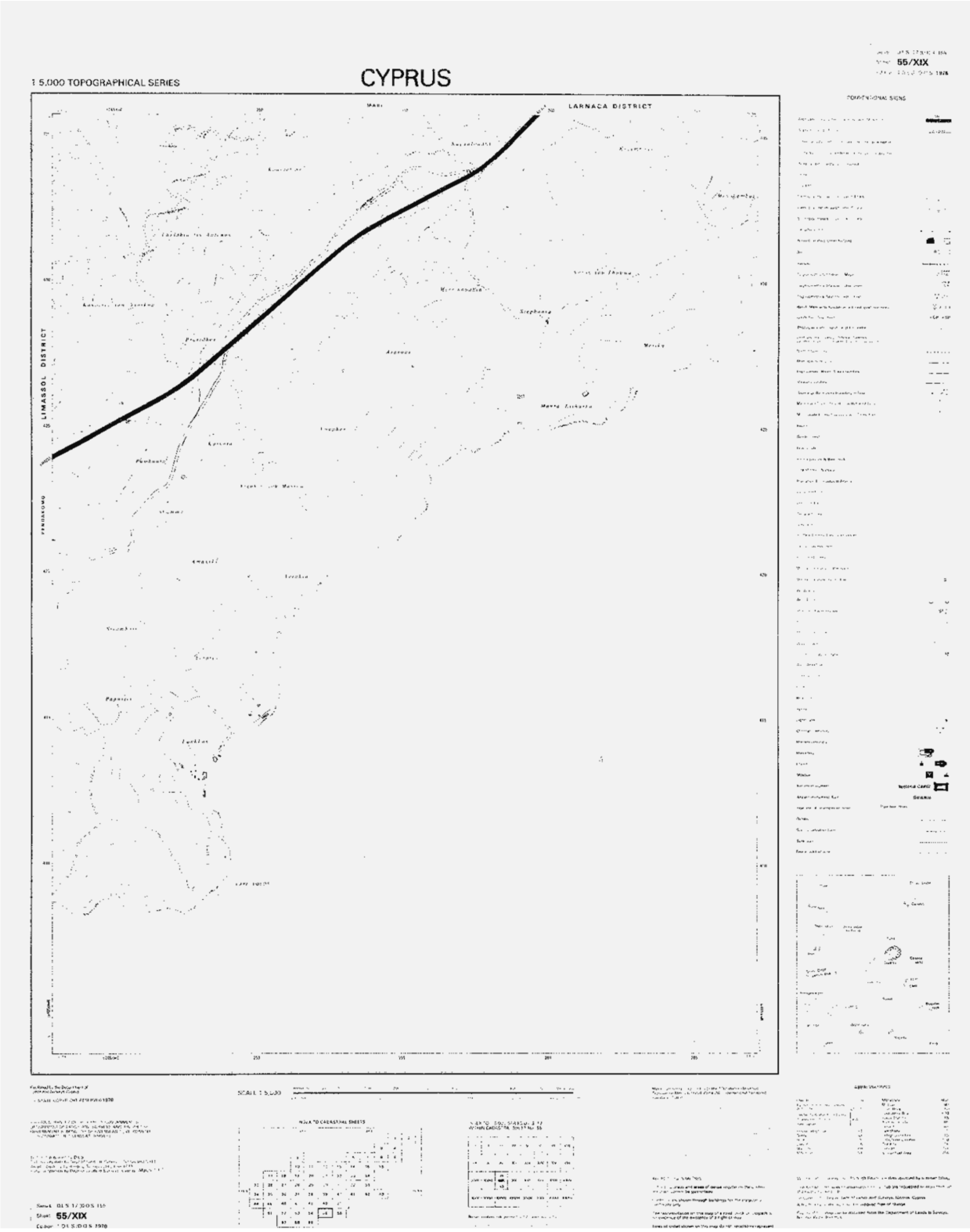
Figure 0-2: Geographic Coordinate System for the Contiguous United States

