Energy Resources and Policy

Tutorial:
Solar power

1. Inclined surface solar irradiance

Using the data tables provided and the information that follows, determine the total solar irradiation of the given surface.

Latitude: 55°N
Ground reflectivity: 0.25
Date and time: 22 August @ 15:00
Surface azimuth: 180° from N
Sky condition: clear
Surface inclination (β_f): 15°

Angle of incidence:

$$i_\beta = \cos^{-1}\left(\sin\ \beta_s \cos(\ 90\ -\ \beta_f\ ) + \cos\ \beta_s \cos\ \omega \sin(\ 90\ -\ \beta_f\ )\right)$$

where β_s is the solar altitude, β_f the surface inclination, $\omega = |\alpha_f - \alpha_s|$, α_s the solar azimuth, and α_f the surface azimuth.

Surface diffuse irradiance:

$$I_{s\beta} = I_{fh}\left(\frac{1+\cos(90-\beta_f)}{2}\right)\times\left(1+\left[1-\left(\frac{I_{fh}{}^2}{I_{gh}^2}\right)\right]\sin^3\left(\frac{\beta_f}{2}\right)\right)$$

$$\times\left(1+\left[1-\left(\frac{I^2{}_{fh}}{I_{gh}^2}\right)\right]\cos^2(i_\beta)\sin^3(90-\beta_s)\right)$$

where $I_{s\beta}$ is the sky diffuse irradiance, I_{fh} the diffuse horizontal irradiance and I_{gh} the global horizontal irradiance (all in W/m²).

[571 W/m^2]

2. PV panel power output

A photovoltaic panel is to be deployed on a building roof, which faces South-West (225° from N) and has an inclination angle of 45°. Calculate the panel power output using the data tables provided and under the following conditions:

Latitude: 55°N;
Sky condition: clear
Ground reflectivity: 0.2
Date and time: 22 April @ 11:00

You may assume the following equations.

$$i_\beta = \cos^{-1}\left(\sin\ \beta_s \cos(\ 90\ -\ \beta_f\ ) + \cos\ \beta_s \cos\ \omega \sin(\ 90\ -\ \beta_f\ )\right)$$

where the parameters are as in question 1; and

$$I_{s\beta} = I_{fh}\left(\frac{1+\cos(90-\beta_f)}{2}\right)\times\left(1+\left[1-\left(\frac{I_{fh}{}^2}{I_{gh}^2}\right)\right]\sin^3\left(\frac{\beta_f}{2}\right)\right)$$

$$\times\left(1+\left[1-\left(\frac{I^2{}_{fh}}{I_{gh}^2}\right)\right]\cos^2(i_\beta)\sin^3(90-\beta_s)\right)$$

where $I_{s\beta}$ is the sky diffuse irradiance, I_{fh} the diffuse horizontal irradiance and I_{gh} the global horizontal irradiance (all in W/m²).

PV power output: $P = 0.13\ I_T$ where I_T is the total radiation incident on the panel.

[93 W/m^2]

