District/Central Solar Hot Water Systems Design Guide



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Contents

1. Introduction **1**

2. Solar Energy **5**

2.1 Solar radiation intensity 5
2.2 Cloud cover 7
2.3 Site latitude 7
2.4 Orientation to path of sun 10
2.5 Shading 11
2.6 Collector placement within a building cluster 11

3. Solar Hot Water Thermal System **15**

3.1 Collector performance indices 15
3.2 Types of hot water solar systems 18
3.3 Solar thermal energy collectors 22
3.4 Heat transfer fluid 34
3.5 Piping arrangements 36
3.6 Storage tank 48
3.7 Heat exchangers 51
3.8 Pumps 52
3.9 Expansion tank 52
3.10 Back-up/supplemental heater 53
3.11 Controls 53

4. DOD Installation Solar Hot Water Applications **55**

4.1 Areas of potential Army use 55
4.2 Building hot water demands 57
4.3 Basic solar system design 59
4.4 Cost effectiveness 65
4.5 Case studies 70

5. Design Considerations **73**

5.1 Collector site placement 73
5.2 Structural (foundation) 74
5.3 Mechanical 78
5.4 System startup considerations 86

6. System Maintenance **87**

6.1 General maintenance 87
6.2 Glycol fluid care 87

References **89**

Acronyms and Abbreviations **93**

Appendix A: Solar Hot Water Case Studies **95**

Appendix B: Examples of Design Options (Fort Bliss / Fort Bragg) **247**

Appendix C: Market Price Scenario Europe – Climate related Economic Comparisons of Solar Systems **303**

Appendix D: Sample SRCC Rating Page (Flat-Plate Collector) **311**

List of Figures and Tables

Figure		Page
2.1	Map showing the maximum daily solar resource available for tilted flat plate solar collectors in the United States	5
2.2	Map showing the average daily solar resource for tilted flat plate collectors in the United States	6
2.3	Left: Solar Constant and proportions of beam and diffuse solar radiation in relation to cloud cover; Right: Photo of the effects of scattering at sunset taken at 1640 ft (500 m) height	7
2.4	Path of the sun for latitude = 38° 53" (Washington, DC) relative to a horizontal plane	8
2.5	Variation of daily month average beam and diffuse radiation over the year for three locations. The beam (bar) and diffuse (stick) daily radiation are shown for a 40-degree tilted, south facing collector surface	8
2.6	Annual average beam and diffuse fractions (left) and daily June average total radiation for three locations (right)	9
2.7	Influence of tilt and orientation on the percent of total solar radiation received annually. In this example the maximum annual radiation on a 45-degree tilted surface facing south at Latitude = 50 degrees is indicated by 100%	10
2.8	Influence of structures on shading of incoming solar radiation. Height and distance both need to be taken into account	11
2.9	Placement of flat plate air collectors on a flat roof	12
2.10	Flat plate collectors on mounting construction	12
2.11	Two examples of aesthetic placements of collectors. At the right the collectors are integrated into the roof cover together with PV collectors at either side	12
2.12	Flat plate collectors with mounting construction	13
3.1	A schematic example of a solar domestic hot water system, showing the characteristic components	15
3.2	Allocation of the heat flow and reference values in the solar thermal system	16
3.3	A simple passive solar water heating system with a batch collector	19
3.4	Schematic of a typical thermosiphon system	19
3.5	An active, direct solar water heating system. These systems offer no freeze protection, have minimal hard water tolerance, and have high maintenance requirements	20
3.6	An active, drainback solar water heating system. These systems offer good freeze and overheat protection, tolerate hard water well, and have high maintenance requirements	21
3.7	Schematic of an indirect active system that uses a heat exchanger to transfer heat from the collector to the water in the storage tank. These systems offer excellent freeze protection, tolerate hard water well, and have high maintenance requirements	21
3.8	Schematic of a recirculating loop system. These systems require well insulated collectors such as evacuated tube to provide protection for freezing and overheating	22
3.9	A Schematic of a flat plate collector (FPC) showing the heat gain and loss mechanisms that Play a role in determining the thermal efficiency of a collector	

Figure **Page**

(Regenerative Energiesysteme) 23

3.10 Spectral distribution over the wave length (Wellenlänge) of the solar radiation (AM 1.5) and of the thermal infrared radiation from an absorber at 212 °F (100 °C) (graph on the right). The spectral reflectivity (Reflection) of a selective absorber is indicated by the red line 24

3.11 Types of solar thermal energy collectors 25

3.12 An unglazed solar mat-type solar collector made by FAFCO installed on a roof in California 26

3.13 Flat plate collector with selective coating on the absorber. The parallel lines indicate where the riser tubes are connected to the absorber by ultra-sonic welding 27

3.14 Evacuated-tube collector 28

3.15 Basic elements of an evacuated Sydney tube collector. The ends of the tubes in the drawing are cut to show the internal tubing. On the left the tube is additionally equipped with an optional CPC (compound parabolic concentrating) reflector 29

3.16 SunMaxx evacuated tube solar collectors on the roof of a commercial building 30

3.17 Parabolic trough collectors used to heat water at a large prison facility in Colorado 31

3.18 Typical solar collector efficiency curve with losses and useful heat indicated 32

3.19 Power curves for four typical low temperature collectors 33

3.20 The graph shows the Incidence Angle Modifier (IAM) for evacuated tube and flat plate collectors in transversal and longitudinal directions across the collector 34

3.21 Solar supported two-pipe network with centralized energy storage and decentralized heat transfer units 41

3.22 Solar supported two-pipe network with centralized energy storage and decentralized domestic hot water storages 42

3.23 Modular expandable solar supported two-pipe network with decentralized energy storages for all buildings connected 42

3.24 Solar supported four-pipe network with centralized energy storage and centralized hot water storage 43

3.25 Solar supported four-pipe network with centralized energy storage and decentralized hot water storage 43

3.26 Solar supported district heating network with direct interconnection of a central solar thermal system 44

3.27 Piping arrangements of collectors for balanced flow 45

3.28 Overview of storage system types and their application 49

3.29 Example of internal heat exchanger in a storage tank for heating domestic hot water 50

4.1 BCT building grouping at Fort Bliss 57

4.2 Weekly barracks domestic hot water heating profile, Btu/sq ft by hour 58

4.3 Weekly domestic hot water heating profile, Btu/sq ft by hour for a dining facility 58

4.4 Solar system costs 62

4.5 Sizing is a compromise between costs and yield 65

Figure **Page**

4.6 Distribution of costs for a large solar thermal system installation (Regenerative Energiesysteme) 66

4.7 Cost effectiveness of solar hot water systems priced at $50/sq ft (~377 €/$m^2$) replacing electrical heating use 68

4.8 Cost effectiveness of solar hot water systems priced at $75/sq ft (~565 €/$m^2$) replacing electrical heating use 69

4.9 Cost effectiveness of solar hot water systems priced at $50/sq ft (~377 €/$m^2$) replacing gas-fired heating use 69

4.10 Cost effectiveness of solar hot water systems priced at $75/sq ft (~565 €/$m^2$) replacing gas-fired heating use 70

4.11 Cost/Benefit ratios of small decentralized solar thermal systems vs. large solar thermal systems with different storage capacities connected to heating networks 71