Appendix C.1. List of desalination plant capacity

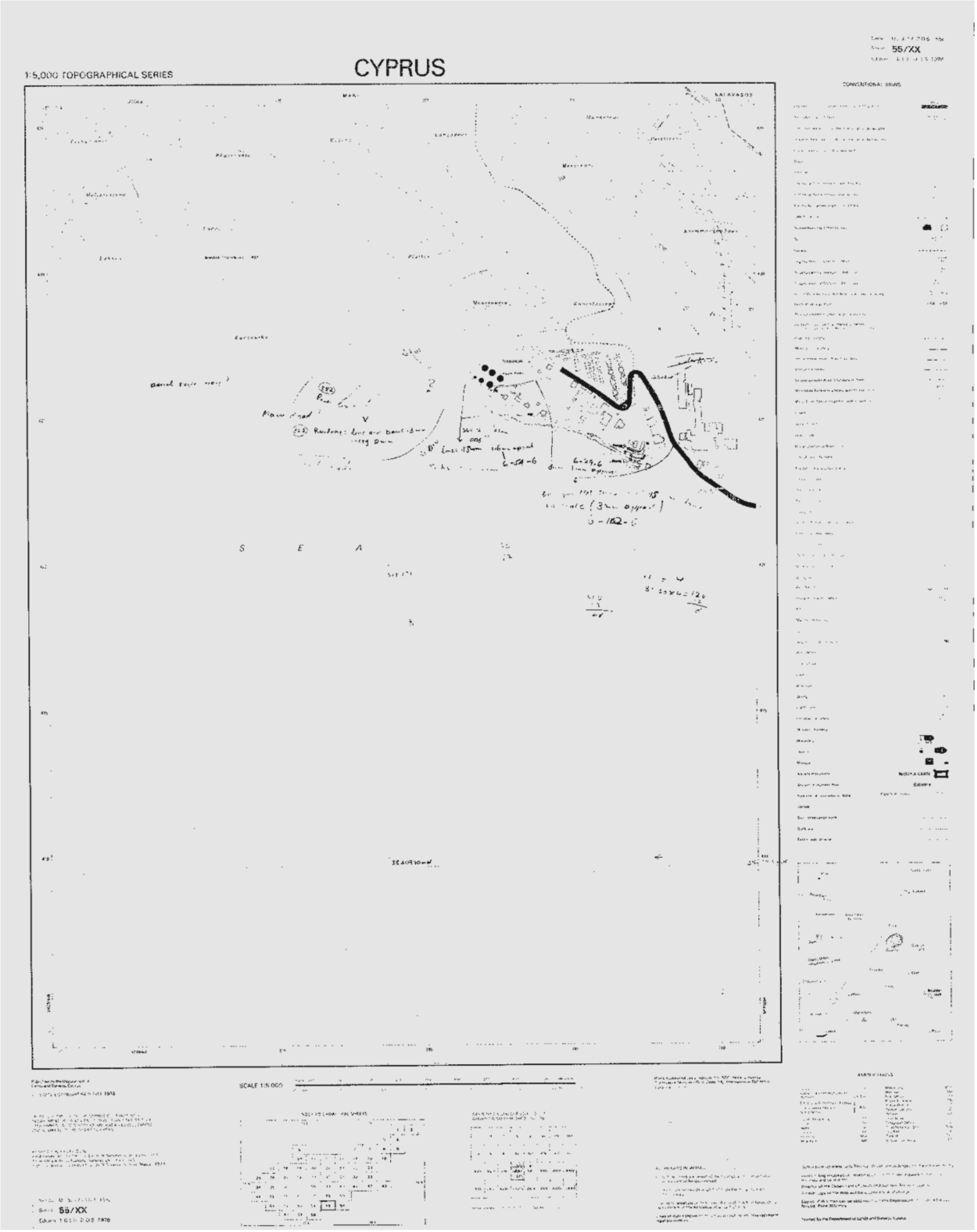
Plant	Location	Distillate capacity (million liters /day)	Method	Year completed
Shoaiba	Saudi Arabia	880	MSF	2010
Marafiq	Saudi Arabia	800	MED	2011
Jabel Ali	UAE	640	MED	2011
Fujairah 2	UAE	590	MED/RO	2011
Mactaa	Algeria	500	RO	2012
Shuweihat	UAE	455	MSF	2004
Fujairah 1	UAE	450	MSF/RO	2004
Tianjin	China	400	MED	2011
Sulaibya	Kuwait	375	RO	2004
Ashkelon	Israel	330	RO	2005
Jebel Ali	UAE	320	MSF	2005
Moni	Cyprus	20	RO	2009
Las Palmas	Spain	20	MED	1999
Trapani 12-effect	Italy	9	MED	1995
Mirfa 4-effect	UAE	4.5	MED	1990
AQUASOL	Spain	0.72	MED/Abs	2007

