AVAILABILITY OF SOLAR RADIATION AND POSSIBILITY OF ITS UTILIZATION IN POLAR ZONES

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Abstract

The availability of solar radiation in the polar zones greatly influences the climate of the Earth. However, solar radiation conditions and its dependence upon ozone layer, carbon dioxide, meteorological and locational parameters at polar zones are hardly investigated. To study solar radiation conditions at polar zones, a special algorithm and software are developed. The software developed allows for the simulation of all solar radiation parameters: hourly direct beam, beam, diffuse and global, daily and mean monthly components, clearness and anisotropy indices. The simulations are conducted for different latitudes and for different possible meteorological conditions. The effects of ozone layer and carbon dioxide were also investigated. It is shown that O_3 has minimal affect the climate in the polar zones, because it absorbs only the uv-component of solar radiation. The increase in CO_2 above the polar zones increase solar radiation absorbed by the atmosphere and decrease solar radiation incident on the surface of the Earth and, hence, would probably cause little climate change. Simulations results revealed interesting facts. For example, at the South Pole the hourly direct beam radiation, I_{bn}, can be as high as 1200 W/m^2. Daily direct beam radiation, H_{bn}, could be as high as 109000 MJ/m^2. However, for the North Pole this parameter is much lower, H_{bn} = 72000 MJ/m^2. At the same time diffuse components are low. For South Pole I_d = 43 W/m^2, and for North Pole I_d = 74 W/m^2. This is understandable, because the atmosphere there is clear and not polluted. The effect of different slopes upon the total solar radiation on a horizontal surface is also investigated. For both poles, the optimum slope is zero. The conclusion made is that polar zones are promising for utilization of solar energy (during summer times) by PV-arrays. It is especially promising at the Southern Polar Zone.

KEY WORDS: solar energy, polar zones.

1. Introduction

The Northern Polar Zone is situated further to the north from the Northern Polar Circle, $\phi = 66.55^\circ$, while the Southern Polar Zone is situated to the south from the Southern Polar Circle, $\phi = -66.55^\circ$. The climates and topography of these polar zones ($90^\circ \geq \phi \geq 66.5^\circ$ and $-90^\circ \leq \phi \leq -66.5^\circ$) are different. Most of the area of the Northern Polar Zone is covered by the Arctic Ocean and low altitude tundra. During winter time temperature at the North Polar Zone is in the range -34 °C to - 40 °C and the average summer temperature is 0 °C. The Southern Polar Zone is mostly continental area which is covered by glaciers and snow. The elevation could be as high as 2800 m. During winter time, temperature could be as low as -80 °C. In fact the lowest recorded temperature at the South Pole during winter time is -89.2 °C and the highest temperature ever recorded during summer time (21 September to 21 March) is -13.6 °C [1]. Humidity in the Southern Polar Zone is always low; frequently less than 1 %, that is why it called the “dry ice desert”. It is generally considered that the ozone layer above the Antarctic zone is almost depleted. The availability of solar radiation in the Arctic and Antarctic zones is hardly studied. However, to explore the potential use of solar energy in the above zones, one need to know such solar parameters as hourly and daily direct beam, diffuse and global solar radiation components [2].

2. Results and Discussion

To study solar radiation components at Polar Zones a special algorithm and software were developed based on previous publications [3-6]. The software requires three types of input data, namely: (a) Location and Date (latitude, ϕ; month, M; day of the month, Dm,); (b) Meteorological Data (temperature, T (°C); relative humidity, RH; visibility, V (km); thickness of the ozone layer, Po (cm); and sunshine hours, Sh); (c) Orientation of an absorber plate (slope, β; surface azimuth angle, γ, and ground albedo, ρ). The software simulates: all hourly components, all daily components (for clear cloudless and partly cloudy weather), mean daily optimum slope, air mass at sunset, daily clearness and anisotropy indices and diffuse fractions. The algorithm of the software used for the simulations is shown in Fig. 1. An example of simulation of solar radiation components for South Pole ($\phi = -90^{\circ}$) on 21 December is given in Fig. 2.