Table A2.23— Solar altitude and azimuth angles

North Latitude	Sun Time	Jan. 21		Feb. 21		Mar. 21		Apr. 22		May 22		June 21		July 23		Aug. 22		Sept. 22		Oct. 22		Nov. 22		Dec. 21		Sun Time
		Alt	Az	Alt	Az	Alt	Az	Alt	Az	Alt	Az	Alt	Az	Alt	Az	Alt	Az	Alt	Az	Alt	Az	Alt	Az	Alt	Az	
	06					0	90	8	81	13	74	15	72	13	74	8	81	0	90							06
	07			4	108	11	100	19	90	24	83	26	80	24	83	19	90	11	100	4	108					07
	08	8	125	15	118	22	110	31	100	36	92	37	89	36	92	31	100	22	110	15	118	8	125	6	127	08
	09	17	136	24	130	33	123	42	112	47	104	49	100	47	104	42	112	33	123	24	130	17	136	14	138	09
	10	24	149	32	145	42	138	52	128	58	118	60	114	58	118	52	128	42	138	32	145	24	149	21	151	10
	11	28	164	37	161	48	157	59	150	67	142	69	138	67	142	59	150	48	157	37	161	28	164	25	165	11
40°	12	30	180	39	180	50	180	62	180	70	180	74	180	70	180	62	180	50	180	39	180	30	180	27	180	12
	13	28	196	37	199	48	203	59	210	67	218	69	222	67	218	59	210	48	203	37	199	28	196	25	195	13
	14	24	211	32	215	42	222	52	232	58	242	60	246	58	242	52	232	42	222	32	215	24	211	21	209	14
	15	17	224	24	230	33	237	42	248	47	256	49	260	47	256	42	248	33	237	24	230	17	224	14	222	15
	16	8	235	15	242	22	250	31	260	36	268	37	271	36	268	31	260	22	250	15	242	8	235	6	233	16
	17			4	252	11	260	19	270	24	277	26	280	24	277	19	270	11	260	4	252					17
	18					0	270	8	279	13	286	15	288	13	286	8	279	0	270							18
	06					0	90	8	81	14	75	16	73	14	75	8	81	0	90							06
	07			3	108	10	101	19	92	25	85	27	83	25	85	19	92	10	101	3	108					07
	08	5	125	12	120	21	112	30	103	35	96	37	93	35	96	30	103	21	112	12	120	5	125	2	127	08
	09	13	137	21	132	30	125	40	116	46	108	48	105	46	108	40	116	30	125	21	132	13	137	10	139	09
	10	19	150	28	146	38	141	48	133	55	125	58	121	55	125	48	133	38	141	28	146	19	150	16	152	10
	11	24	165	32	162	43	159	55	154	62	148	65	146	62	148	55	154	43	159	32	162	24	165	20	165	11
45°	12	25	180	34	180	45	180	57	180	65	180	68	180	65	180	57	180	45	180	34	180	25	180	22	180	12
	13	24	195	32	198	43	201	55	206	62	212	65	214	62	212	55	206	43	201	32	198	24	195	20	195	13
	14	19	210	28	214	38	219	48	227	55	235	58	239	55	235	48	227	38	219	28	214	19	210	16	208	14
	15	13	223	21	228	30	235	40	244	46	252	48	255	46	252	40	244	30	235	21	228	13	223	10	221	15
	16	5	235	12	240	21	248	30	257	35	264	37	267	35	264	30	257	21	248	12	240	5	235	2	233	16
	17			3	252	10	259	19	268	25	275	27	277	25	275	19	268	10	259	3	252					17
	18					0	270	8	279	14	285	16	287	14	285	8	279	0	270							18
	06					0	90	9	82	16	76	18	74	16	76	9	82	0	90							06
	07			1	108	10	102	19	94	25	88	27	85	25	88	19	94	10	102	1	108					07
	08	2	126	10	120	19	114	28	106	35	99	37	97	35	99	28	106	19	114	10	120	2	126			08
	09	10	138	18	133	27	128	37	120	44	113	46	110	44	113	37	120	27	128	18	133	10	138	6	139	09
	10	15	151	24	148	34	143	45	136	52	130	55	128	52	130	45	136	34	143	24	148	15	151	12	152	10
	11	19	165	28	163	38	161	50	157	58	153	61	151	58	153	50	157	38	161	28	163	19	165	15	166	11
50°	12	20	180	29	180	40	180	52	180	60	180	64	180	60	180	52	180	40	180	29	180	20	180	17	180	12
	13	19	195	28	197	38	199	50	203	58	207	61	209	58	207	50	203	38	199	28	197	19	195	15	194	13
	14	15	209	24	212	34	217	45	224	52	230	55	232	52	230	45	224	34	217	24	212	15	209	12	208	14
	15	10	222	18	227	27	232	37	240	44	247	46	250	44	247	37	240	27	232	18	227	10	222	6	221	15
	16	2	234	10	240	19	246	28	254	35	261	37	263	35	261	28	254	19	246	10	240	2	234			16
	17			1	252	10	258	19	266	25	272	27	275	25	272	19	266	10	258	1	252					17
	18					0	270	9	278	16	284	18	286	16	284	9	278	0	270							18
	06					0	90	10	83	17	78	19	76	17	78	10	83	0	90							06
	07					8	102	18	95	25	90	28	88	25	90	18	95	9	103							07
	08			7	121	17	115	27	108	34	103	36	100	34	103	27	108	18	115	7	121					08
	09	6	138	14	134	24	129	34	123	42	117	44	115	42	117	34	123	24	129	14	134	6	138	3	140	09
	10	11	151	20	149	30	145	41	140	49	135	51	133	49	135	41	140	30	145	20	149	11	151	8	152	10
	11	14	166	23	164	34	162	45	159	54	156	56	154	54	156	45	159	34	162	23	164	14	166	10	166	11
55°	12	15	180	24	180	35	180	47	180	55	180	58	180	55	180	47	180	35	180	24	180	15	180	12	180	12
	13	14	194	23	196	34	198	45	201	54	204	56	206	54	204	45	201	34	198	23	196	14	194	10	194	13
	14	11	209	20	211	30	215	41	220	49	225	51	227	49	225	41	220	30	215	20	211	11	209	8	208	14
	15	6	222	14	226	24	231	34	237	42	243	44	245	42	243	34	237	24	231	14	226	6	222	3	220	15
	16			7	239	17	245	27	252	34	257	36	260	34	257	27	252	18	245	7	239					16
	17					8	258	18	265	25	270	28	272	25	270	18	265	9	257							17
	18					0	270	10	277	17	282	19	284	17	282	10	277	0	270							18
South* Latitude	Sun Time	July 23		Aug. 22		Sept. 22		Oct. 22		Nov. 22		Dec. 21		Jan. 21		Feb. 21		Mar. 21		Apr. 22		May 22		June 21		Sun Time