Table: List of desalination plant capacity: top 10 and bottom 5

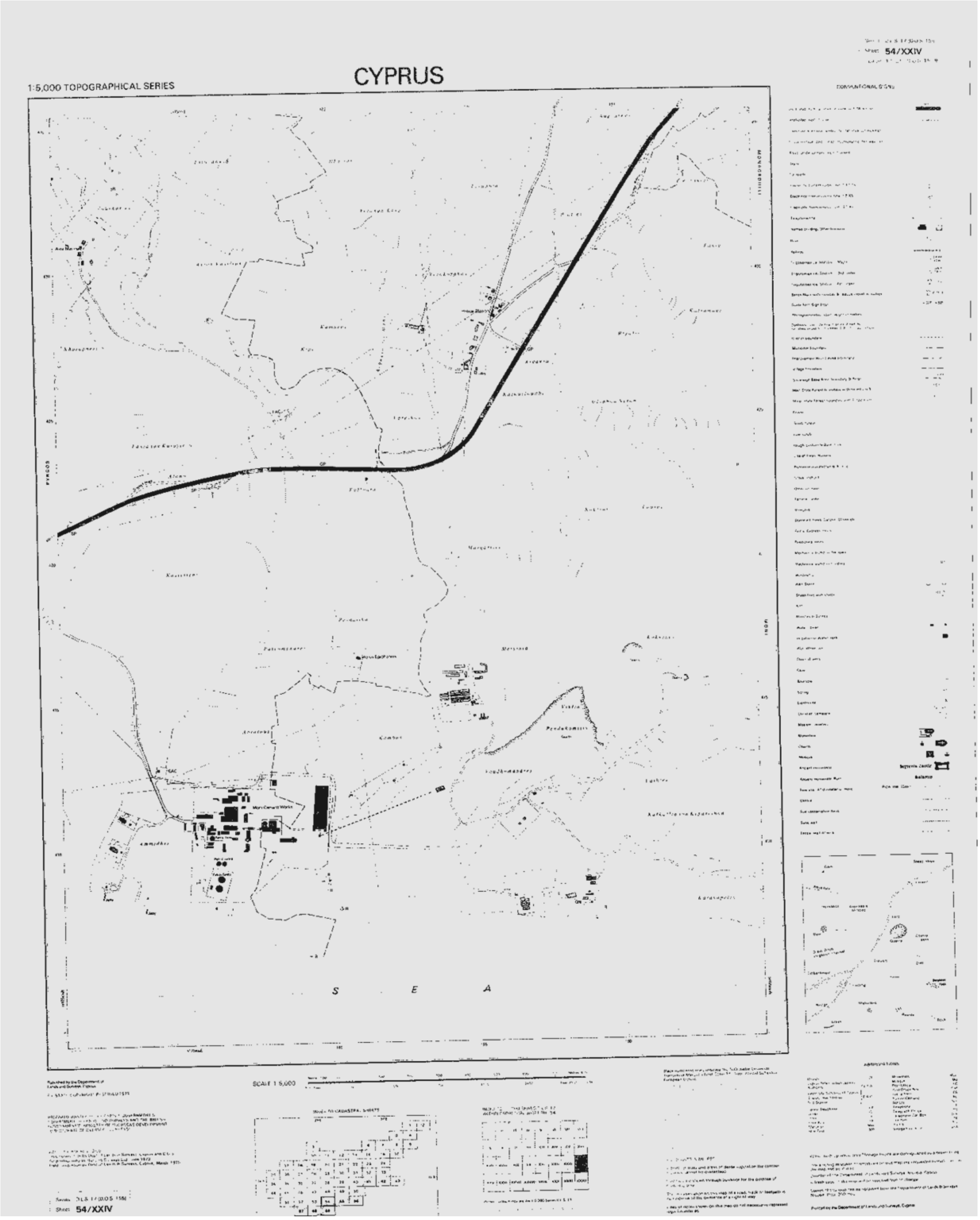
Appendix D.1. The area south of the Technological Park at Pentakomo