5.1 Solar hot water collectors place above automobiles where they are parked 73

5.2 Forces on solar collector that determine structural requirements 74

5.3 Collectors integrated into the roof as a structural element 75

5.4 Collectors integrated into the façade as a structural element 75

5.5 Spacing between collector rows 76

5.6 Collectors mounted on a trapezoidal sheet filled with a rock material 77

5.7 Collectors mounted on concrete slab 77

5.8 Roof support construction example 78

5.9 Pipe sizes used in a reversed return piping system 79

5.10 Pump motor energy use under various modes of operation 82

5.11 Shell and double tube heat exchanger used to protect potable water from harmful heat transfer fluid leaks 83

A-1 Aerial view: residential terraced house complex Gneis-Moos, Salzburg 95

A-2 South oriented glazed façade with greenhouse for passive solar heating 96

A-3 Solar system performance Gneis-Moos, Salzburg 2001 97

A-4 Heat Balance Gneis-Moos, Salzburg 2001 98

A-5 Energy Balance including system losses Gneis-Moos, Salzburg 2001 98

A-6 Solar supported heating grid with weekly storage and two-pipe network connected to decentralized heat transfer units in Gneis-Moos, Salzburg 100

A-7 Part of the 26,420 gal (100 m^3) energy storage tank appears from the underground in the middle of the housing estate Gneis-Moos 100

A-8 Temperatures of the solar loop and the distribution grid in March 23rd 2001, Gneis-Moos 101

A-9 Temperatures of the solar loop and the distribution grid in July 2nd 2001, Gneis-Moos 101

A-10 Temperatures of the solar loop and the distribution grid in December 9th 2001, Gneis-Moos 102

A-11 Simple payback time of the solar thermal system for different energy sources

Figure		Page
	replaced	103
A-12	Net present value of the solar thermal system	104
A-13	Overview of solar supported district heating network Water works, Andritz Graz, Styria	105
A-14	Block diagram of the centralized collector array connected to the district heating network Water works, Andritz Graz, Styria	106
A-15	Block diagram of the centralized energy storage connected to the two-pipe building transfer unit Water works Andritz Graz, Styria	107
A-16	Operating characteristics of the solar thermal system connected to the district heating network Water works Andritz Graz, Styria	108
A-17	Overview of the solar supported district heating network UPC arena Graz-Liebenau	111
A-18	Block diagram of the centralized collector array connected to the district heating network, UPC arena, Graz-Liebenau, Styria	112
A-19	Operating characteristics of the solar thermal system connected to the district heating network, UPC arena, Graz-Liebenau, Styria	113
A-20	Aerial picture of the district heating plant of Ulsted and the solar collector field	116
A-21	Cross-section of the ARCON HT collector	118
A-22	Aerial image of the district heating plant of Strandby and the solar collector field	120
A-23	Diagram of district heating system	122
A-24	Cross section of the ARCON HT collector	123
A-25	Different types of buildings in the complex	125
A-26	Service building with collectors	125
A-27	Diagram of the heating system	126
A-28	The collector field	128
A-29	Diagram of the heating system	130
A-30	Diagram of house installation	130
A-31	Cross section of seasonal storage system	131
A-32	Aerial image of the district heating plant of Brædstrup and the solar collector field	132
A-33	The district heating plant at Brædstrup, Denmark	133
A-34	Overview of the District Heating System of Brædstrup	134
A-35	Cross section of the ARCON HT collector	135
A-36	Subprogram 2, domestic hot water, 2006 Apartment House Frankfurt, 2700 sq ft (250 m^2)	139
A-37	Piping schematic of the fassade collector field (Apartment House Frankfurt)	139
A-38	Solar system for drinking water heating with pre-heating store and thermal disinfection for legionella-protection (no coverage of circulation losses)	139
A-39	Solar system for drinking water heating with pre-heating store and thermal disinfection for legionella-protection (with coverage of circulation losses)	140
A-40	Piping schematic of the solar system (Apartment House Frankfurt)	140

Figure		Page
A-41	District heating Speyer “Old slaughterhouse” 5866 sq ft/26,400 gal (545 m^2 / 100 m^3)	142
A-42	District heating Speyer “Old Slaughterhouse”	142
A-43	Heating net with four-pipe boiler reheating inside buffer store	142
A-44	Piping schematic of heat transfer stations in family houses (District heating Speyer “Old Slaughterhouse”)	143
A-45	Piping schematic of the solar system and the connection to district heating net (Speyer “Old Slaughterhouse”)	143
A--46	Residential area former barracks Normand, highlighting CHP	144
A-47	Front view of the heating central with two collector rows on a flat roof	146
A-48	Collector row piping seen from the backside of first collector row (left side) one of two solar storage tanks (right side)	146
A-49	Highly simplified schematics of the solar system, solar storage tanks arrangement and the integration in the district heating network (DH)	147
A-50	Irradiation, energy output, and efficiency solar system in 2008, daily data solution	150
A-51	Highly simplified schematics showing the positioning of the control sensors	151
A-52	Energy demand DH, energy output solar system, and solar fraction measured in 2008	155
A-53	Volume flow DH, volume flow through solar storage tanks, and temperatures DH	155
A-54	One of five collector areas partly roof-integrated	158
A-55	Heating central with in-housed solar storage tank (left), collector loop flat plate heat exchanger (red box) with piping (right)	158
A-56	Highly simplified schematics of the solar system, solar storage tank arrangement, and the integration in the district heating networks	159
A-57	Irradiation in collector area, solar energy output from collector loop, and collector loop efficiency	162
A-58	Irradiation in collector area, solar energy output from the solar storage tank, and solar system efficiency	162
A-59	Volume flow discharge solar storage tank, advance and return temperature DH	163
A-60	Irradiation, energy output solar storage tank and efficiency solar system in 2008, daily data solution	163
A-61	Highly simplified schematics showing the positioning of the control sensors	164
A-62	Discharge flow through solar storage tank and temperatures DH in 2008	169
A-63	Front view of the heating central with two roof-integrated collector areas	172
A-64	Solar storage tanks	172
A-65	Highly simplified schematics of the solar system, solar storage tanks arrangement and the integration in the district heating network (DH)	173
A-66	Irradiation in collector area, solar energy output from solar storage tanks and solar system efficiency	176
A-67	Energy demand DH, solar energy output from solar storage tanks and solar fraction of total energy demand DH	176

Figure		Page
A-68	Energy demand DH, volume flow DH, advance and return temperature DH	177
A-69	Irradiation in collector area, solar energy output from solar storage tanks, and solar system efficiency in 2008, daily data solution	177
A-70	Highly simplified schematic showing the positioning of the control sensors	178
A-71	Energy demand DH, solar energy output solar storage tanks and solar fraction of energy demand DH measured in 2008	182
A-72	Volume flow DH, discharge flow through solar storage tanks and temperatures DH	182
A-73	Front view of the apartment building with nine collector rows on a flat roof	185
A-74	Collector row arrangement	185
A-75	Highly simplified schematics of the solar system, solar storage tanks arrangement and the integration in the district heating network (DH)	186
A-76	Irradiation, energy output, and efficiency collector loop in 2009, daily data solution	189
A-77	Highly simplified schematics showing the positioning of the control sensors	190
A-78	Energy demand DH, energy output solar system and solar fraction of total energy demand DH measured in 2009	193
A-79	Volume flow DH, volume flow through solar storage tanks and temperatures DH measured in 2009	194
A-80	View from the heating central to some of the buildings carrying a roof-integrated collector area	197
A-81	Solar storage tank encased in a concrete structure and the stacks from the heating central	197
A-82	Highly simplified schematics of the solar system, solar storage tank arrangement and the integration in the district heating network (DH)	198
A-83	Irradiation, energy output, and efficiency of collector loop in 2002/2003, daily data solution	201
A-84	Highly simplified schematics showing the positioning of the control sensors	202
A-85	Volume flow DH, volume flow through solar storage tank, and temperatures DH	205
A-86	Aerial view of solar district heating installation at Saint Paul, MN	207
A-87	US district energy systems	209
A-88	District Energy St. Paul service area map	210
A-89	Saint Paul RiverCentre pre-installation aerial view	211
A-90	Solar energy flow	211
A-91	Solar district energy system	212
A-92	Gross area performance data for competitive bidders	213
A-93	Arcon HT-SA 28/10	213
A-94	Sheehy/Amerect installation of Arcon panel (2010)	213
A-95	Steel “Exoskeleton”	215
A-96	Steel bracing	215