* Use months indicated at top for North Latitudes and use months at bottom for South Latitudes. Azimuth angles in the southern hemisphere are obtained by subtracting the tabulated azimuth angles from 180° when they are less than or equal to 180° or from 540° when they are greater than 180°.

Table A2.35 *(m)* Basic direct solar irradiances on vertical, I_{DV}, and horizontal, I_{DH}, surfaces and basic diffuse (cloudy and clear sky) solar irradiances on horizontal surfaces, I_{dH}, (W/m²).

55°N

Date	Orientation	Daily mean	Sun Time 03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21
June 21	N	35		95	175	135	25	0	0	0	0	0	0	0	0	0	25	135	175	95	
	NE	85		160	385	485	470	365	205	20	0	0	0	0	0	0	0	0	0	0	
	E	145		130	365	550	640	630	545	395	210	0	0	0	0	0	0	0	0	0	
	SE	145		20	135	290	435	530	565	540	455	325	160	0	0	0	0	0	0	0	
	S	115		0	0	0	0	115	255	365	435	465	435	365	255	115	0	0	0	0	
	SW	145		0	0	0	0	0	0	0	160	325	455	540	565	530	435	290	135	20	
	W	145		0	0	0	0	0	0	0	0	0	210	395	545	630	640	550	365	130	
	NW	85		0	0	0	0	0	0	0	0	0	0	20	205	365	470	485	385	160	
	H	290		10	80	195	335	465	585	675	735	755	735	675	585	465	335	195	80	10	
Diff (Cldy)		115		20	55	95	140	180	225	260	285	295	285	260	225	180	140	95	55	20	
Diff (Clr)		50		15	45	60	75	80	90	95	100	100	100	95	90	80	75	60	45	15	
July 23 and May 22	N	25		25	135	110	0	0	0	0	0	0	0	0	0	0	0	110	135	25	
	NE	75		45	310	445	445	345	185	0	0	0	0	0	0	0	0	0	0	0	
	E	135		35	305	520	625	630	545	400	210	0	0	0	0	0	0	0	0	0	
	SE	150		5	120	290	445	545	585	565	480	350	185	0	0	0	0	0	0	0	
	S	130		0	0	0	0	145	285	395	470	495	470	395	285	145	0	0	0	0	
	SW	150		0	0	0	0	0	0	0	185	350	480	565	585	545	445	290	120	5	
	W	135		0	0	0	0	0	0	0	0	0	210	400	545	630	625	520	305	35	
	NW	75		0	0	0	0	0	0	0	0	0	0	0	185	345	445	445	310	45	
	H	265		0	50	160	295	430	550	640	700	720	700	640	550	430	295	160	50	0	
Diff (Cldy)		110		5	40	85	125	170	210	245	270	280	270	245	210	170	125	85	40	5	
Diff (Clr)		50		5	35	55	70	80	90	95	100	100	100	95	90	80	70	55	35	5	
August 22 and April 22	N	5			20	45	0	0	0	0	0	0	0	0	0	0	0	45	20		
	NE	45			60	295	355	285	135	0	0	0	0	0	0	0	0	0	0		
	E	115			65	370	555	605	540	400	215	0	0	0	0	0	0	0	0		
	SE	155			30	230	430	570	630	620	540	410	240	50	0	0	0	0	0		
	S	160			0	0	50	200	350	470	550	580	550	470	350	200	50	0	0		
	SW	155			0	0	0	0	0	50	240	410	540	620	630	570	430	230	30		
	W	115			0	0	0	0	0	0	0	0	215	400	540	605	555	370	65		
	NW	45			0	0	0	0	0	0	0	0	0	0	135	285	355	295	60		
	H	205			0	65	185	320	445	540	600	620	600	540	445	320	185	65	0		
Diff (Cldy)		85			5	50	95	135	175	205	230	235	230	205	175	135	95	50	5		