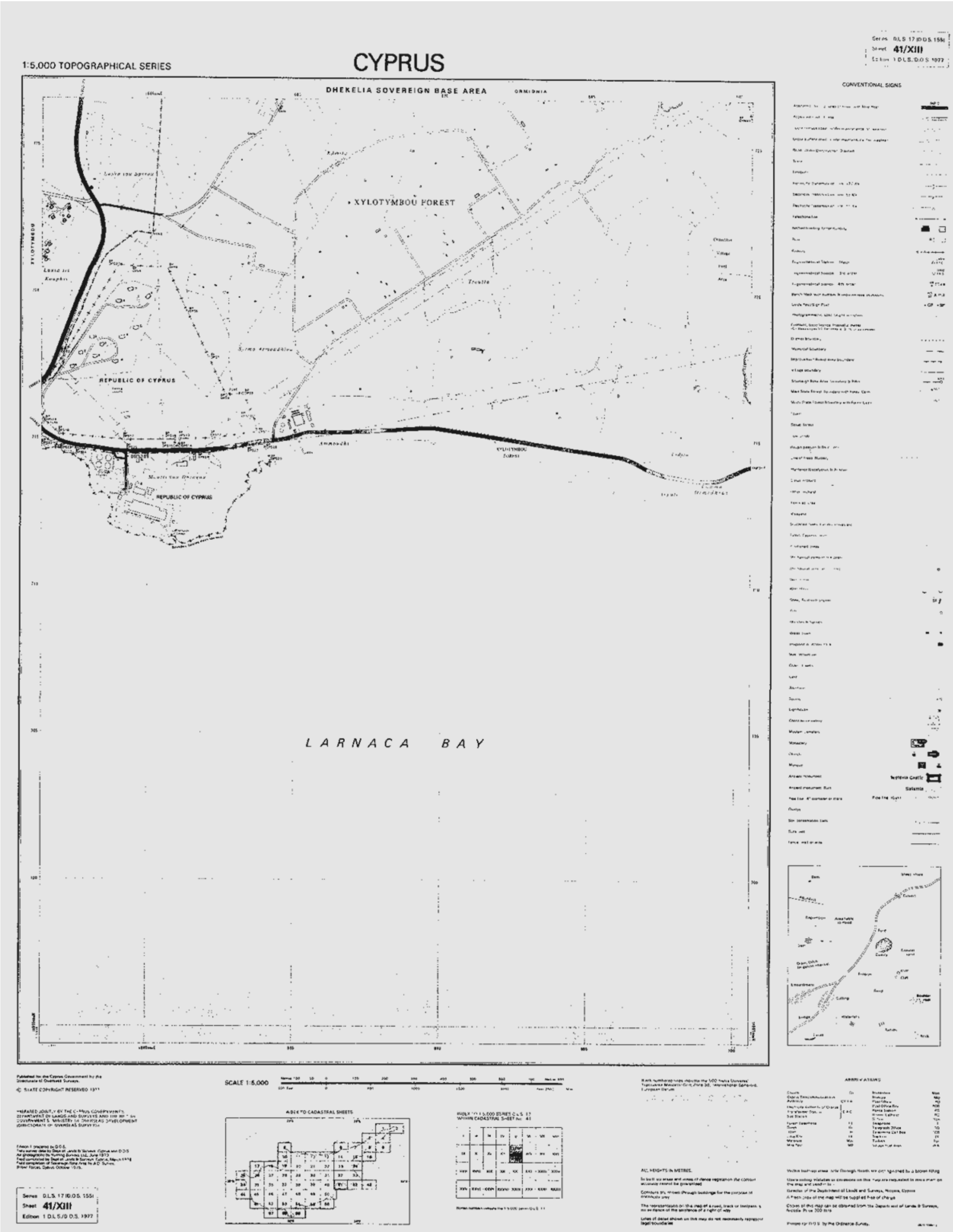
Appendix D.2. The area surrounding Vassilicos Power Plant



Appendix D.3. The area surrounding Moni Power Plant



Appendix D.4. The area surrounding Dhekelia Power Plant



Appendix D.5. Application for Exemption from License for Units producing less than 5MW from Renewable Energy Sources