Figure **Page**

A-97 Energy generation ratio – estimated pre-installation (2010) 215

A-98 Actual output (2011) vs. estimates (2010) 215

A-99 District energy total solar contribution – RiverCentre installation 215

A-100 Solar fraction (2011) 215

A-101 Solar fraction of DE total system (2011) 216

A-102 Monthly energy conventional and solar (2011) 216

A-103 Calculate and actual for 12/20/2011 216

A-104 District Energy St. Paul Integrated Energy Diagram™ 217

A-105 Evacuated tube collectors installed on the EPA lab in New Jersey 218

A-106 The solar water heating system installed on the SSA building is a re-circulation loop system using 360 evacuated tube collectors that cover 54 m^2 gross area 219

A-107 Schematic diagram of solar water heating system applied to commercial building recirculation loop. This Fig. shows one of two identical systems on the Mid Atlantic Social Security Center 220

A-108 Paradigma DH network 221

A-109 Schematic view of First Paradigma DH network 221

A-110 Solar cooling plant at Festo, Esslingen, Germany 223

A-111 Schematic view of solar cooling plant at Festo, Esslingen, Germany 223

A-112 Solar system at Alta Leipziger, Oberunsel, Germany 226

A-113 Schematic view of solar system at Alta Leipziger, Oberunsel, Germany 226

A-114 Solar system at Panoramasauna, Holzweiler, Germany 228

A-115 Schematic view of solar system at Panoramasauna, Holzweiler, Germany 228

A-116 Solar panel installation at Wohnheim Langendamm, Nienburg, Germany 230

A-117 Schematic view of solar system at Wohnheim Langendamm, Nienburg, Germany 230

A-118 Location of solar system at Wohnheim Langendamm, Nienburg, Germany 231

A-119 View of solar system at Kraftwerk, Halle, Germany 232

A-120 Schematic view of solar system at Kraftwerk, Halle, Germany 232

A-121 View of solar panels installed at AWO Rastede, Oldenburg, Germany 236

A-122 Schematic view of solar system at AWO Rastede, Oldenburg, Germany 236

A-123 Solar system at METRO, Istanbul, Turkey 238

A-124 Schematic view of solar system at METRO, Istanbul, Turkey 238

A-125 Solar field of collectors at the Phoenix correctional facility (left); close-up of a row of parabolic collectors at the prison (right) 240

A-126 Schematic of the collector field at the Modesto plant 242

A-127 The balance of systems for the SunChips manufacturing facility includes 285 m of pipe from the solar field to the plant, an unfired steam generator (see Fig. A-109), a heat exchanger, a 25 hp pump, 447 m of pipe running back to the solar field from the plant, and bypass valves and controls 243

Figure		Page
A-128	Components of a 54,000 sq ft (5022 m^2) solar industrial process heat plant at Frito Lay Modesto CA, including an unfired steam generator, pump, and controls	243
A-129	Governor Arnold Schwarzenegger gets a close-up look at the field of parabolic solar collectors at the SunChips factory	244
A-130	Peak hourly-averaged efficiency for each day since mid-June 2009. Dark circles represent measured peak hourly efficiency for each day; open circles represent the derated-Sandia-curve goal	244
A-131	Chart showing the monthly energy delivery of the solar water heating system at the SunChips® factory in Modesto, CA, which is owned by Frito Lay. The annual energy collected was 14,600 MBtu/yr/sq ft in 2009	245
B-1	Relationship between supply temperature and outdoor temperature	248
B-2	Typical pressure diagram of a DH system between generation and critical building with the lowest differential pressure	250
B-3	COSCOM network model and the location of the CEP	251
B-4	Fort Bliss network model of the DH system	254
B-5	Energy demand for cooling (Fort Bliss)	255
B-6	System type	257
B-7	Solar fraction and solar efficiency depending on vacuum pipe area, Fort Bliss, cooling	257
B-8	Energy demand for DHW, space heating and cooling, Fort Bliss solar collector	258
B-9	System type	259
B-10	Solar fraction and solar efficiency depending on vacuum pipe area, Fort Bliss, DHW, space heating and cooling	260
B-11	Energy demand for DHW and space heating, Fort Bliss	261
B-12	System type	263
B-13	Solar fraction and solar efficiency depending on flat plate area, Fort Bliss, DHW and space heating	264
B-14	Metered energy data from COSCOM Plant	265
B-15	System type	266
B-16	Solar fraction and solar efficiency depending on vacuum pipe area, Fort Bragg, DHW and space heating	267
B-17	Metered energy data from COSCOM Plant	269
B-18	System type	270
B-19	Solar fraction and solar efficiency depending on flat plate area, Fort Bragg, DHW and space heating	271
B-20	Basic schematic – Fort Bliss – vacuum tube collectors	276
B-21	Payback time - Fort Bliss – cooling – vacuum tube	278
B-22	Energy cost - Fort Bliss – cooling – vacuum tube	278
B-23	Energy cost saving / year (cum) – Fort Bliss – cooling – vacuum tube	279

Figure		Page
B-24	Basic schematic – Fort Bliss – DHW / SPH / cooling – vacuum tube collectors	280
B-25	Payback time - Fort Bliss – DHW / SPH / cooling – vacuum tube collectors	281
B-26	Energy cost - Fort Bliss – DHW / SPH / cooling – vacuum tube collectors	282
B-27	Energy cost saving / year (cum) – Fort Bliss – DHW / SPH / cooling – vacuum tube	282
B-28	Simple payback time depending on flat plate area, Fort Bliss, DHW and space heating	284
B-29	Basic schematic – Fort Bliss – DHW / SPH – flat plate collectors	285
B-30	Payback Time - Fort Bliss – DHW / SPH – flat plate collectors	286
B-31	Energy cost - Fort Bliss – DHW / SPH – flat plate collectors	287
B-32	Energy cost saving / year (cum) – Fort Bliss – DHW / SPH – flat plate collectors	287
B-33	Simple payback time as a function of solar fraction Fort Bliss	288
B-34	Simple payback time as a function of solar fraction Fort Bragg, DHW and space heating	291
B-35	Basic schematic – Fort Bragg – DHW / SPH – vacuum tube collectors	292
B-36	Payback time - Fort Bragg – DHW / SPH – vacuum tube collectors	294
B-37	Energy cost - Fort Bragg – DHW / SPH – vacuum tube collectors	294
B-38	Energy cost saving / year (cum) – Fort Bragg – DHW / SPH – vacuum tube collectors	295
B-39	Basic schematic – Fort Bragg – DHW / SPH – flat plate collectors	296
B-40	Payback time - Fort Bragg – DHW / SPH – flat plate collectors	297
B-41	Energy cost - Fort Bragg – DHW / SPH – flat plate collectors	298
B-42	Energy cost saving / year (cum) – Fort Bragg – DHW / SPH – flat plate collectors	298
B-43	Solar fraction of energy demand	301
C-1	Price range total investment solar system depending on solar field area	304
C-2	Schematics of solar system – comparison	306
C-3	Solar contribution to energy demand / daily maximum temperature at collector	307
C-4	Comparison of payback time scenario 1 – climate zones	308
C-5	Comparison of payback time scenario 2 – climate zones	308
C-6	Comparison of heat production price	309
C-7	Energy savings within 30 years	310