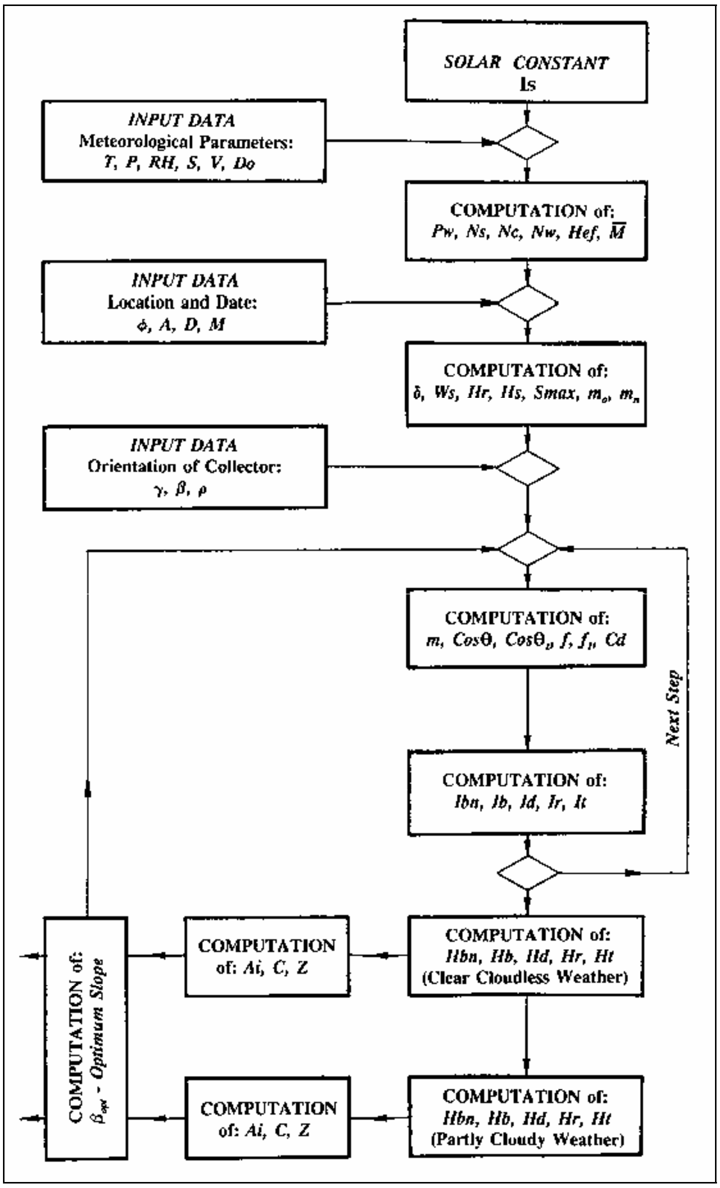


Fig. 1. The algorithm of the software. (Symbols and notations are defined in [7]).

By N.Nijegorodov ISOTROPIC SKY MODEL IS USED

INPUT DATA:
Location and Date: L=-89.9999, A= 2800, Lg= 0, Ls = 0, M= 12, Dm= 21
Meteorolog. Data: Tc=-10, Ap= 528.1431, Rh= 03, Po= 0 V= 115, Dsh= 12
Orientation of an Absorber: Slope S = 0, Azimuth Angle: G = 0, Ground Albedo Ga = .2
Declination: D = -23.44978, No Sunset - POLAR DAY
Day Duration: Dd = 24h , Number of Cloudy Hours Dc 12

HOURLY AND DAILY SOLAR INSOLATION ON A CLEAR DAY (W/m^2)