ΑΙΤΗΣΗ ΠΡΟΣ ΤΗ ΡΥΘΜΙΣΤΙΚΗ ΑΡΧΗ ΕΝΕΡΓΕΙΑΣ ΚΥΠΡΟΥ (ΡΑΕΚ) ΓΙΑ ΠΑΡΟΧΗ ΕΞΑΙΡΕΣΗΣ ΑΠΟ ΑΔΕΙΑ ΜΟΝΑΔΑΣ ΠΑΡΑΓΩΓΗΣ ΗΛΕΚΤΡΙΣΜΟΥ (ΜΕΧΡΙ 5MW) ΑΠΟ ΑΝΑΝΕΩΣΙΜΕΣ ΠΗΓΕΣ ΕΝΕΡΓΕΙΑΣ (ΑΠΕ)

ΟΙ ΠΕΡΙ ΡΥΘΜΙΣΗΣ ΤΗΣ ΑΓΟΡΑΣ ΗΛΕΚΤΡΙΣΜΟΥ ΝΟΜΟΙ ΤΟΥ 2003 έως 2006, Ν.122(Ι)/2003, Ν.239(Ι)/2004, Ν.143(Ι)/2005, Ν.173(Ι)/2006 & Ν.92(Ι)/2008.

1. Πλήρες όνομα αιτητή...
....

2. Διεύθυνση αιτητή, ή στην περίπτωση νομικού προσώπου, το εγγεγραμμένο γραφείο και ο αριθμός εγγραφής εταιρείας
....
....
....

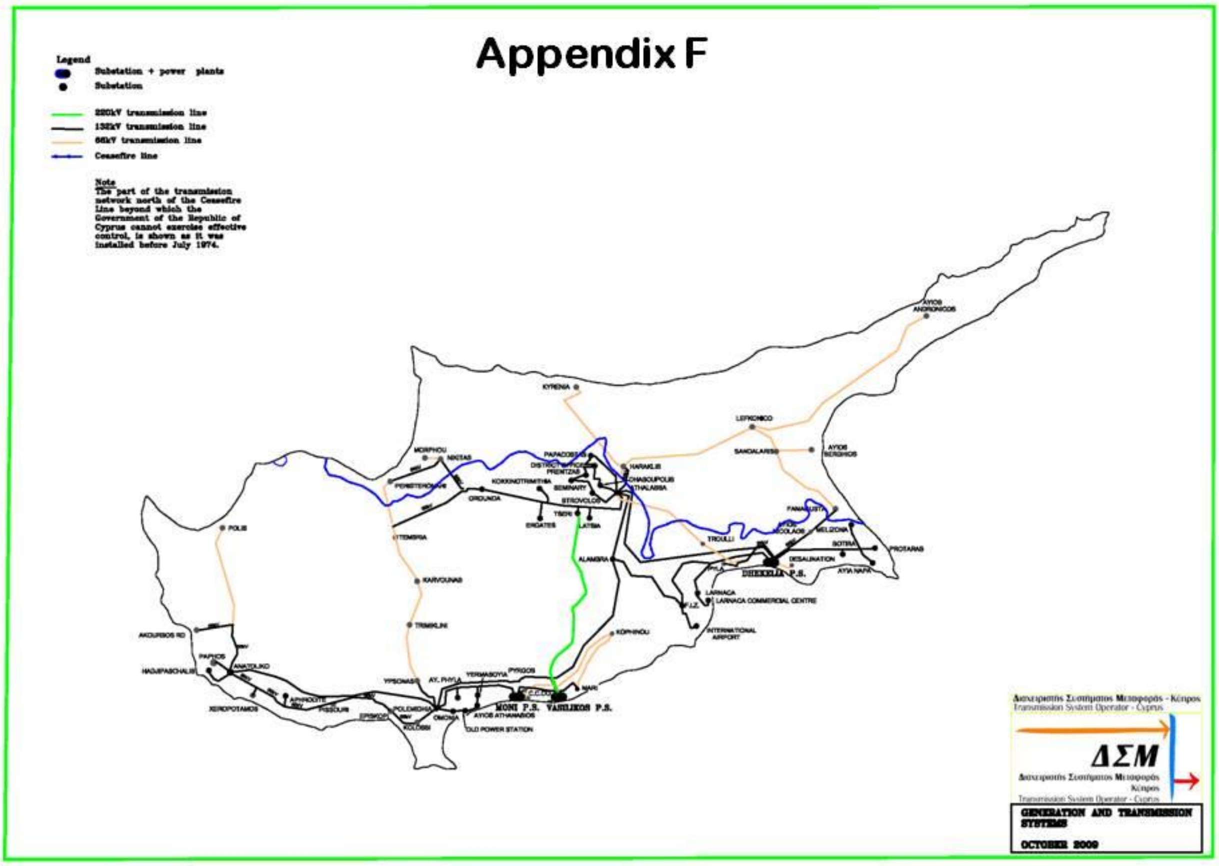
3. Όπου ο αιτητής είναι εταιρεία, τα πλήρη ονόματα των υφισταμένων διευθυντών, τον αριθμό φορολογικού μητρώου, το πιστοποιητικό μετόχων και το καταστατικό της εταιρείας..
....
....