Table		Page
2.1. Daily solar radiation values for specific locations, I [kWh/m^2/day]		6
2.2. Tilt angles corrected for maximum winter season energy collection		9
3.1	Evacuated tube collector 1 (ETC), SPP 14,130 Btu/hr/sq ft (385 W/m^2)	37
3.2	Flat plate collector 1 (FPC), SPP 5,505 Btu/hr/sq ft (150 W/m^2)	37
3.3	*ETC 3,* SPP 2, 202 Btu/hr/sq ft (60 W/m^2), The collector does produce steam. Whether it is too much or not depends on the system	37
3.4	*FPC 2,* SPP 551 Btu/hr/sq ft (15 W/m^2)	38
3.5	*ETC 1 upside down*	38
3.6	*FPC*	38
3.7	*FPC, horizontal*	39
3.8	*FPC*	39
3.9	*FPC, horizontal*	39
3.10	Comparison of mass flow rates for high flow, low flow and matched flow systems	46
3.11	Techno-economic comparison of different storage concepts for local heating networks†	50
4.1	Method to estimate solar system size and cost effectiveness	60
4.2	Typical daily water heating loads	60
4.3	Solar collector categories	63
4.4	Economies of scale	67
4.5	Summary of selected solar system case studies	71
A-1	Static payback time and cost of electricity, oil, and natural gas	103
A-2	Costs	110
A-3	Expected data during planning	148
A-4	Measured data from 2008 and 2009	149
A-5	Summary of control activities and control conditions	152
A-6	Economics	153
A-7	Expected data during planning	153
A-8	Measured data from 2008 to 2009	154
A-9. Measured data from 2003 to 2009		161
A-10. Summary of control activities and control conditions		166
A-11	Economics	167
A-12	Measured data from 2003 to 2009	168
A-13	Expected data during planning	174
A-14	Measured data from 2002 to 2009	175
A-15	Summary of control activities and control conditions	179
A-16	Economics	180

Table		Page
A-17	Measured data from 2002 to 2009	181
A-18	Expected data during planning	187
A-19	Measured data from 2007 and 2009	188
A-20	Summary of control activities and control conditions	191
A-21	Economics	191
A-22	Expected data during planning	192
A-23	Measured data from 2007 to 2009	192
A-24	Expected data during planning	199
A-25	Measured data from 3rd July 2002 to 2nd July 2003,	200
A-26	Summary of control activities and control conditions	203
A-27	Economics	203
A-28	Expected data during planning	204
A-29	Measured data from 2002/2003	204
A-30	General information for the Solar Thermal District Energy System at Saint Paul, MN	207
A-31	District heating specifications	212
A-32	Solar specifications	214
B-33	Flat plate and vacuum pipe collector area and solar storage volume at the same solar fraction	267
B-34	Specific costs of solar systems with flat plate collectors connected to district heating net in Fort Bliss or Fort Bragg dependent on m^2 collector area and m^3 solar storage volume	272
B-35	Absolute costs of solar systems with flat plate collectors connected to district heating net in Fort Bliss or Fort Bragg dependent on m^2 collector area and m^3 solar storage volume	272
B-36	Absolute costs of solar systems with vacuum pipe collectors connected to district heating net in Fort Bliss or Fort Bragg dependent on m^2 collector area and m^3 solar storage volume	273
B-37	Absolute costs of solar systems with vacuum pipe collectors connected to district heating net in Fort Bliss or Fort Bragg dependent on m^2 collector area and m^3 solar storage volume	273
B-38	Specific solar yield in Btu/(yr sq ft) [kWh/(yr·m^2)] Fort Bliss, vacuum pipe-collectors, demand: cooling	274
B-39	Specific solar yield in Btu/(yr sq ft) [kWh/(yr·m^2)] Fort Bliss, vacuum pipe-collectors; demand: DHW, space heating, cooling	274
B-40	Simple payback time; Fort Bliss, vacuum pipe-collectors; demand: cooling	275
B-41	Simple payback time, Fort Bliss, vacuum pipe-collectors demand: DHW, space heating and cooling	275
B-42	Basic data – Fort Bliss – cooling – vacuum tube collectors	275
B-43	Solar system data – Fort Bliss – cooling – vacuum tube collectors	276

Table		Page
B-44	Basic data – Fort Bliss – DHW / SPH / cooling – vacuum tube collectors	279
B-45	Solar system data – Fort Bliss – DHW / SPH / cooling – vacuum tube collectors	280
B-46	Specific solar yield in Btu/(yr•sq ft) [kWh/(yr•m^2)] Fort Bliss, flat-plate-collectors; demand: DHW and space heating	283
B-47	Simple payback time; Fort Bliss, flat-plate-collectors; demand: DHW and space heating	283
B-48	Basic data – Fort Bliss – DHW / SPH – flat plate collectors	284
B-49	Solar system data – Fort Bliss – DHW / SPH – flat plate collectors	285
B-50	Overview economic results (annuity method) solar systems for Fort Bliss	289
B-51	Specific solar yield in kWh/(yr•m^2) Fort Bragg, flat plate-collectors, demand: DHW and space heating	290
B-52	Specific solar yield in kWh/(yr•m^2) Fort Bragg, vacuum pipe-collectors; demand: DHW and space heating	290
B-53	Basic data – Fort Bragg – DHW / SPH – vacuum tube collectors	291
B-54	Solar system data – Fort Bragg – DHW / SPH – vacuum collectors	293
B-55	Basic data – Fort Bragg – DHW / SPH – vacuum tube collectors	295
B-56	Solar system data – Fort Bragg – DHW / SPH – flat plate collectors	296
B-57	Overview economic results (annuity method) solar systems for Fort Bliss	299
C-1	Example - 5000 m^2 Solar System Investment – Paradigma and Arcon	303
C-2	Design criteria for solar system comparison	304
C-3	Overview solar system comparison in different climate zones	306
C-4	Comparison price Increase – heat production cost	309

1. Introduction

Solar thermal systems are commonly used for the domestic water heating, space heating, (industrial) process heating, and even for cooling of goods and buildings. The Energy Independence and Security Act (EISA) 2007 SEC. 523 requires that “if lifecycle cost-effective, as compared to other reasonably available technologies, not less than 30% of the hot water demand for each new Federal building or Federal building undergoing a major renovation be met through the installation and use of solar hot water heaters.” In the United States, different types of solar water heating systems are available and primarily used for standalone buildings. Different design guidelines are available from the National Renewable Energy Laboratory (NREL) and American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) for small size systems. These systems are relatively complex and application of solar based heating in the United States is often limited by economical considerations when compared to traditional heating systems and local cost of fossil fuels.

In recent years, numerous innovations in solar thermal technologies have resulted in cost effective large scale systems including integrated solar supported heating networks. Examples of such systems installed in Denmark, Germany, Austria and other countries have proven that such systems are reliable and may be more economical compared to small scale systems. Such systems may be cost effective for clusters of buildings containing e.g., Army barracks, dining facilities, gyms, child development centers and swimming pools. Similar opportunities exist on large hospital campuses, family housing complexes, etc.

The District/Central Solar Water Heating Systems – Design Guide is the first attempt to develop recommendations on optimal and reliable configurations of solar water heating systems in different climates along with design specifications, planning principles, and guidelines for such systems that serve building clusters with significant domestic hot water (DHW) needs (e.g., barracks, dining facilities, Child Development Center [CDC], Gyms) that operate in combination with district/central heating systems. Note that, throughout the industry, the terms “district heating system” and “central heating system” are commonly used interchangeably. For the purposes of this document, the term “Central Solar Hot Water System” is used to denote systems that serve clusters of buildings from a large centralized solar thermal field(s) (in contrast with small size solar thermal systems that serve standalone buildings). The guidelines are complemented by numerous case studies of successfully implemented solar supported thermal networks along with results of exemplary simulations of different system options based on real world scenarios. This document also discusses the benefits and disadvantages of large scale centralized versus decentralized solar thermal systems.