Diff (Clr)		40			5	40	60	70	80	85	90	90	90	85	80	70	60	40	5		
September 22 and March 21	N	0				0	0	0	0	0	0	0	0	0	0	0	0	0			
	NE	20				0	180	180	60	0	0	0	0	0	0	0	0	0			
	E	80				0	330	480	480	370	200	0	0	0	0	0	0	0			
	SE	145				0	285	500	615	635	575	455	290	110	0	0	0	0			
	S	180				0	70	225	390	530	615	645	615	530	390	225	70	0			
	SW	145				0	0	0	0	110	290	455	575	635	615	500	285	0			
	W	80				0	0	0	0	0	0	0	200	370	480	480	330	0			
	NW	20				0	0	0	0	0	0	0	0	0	60	180	180	0			
	H	125				0	50	160	275	370	430	450	430	370	275	160	50	0			
Diff (Cldy)		55				0	45	85	120	150	170	175	170	150	120	85	45	0			
Diff (Clr)		30				0	35	55	70	75	80	80	80	75	70	55	35	0			
October 22 and February 21	N	0						0	0	0	0	0	0	0	0	0					
	NE	5						70	5	0	0	0	0	0	0	0					
	E	45						255	345	300	170	0	0	0	0	0					
	SE	115						290	480	555	535	440	295	135	0	0					
	S	155						155	335	490	585	620	585	490	335	155					
	SW	115						0	0	135	295	440	535	555	480	290					
	W	45						0	0	0	0	0	170	300	345	255					
	NW	5						0	0	0	0	0	0	0	5	70					
	H	65						40	120	200	260	280	260	200	120	40					
Diff (Cldy)		30						35	70	100	115	120	115	100	70	35					
Diff (Clr)		20						30	50	60	65	70	65	60	50	30					
November 22 and January 21	N	0							0	0	0	0	0	0	0						
	NE	0							0	0	0	0	0	0	0						
	E	20							160	190	120	0	0	0	0						
	SE	75							245	385	410	355	240	115	15						
	S	105							180	350	460	500	460	350	180						
	SW	75							15	115	240	355	410	385	245						
	W	20							0	0	0	0	120	190	160						
	NW	0							0	0	0	0	0	0	0						
	H	25							25	75	120	135	120	75	25						
Diff (Cldy)		15							30	55	70	75	70	55	30						
Diff (Clr)		10							25	45	50	50	50	45	25						
December 21	N	0							0	0	0	0	0	0	0						
	NE	0							0	0	0	0	0	0	0						
	E	15							80	140	95	0	0	0	0						
	SE	55							120	290	340	300	205	90	10						
	S	80							90	270	385	420	385	270	90						
	SW	55							10	90	205	300	340	290	120						
	W	15							0	0	0	0	95	140	80						
	NW	0							0	0	0	0	0	0	0						
	H	15							5	40	75	85	75	40	5						
Diff (Cldy)		10							15	40	55	60	55	40	15						
Diff (Clr)		10							10	30	40	45	40	30	10						

THE TABULATED VALUES HAVE THE FOLLOWING BASIS:
Direct radiation factor, $k_D = 1.0$
Diffuse radiation factor, $k_d = 1.0$
Height correction factor, $k_a = 1.0$

For southern latitudes, this table may be used by reading northern values for southern aspects and vice-versa, substituting dates as follows:

NORTH	June	May July	April August	March September	February October	January November	December
SOUTH	December	November January	October February	September March	August April	July May	June