4. Όνομα, διεύθυνση, τηλέφωνο και Φαξ του προσώπου στο οποίο θα πρέπει να αποστέλλεται αλληλογραφία και ερωτήσεις σχετικά με την αίτηση αυτή..
....
....

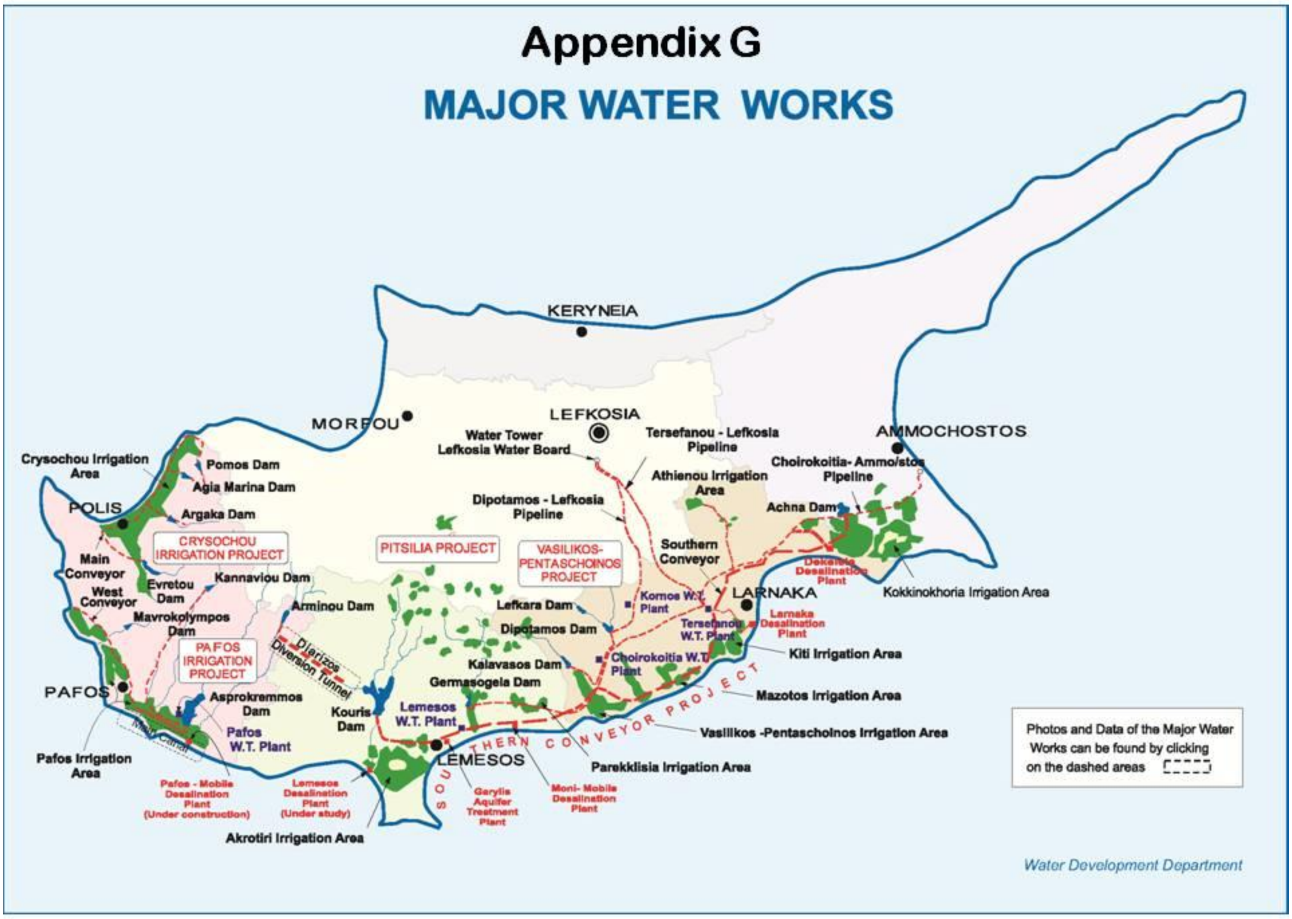
5. Όταν ο αιτητής είναι εταιρεία, πρέπει να παρασχεθούν λεπτομέρειες πιο κάτω για οποιαδήποτε κατακράτηση των μετοχών της εταιρείας αυτής από