The Guide was developed by a group of government, institutional, and private-sector parties funded by the US Army Installations Management Command (IMCOM), US Army Corps of Engineers (USACE) and the US Department of Energy Federal Energy Management Program (DOE FEMP), and reviewed and approved by American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Technical Committee (TC) 6.7. The work on the Guide was managed and executed by the Energy Branch of Engineer Research and Development Center Construction Engineering Research Laboratory (ERDC-CERL). The project manager and principle investigator was Dr Alexander Zhivov. Major contributors to the Guide were: Alfred Woody (Ventilation and Energy Applications, USA), Andy Walker (USDOE National Renewable Energy Laboratory), Reiner Croy (ZfS – Rationelle Energietechnik GmbH, Germany), Dr. Stephan Richter (GEF Ingenieur AG, Germany), Dr. Rolf Meißner and Detlev Seidler (Ritter XL Solar GmbH, Germany), Wolfgang Striewe and Stefan Fortuin (Dept. Thermal Systems and Buildings, Fraunhofer Institute for Solar Energy Systems ISE, Germany), Dieter Neth (Senergy Consulting, Germany), Franz Mauthner and Dr. Werner Weiss (AEE – Institute for Sustainable Technologies, Austria), Harald Blazek (S.O.L.I.D. Gesellschaft für Solarinstallation und Design m.b.H, Austria), and Anders Otte Jørgensen and Rene Rubak (ARCON Solar, Denmark).

2. Solar Energy

2.1 Solar radiation intensity

The efficiency and performance of solar water heating systems depend on a site's solar energy resource. Solar resource is measured by the solar radiation intensity of an area, but cloud cover and latitude must also be factored into the system purchase decision. The amount of solar energy available for heating water varies by geographical location. Figures 2.1 and 2.2 show that tilted flat plate collectors located in the United States at an angle equal to the latitude receive the most sunlight in the desert Southwest and the least sunlight in the Pacific Northwest and states in the Northeast. Table 2.1 lists the maximum daily solar radiation and average daily solar radiation for selected US locations. Detailed monthly solar radiation information for a multitude of locations in the United States is available from the National Renewable Energy Laboratory at:
www.nrel.gov/gis/solar_map_development.html

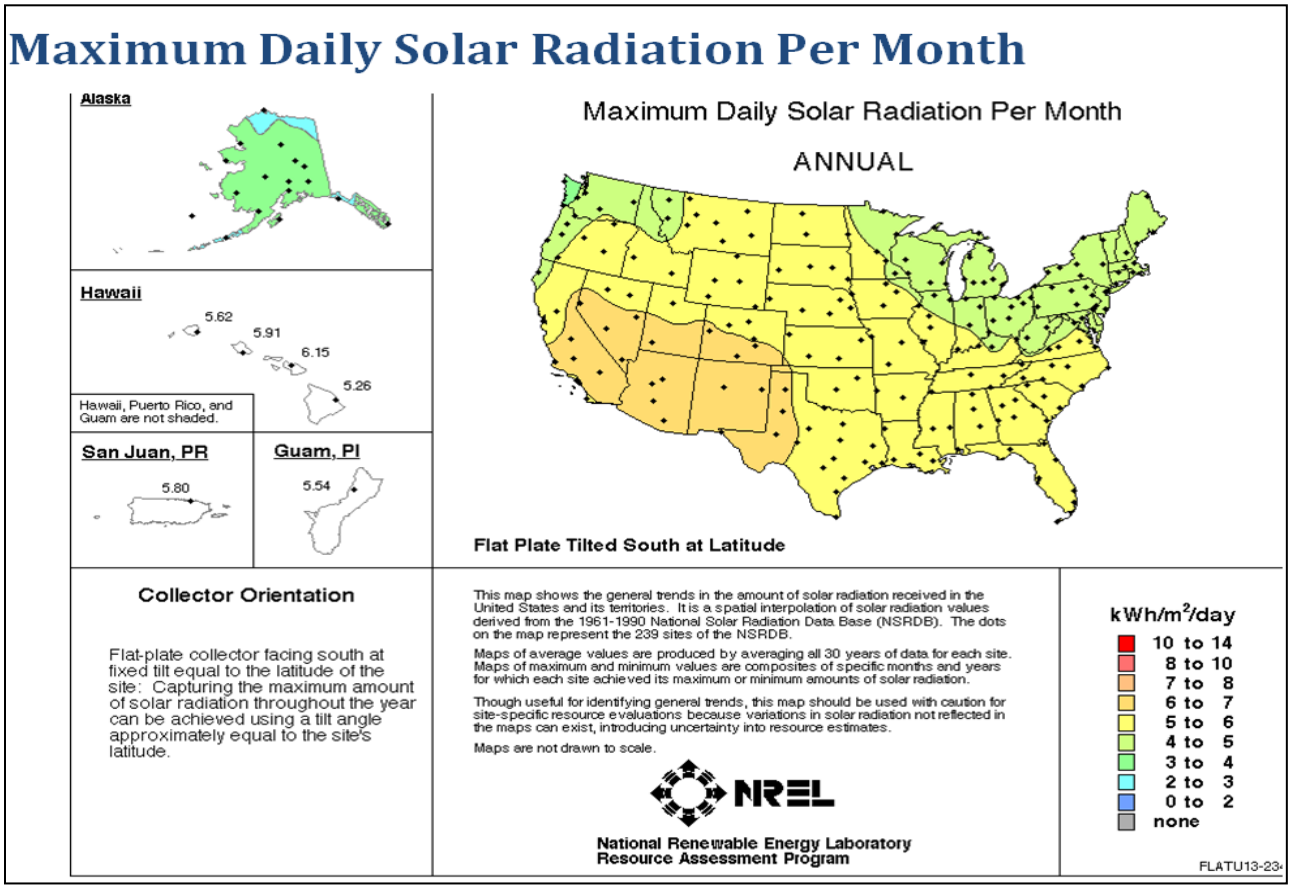


Figure 2.1. Map showing the maximum daily solar resource available for tilted flat plate solar collectors in the United States.