Hour	Ibn	Ib	Id	Ir	It
0	1211.107	481.9503	42.9775	0	524.9277
1	1211.107	481.9503	42.97752	0	524.9279
2	1211.107	481.9507	42.97754	0	524.9283
3	1211.107	481.9512	42.97748	0	524.9287
4	1211.107	481.9519	42.97755	0	524.9295
5	1211.107	481.953	42.97754	0	524.9305
6	1211.107	481.9538	42.97761	0	524.9315
7	1211.107	481.9548	42.9776	0	524.9324
8	1211.107	481.9556	42.97756	0	524.9332
9	1211.108	481.9565	42.97764	0	524.9341
10	1211.108	481.957	42.97758	0	524.9346
11	1211.108	481.9574	42.97761	0	524.935
12	1211.108	481.9575	42.97762	0	524.9351
13	1211.108	481.9574	42.97761	0	524.935
14	1211.108	481.957	42.97758	0	524.9346
15	1211.108	481.9565	42.97764	0	524.9341
16	1211.107	481.9556	42.97756	0	524.9332
17	1211.107	481.9548	42.9776	0	524.9324
18	1211.107	481.9538	42.97761	0	524.9315
19	1211.107	481.953	42.97754	0	524.9305
20	1211.107	481.9519	42.97755	0	524.9295
21	1211.107	481.9512	42.97748	0	524.9287
22	1211.107	481.9507	42.97754	0	524.9283
23	1211.107	481.9503	42.97752	0	524.9279
24	1211.107	481.9503	42.9775	0	524.9277
Total:	30277.68	12048.84	1074.439	0	13123.28

DAILY TOTAL IRRADIANCE FOR A CLEAR DAY Et = 47.24382 (MJ/m^2)
Extraterrestreal Radiation on a Horisontal: Ho = 48.74189 (MJ/m^2)
Clearence Index for a clear Day : Kt= .9692653
MEAN DAILY IRRADIANCE FOR A PARTLY CLOUDY DAY = 26.7163 (MJ/m^2)
Clearence Index for a Cloudy Day: Kt= .5481178
RELATIVE AIR MASS AT SUNSET: m = 15.11619
S.noon = 0, Ma= 28.96442 (g.), Hef 26.92669 (km.), W= 1.577837E-04, (2.604724E-04) (p cm)

MEAN DAILY IRRADIANCE FOR CLEAR AND PARTLY CLOUDY DAY (MJ/m^2)
Hbn1= 108.9996, Hb1= 43.37584, Hd1 3.867981, Hr1= 0, Ht1 47.24382
Hbn2 54.49982, Hb2= 21.68792, Hd2= 5.028375, Hr2= 0, Ht2= 26.7163

RECOMMENDED SLOPE for Dc 0: S(rec.)= 7.319746E-05 (degrees)
RECOMMENDED SLOPE for Dc= 12: S(rec) 7.050951E-05 (degrees)

CLEANNESS AND AN ISOTROPY INDEXES and DIFFUSE FRACTIONS

Clear Day Kt= .9692653, Ai= .889909, Z1 = 8.917362E-02, CI = 3.548617E-02, DI= 8.187273E-02
Cloud Day. Kt= .5481178 , Ai= .4449545, Z1 = .1783472, CI 7.097235E-02, DI= .1447798

Fig. 2: Simulation results of solar radiation components for 21 December at South Pole.

Results of simulations for hourly direct normal solar radiation, I_{bn}, for the North and South Poles for different dates are shown in Figs. 3 and 4.