1

Appendix D.6. Electricity Transmission Network



Appendix D.7. Major Water Works



Appendix E. 1. CSP-DSW International Workshop

Workshop Programme

Venue: The Cyprus Institute, Guy Ourisson Building, Athalassa Campus

Wednesday, 23rd of June 2010

	Workshop Opening	
09:00 – 09:45	**Welcome** • **Prof. Loukas Kalisperis** (The Cyprus Institute) **Opening Addresses** • **Dr. Titos Christofides** (Under Secretary to the President) • **Mr. Neoklis Sylikiotis** (Minister of Interior) • **Dr. Odysseas Michaelides** (Director, Department of Control, Ministry of Communications and Works) **The promise and assessment of co-generation – The CSP-DSW project** • **Prof. Costas N. Papanicolas** (The Cyprus Institute)	
	Session I: Invited Lectures	
09:45 – 10:15	***Mr. Solonas Kassinis*** *Energy Service, Ministry of Commerce, Industry and Tourism*	*Cyprus Policy on Renewables*
10:15– 10:45	***Prof. Suhil Kiwan*** *Jordan University of Science and Technology*	*Energy situation in Jordan and current Renewable Energy research at JUST*
10:45– 11:15	***Dr. Amr Radwan*** *Academy of Scientific Research & Technology (ASRT), Egypt*	*Renewable energy and desalination: Current research at ASRT*
11:15– 11:45	***Dr. Andreas Poullikkas*** *Electricity Authority of Cyprus*	*Strategies for Power Generation in Cyprus*
11:45– 12:15	***Prof. Jacob Karni*** *Weizmann Institute of Technology, Israel*	*Large Scale Solar Thermal Power Generation: Present and Future*
12:15 – 12:45	***Prof. Rafi Semiat*** *Technion, Israel Institute of Technology*	*Energy Issues in Desalination Processes*
12:45 – 13:00	**Questions - Discussion**	
13:00 – 14:00	**Lunch Break**	

	Session II: The CSP-DSW study	
14:00 – 14:10	***Dr. Georgios Tzamtzis*** *The Cyprus Institute*	*The CSP-DSW Study Overview*
14:10 – 14:30	***Prof. Alexandros Mitsos*** *MIT*	*Integration and Optimisation of a CSP-DSW system*
14:30 – 14:50	***Mr. Danny Codd*** *MIT*	*Solar harvesting and storage: The CSPonD concept*
14:50 – 15:10	***Dr. Constantinos Rouvas*** *Electricity Authority of Cyprus*	*Parametric thermodynamic modelling of steam turbines*
15:10 – 15:30	***Prof. John Georgiadis*** *University of Illinois and The Cyprus Institute*	*State of the art desalination for a CSP-DSW system*
15:30 – 16:00	**Discussion - Questions**	
16:00 – 16:30	**Coffee Break**	
	Session III: Study Findings and Panel Discussion	
16:30 – 17:00	**Prof. Costas N. Papanicolas** *The Cyprus Institute*	*Conclusions of the CSP-DSW study*
17:00 – 18:00	**Panel Discussion:** **Participants** • Dr. Dario Breschi • Prof. Jacob Karni • Mr. Solonas Kassinis • Prof. Suhil Kiwan • Prof. Costas N. Papanicolas • Prof. Rafi Semiat	*The deployment of CSP and Desalination technologies in the MENA Region*
	Closing Remarks – End of Workshop	

Workshop Secretariat: Ms. Anna Sakkalli.

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EUROPEAN UNION THE REPUBLIC OF CYPRUS DEPARTMENT OF CONTROL

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