Average Daily Solar Radiation Per Month

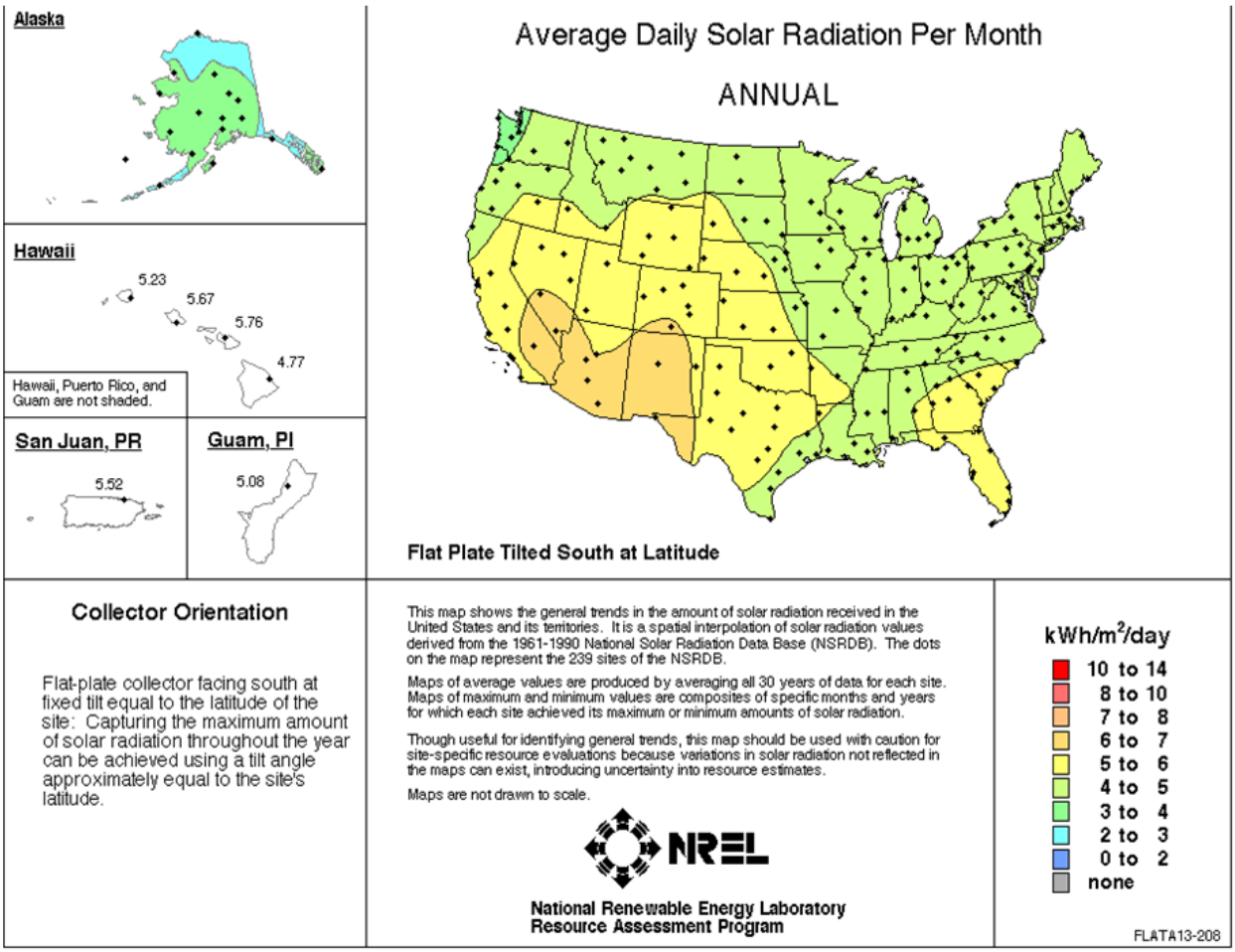


Figure 2.2. Map showing the average daily solar resource for tilted flat plate collectors in the United States.

Table 2.1. Daily solar radiation values for specific locations, I [kWh/m²/day].

Location	I Max	I Ave
Anchorage, AK	4.6	3.0
Austin, TX	6.3	5.3
Boston, MA	5.6	4.6
Chicago, IL	5.7	4.4
Denver, CO	6.1	5.5
Fargo, ND	6.5	4.6
Honolulu, HI	6.5	5.5
Jacksonville, FL	6.1	4.9
Knoxville, TN	5.6	4.7
Sacramento, CA	7.2	5.5
San Diego, CA	6.5	5.7
Seattle, WA	5.7	3.7

The energy delivery of solar water heating systems depends on the environmental conditions of sunlight and temperature. The output of a solar energy system is proportional to the intensity of the sunlight, but its efficiency also depends on temperature. Efficiency decreases as the solar collector gets hotter and more heat is lost to the ambient environment.

2.2 Cloud cover

The power of solar radiation entering the atmosphere, or the "solar constant," is 1367 W/m^2 (50,169 Btu/hr/sq ft). Within the atmosphere, this power is reduced by absorption, scattering, and reflection effects to about 1000 W/m^2 (36,700 Btu/hr/sq ft) on the earth's surface if there is a clear sky (Figure 2.3). The solar radiation that reaches the earth's surface is further reduced by clouds, which reflect part of the radiation back into space, and absorb another part. In addition, a part of the radiation is dispersed into diffuse radiation by multiple reflections. Diffuse irradiation on the earth's surface consists of the irradiation coming from angles different than the solar incidence angle (i.e., the actual sun position). Therefore, cloud cover reduces the total amount of irradiation (global radiation), and (due to scattering), it also changes the relation between beam and diffuse radiation. As cloud cover changes with the seasons, these effects are also seasonal dependent. The diffuse fraction of the total annual global radiation can be higher than 50%, depending on the location.

Even on a clear day a significant amount (>10%) of solar radiation is scattered due to the effects of molecules in the atmosphere. This causes the sky at daytime to appear blue and colors the sun red at sunset, when the distant light waves that enter the atmosphere are longer.

2.3 Site latitude

The latitude of the site will affect the solar radiation collected, so it is important to tilt panels based on the latitude of the installation site. The United States lies closer to the middle latitudes, which means it receives more solar energy in the summer when the sun's path is most perpendicular to locations below. The sun slants far south during the shorter days of the winter months when the sun follows a southern path in the sky. For this reason, solar collectors should face true south in the northern hemisphere, i.e.:

Collector tilt angle = latitude to maximize annual gain

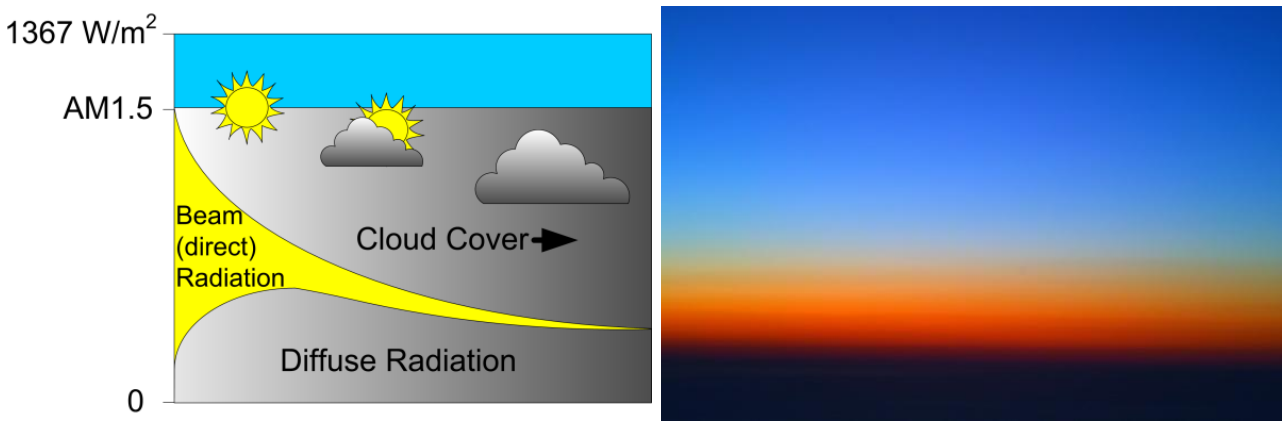


Figure 2.3. Left: Solar Constant and proportions of beam and diffuse solar radiation in relation to cloud cover; Right: Photo of the effects of scattering at sunset taken at 1640 ft (500 m) height.

2.3.1 Season of year

The height of the sun's travel on the horizon varies by season of the year. In the summer, it is more directly overhead; in the winter, it is much lower. Figure 2.4 shows the different paths* of the sun over the sky for Washington, DC. The maximum incidence angle during (solar) noon for the location in this example is 75 degrees on the 21st of June (the summer solstice). The minimum incidence angle occurs on the 21st of December (the winter solstice). And the average incidence angle occurs on the 21st of March and the 21st of September (the autumnal and vernal equinoxes). For locations further north, these curves will be flatter, and for locations further south, steeper.

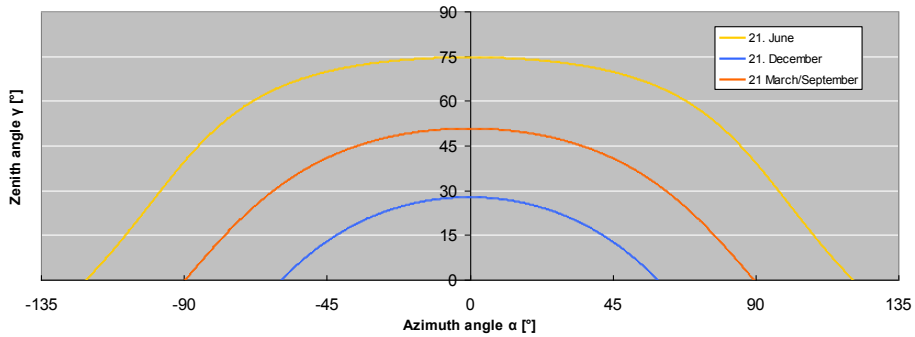


Figure 2.4. Path of the sun for latitude = 38° 53" (Washington, DC) relative to a horizontal plane.

Thus, the amount of solar energy that can be collected varies throughout the year. Monthly available solar radiation values are used to determine the size of the solar collector system required to satisfy the heating demand. Figure 2.5 shows the variation of beam and diffuse radiation over the year for three locations. (The values apply to a collector surface tilted 40 degrees south facing.)

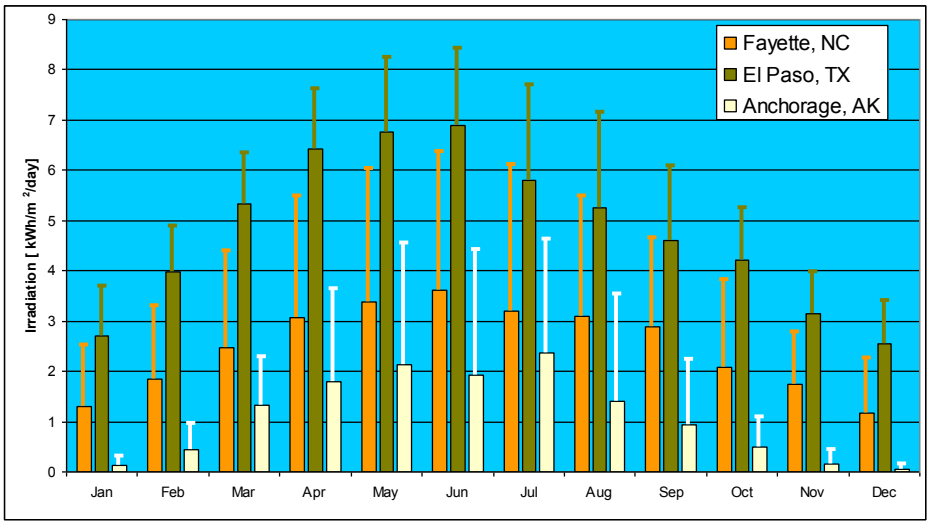


Figure 2.5. Variation of daily month average beam and diffuse radiation over the year for three locations. The beam (bar) and diffuse (stick) daily radiation are shown for a 40-degree tilted, south facing collector surface.

* The relative movement of the Sun around a position on Earth consists of two movements. The daily movement consists of a circular movement around a tilted axis. The annual movement consists of a sinusoidal variation of the tilted axis over the year. In addition, the latitude of the location of the solar thermal system adds an offset to the tilted axis, due to the curvature of the Earth's surface. The latitude ('offset') is equal to the average tilt angle of the sun above the horizon.

The sum of beam and diffuse radiation falling on a horizontal surface is usually called “global solar radiation.” The annual total in the figure above, 40-degree tilted south facing, for Fayette NC is ~507,504 Btu/y*sq ft (~1600 kWh/y*m^2); and for El Paso, TX, 697,818 Btu/y*sq ft (2200 kWh/y*m^2); and for Anchorage, AK, 272,783 Btu/y*sq ft (860 kWh/y*m^2). This results in an annual daily average of 1,396, 1,935, and 761 Btu/sq ft*day (4.4, 6.1, and 2.4 kWh/$m^{2)}$*day respectively. The fraction of diffuse radiation is 44%in Fayette, 21% in El Paso, and 53% in Anchorage. Day and seasonal variation can be very high; a nice summer day may provide as much as 2,030.02 Btu/sq ft*day (6.4 kWh/m^2)*day in Fayette and 2664 and 1459 Btu/sq ft*day (8.4 and 4.6 kWh/m^2 *day) in El Paso and Anchorage and a cloudy winter day may have as little as 63.44 Btu/sq ft*day (0.2 kWh/m^2*day) on average in the month of December in Anchorage (Figure 2.6).

2.3.2 Solar collector tilt

Solar systems should be designed to match the heating demands with the solar energy intensity that varies throughout the year. In the northern hemisphere, a solar thermal system will receive less solar radiation in the winter than in summer. To improve the seasonal solar energy collection, the solar collector can be tilted so that it would be more perpendicular to the sun's path when the heating demand is greatest. Tilting of collectors (from horizontal) should be done to maximize the radiation collection skewed for usage. Thus a system that is providing heat for the winter should have a tilt angle equal to the site's latitude, plus up to 15 degrees; a system for year round heating should have a tilt angle equal to the site's latitude. Table 2.2 lists collector tilt angles at selected locations for maximizing winter solar energy collection.

Maximum radiation can be collected when the collector is faced due South in the Northern Hemisphere. If the system must be East or West facing, using a Westerly azimuth is more optimal than an Easterly one since the collector can take advantage of the warmer part of the day.

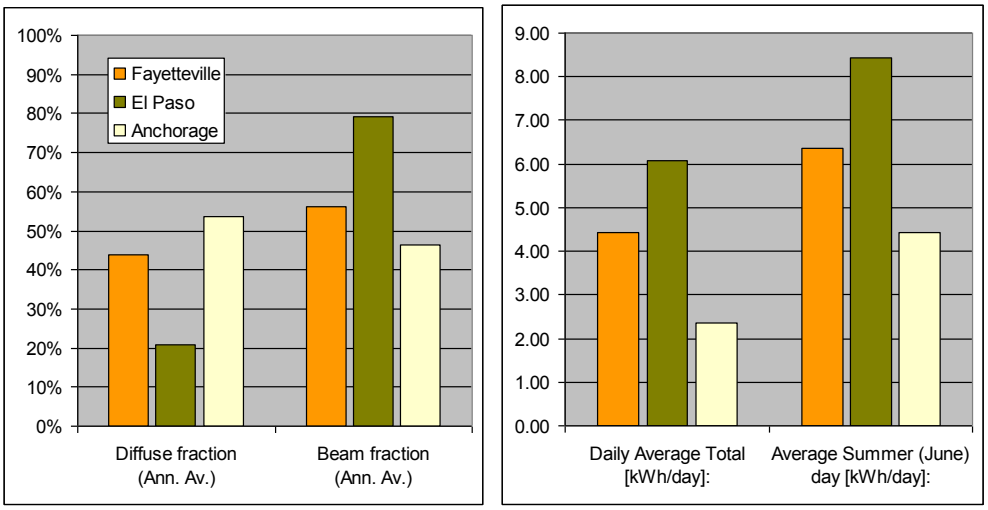


Figure 2.6. Annual average beam and diffuse fractions (left) and daily June average total radiation for three locations (right).

Table 2.2. Tilt angles corrected for maximum winter season energy collection.

Latitude	Angle at +15 degrees
25 degrees (Key West, Florida)	40 degrees
30 degrees (Houston, Texas)	45 degrees
35 degrees (Albuquerque, New Mexico)	50 degrees
40 degrees (Denver, Colorado)	55 degrees
45 degrees (Minneapolis, Minnesota)	60 degrees

2.4 Orientation to path of sun

Two angles describe the orientation of the collector:

- The azimuth* angle α, also called "compass orientation": The angle in a horizontal surface between the collector and the due south direction. Due south, towards the equator, is by definition an orientation of 0˚.
- The tilt angle β ("sky ward orientation"): The angle between the collector and the horizontal surface.†

Costs for supporting structures can be saved by mounting collectors flush with an existing, suitable surface or structure. Tools (brackets etc.) are usually available from the supplier of the collector, which will suit various common surface types like tiled or sheet metal roofs, brick or wood walls etc. The fittings should provide sufficient strength to endure extreme weather conditions like wind and snow loads. It is important that the mounting and structure comply with local standards and regulations.

If mounted in line with an existing structure (e.g., a wall surface) the orientation may be less than optimal, in many cases. The effects of these compromises are often less than expected. This is shown in Figure 2.7. A deviation from the maximum yield tilt and orientation can be compensated for by a larger collector area, if space and costs permit.

A rule of thumb for optimum exposure to solar radiation is that a collector should face the equator (orientation of 0 degrees, due south) with a tilt angle of 0.7 times the Latitude of the location (but at least 10 degrees, or the minimum working angle of the collector). This applies to heating domestic water systems.

The optimum collector tilt angle for the usage of solar energy during winter months is higher because the average sunlight incidence angle is lower. Choosing a larger tilt angle provides a yield that is geared towards winter heat demands. The optimum collector tilt angle for the winter months is higher than the latitude, for example 50 degrees for a site at 45 degrees latitude. Deviations up to 60 degrees from these optimum angles generally will lead to a loss of solar radiation of less than 15% compared to optimum angles. Note that the annual yield also depends on many other factors such as the heat demand characteristics or the storage capacity.

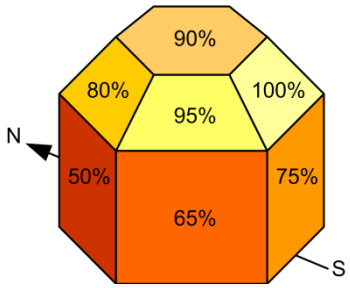


Figure 2.7. Influence of tilt and orientation on the percent of total solar radiation received annually. In this example the maximum annual radiation on a 45-degree tilted surface facing south at Latitude = 50 degrees is indicated by 100%.

* Azimuth: The angular deviation of the collector surface with respect to the direction of due south. Deviation to the west is positive and deviation to the right is negative.

† "Tilt" = angle between horizontal and tilted plane. "Zenith angle" which is the angle between the vertical and the tilted plane, thus "Tilt" = 90˚-"'Zenith angle'")

Choosing a smaller tilt angle gears the yield towards the summer. Usually a summer bias increases the potential overall annual yield of a collector, but only if this extra yield can be used. Solar thermal systems are thus often sized by matching the collector yield during the summer period with the hot water heating need (called economical collector sizing), any increase in collector area will increase the fraction covered in winter, but will also increase the stagnation periods and duration during summer. Refer to Section 3.4.2 (p 35) for an explanation of stagnation.

2.5 Shading

Shading causes less radiation to reach the collector surface. The positioning decision of the collector may be influenced by anything that can cause shade on the collector surface such as mountain ranges on the horizon, nearby or tall buildings, nearby trees (in particular when carrying leaves during winter), and nearby roof construction. Local fog conditions can also cause a loss in sunlight. Shading should be avoided during the peak sun hours of the day, 9 a.m.–3 p.m.

The loss of incoming radiation due to shading must be taken into account during simulations for calculating the prospective yield and usually involves mapping the obstacles on the horizon and sky in the face of the collector orientation (Figure 2.8).

Causes of shade such as fallen leaves and snow depend on location and climatic conditions and should also be considered.

2.6 Collector placement within a building cluster

The solar collectors can be placed on buildings or on the ground. In some cases they could be placed in an elevated position over parking lots providing shade below as an additional benefit. Placement on a building is normally on the roof where a sloped or flat roof exists. Placement on a sloped roof normally creates a collector tilt similar to that of the roof. Also, the orientation may not be directly to the south. In these cases, heating energy obtained from the collector must be derated from that of an optimum placement. Such a placement normally gives a better appearance than that of tilted collectors on a flat roof. Building integrated collectors are assimilated into the original construction of the roof or can be placed slightly above the pitched roof. In either case, the collectors will use the structure framework of the roof as the main support.

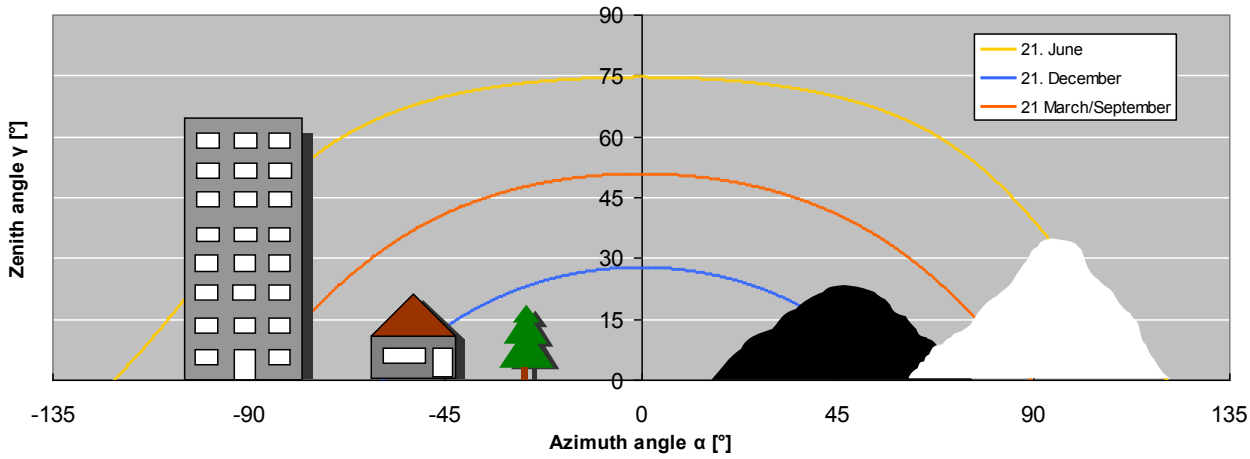


Figure 2.8. Influence of structures on shading of incoming solar radiation. Height and distance both need to be taken into account.

The most important considerations for collector placement is to encourage integration in existing infrastructure, and to avoid shading at periods when solar radiation is plentiful and heating is needed. For large central systems the option of creating a large collector field is usually chosen. This system can be integrated with carport roofing or placed on the flat roof of a large building.

Figures 2.9 and 2.10 show examples of installed collector fields. Integration into new building structures may be more aesthetic and may provide for savings in roof cover material otherwise used. Specially constructed flat plate collectors can provide a closed, insulated surface, which may serve as a roof cover (Figure 2.11).



Figure 2.9. Placement of flat plate air collectors on a flat roof.



Figure 2.10. Flat plate collectors on mounting construction.



Figure 2.11. Two examples of aesthetic placements of collectors. At the right the collectors are integrated into the roof cover together with PV collectors at either side.

Collectors placed on the ground or on flat roofs need a supplemental support to generate the collector tilt to the sun. The rows of collectors must be separated by a short distance so that one row does not shade the row behind it. The distance to assure no shading on the winter solstice can be calculated by:

Separation distance = collector height X tangent of the angle (90 - latitude- 23.5)

Since the energy collected in the winter is a small percentage of the total, then the spacing between rows can be slightly reduced with only minor loss in performance. Figure 2.12 shows how the winter midday sun-angle is (usually) used to determine the angle.

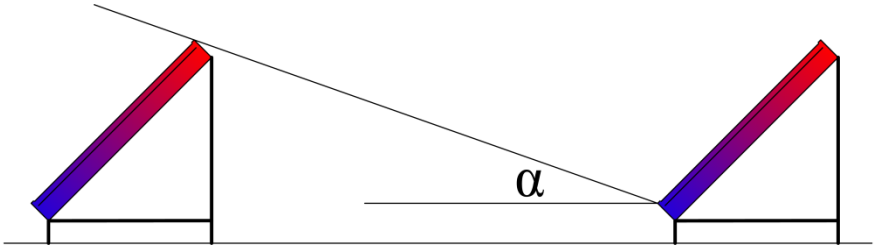


Figure 2.12. Flat plate collectors with mounting construction.