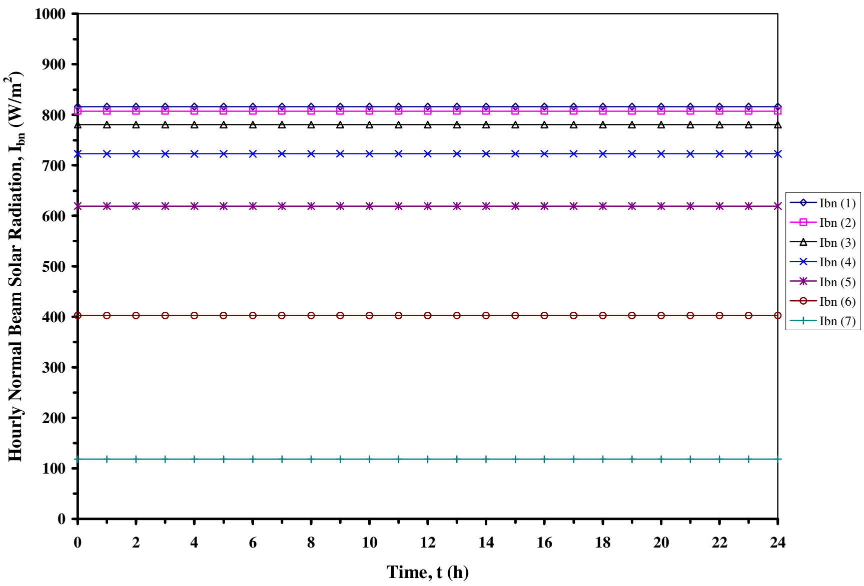


Fig. 3. Variation of hourly normal solar radiation with time for the North Pole for different dates. Meteorological parameters used in the simulations are: *T* = 0 °C, *RH* = 80 % and *V* = 23 km. Subscripts (1) to (7) denote 21 June, 6 July, 21 July, 6 August, 21 August, 6 September and 20 September, respectively.

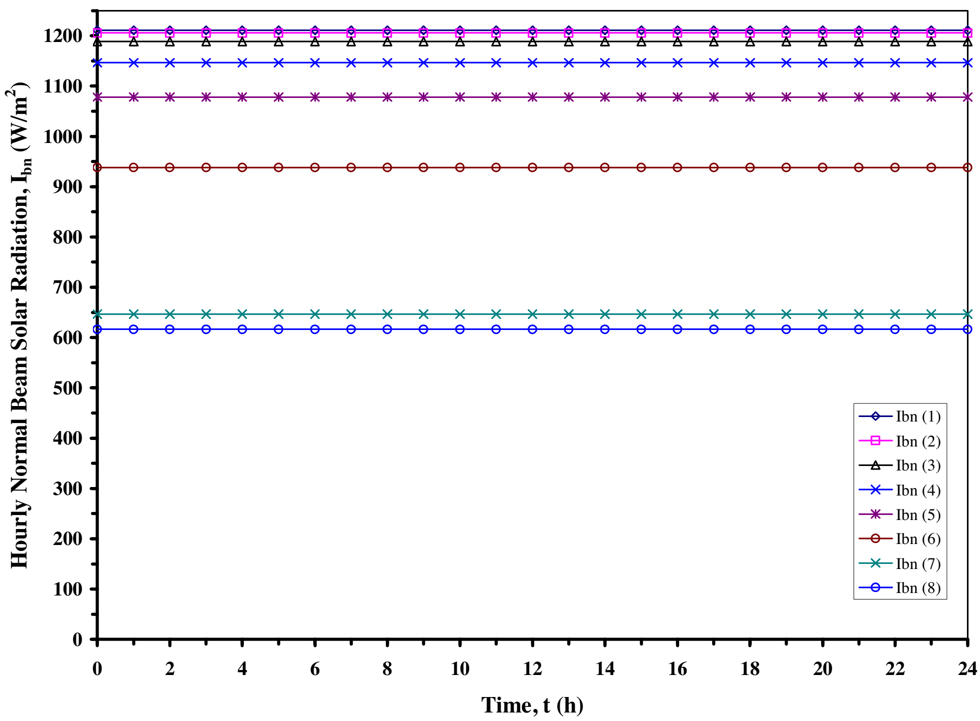


Fig. 4. Variation of hourly normal solar radiation with time for the South Pole for different dates. Meteorological parameters used in the simulations are: *T* = -10 °C, *RH* = 0.03 %, *V* = 115 km and *Sh* =12 h. Subscripts (1) to (8) denote 21 December, 7 January, 21 January, 7 February, 21 February, 7 March, 20 March and 21 March, respectively.

Results for simulation of hourly direct normal solar radiation on 21 June for different latitudes of the Northern Polar Zone are presented in Fig. 5. For all the simulations therein, it was assumed that ϕ=89.9999°, T = 0 °C, RH = 80 %, Sh = 12 h and thickness of the ozone layer is equal to the standard, 0.34 cm [8]. Analogous simulation results for different latitudes of the Southern Polar Zone on 21 December are presented in Fig. 6. For these, it was assumed that ϕ = -89.9999°, T = -10 °C, RH = 0.03 %, Sh = 12 h. Analysis of Figs. 3 and 4, and Figs. 5 and 6 reveals a big difference in the values of I_{bn} values for Northern and Southern Polar Zones. For example, I_{bn} for North Pole on 21 June at noon is equal to 818 W m^{-2}, while for South Pole on 21 December it is much higher and equal to 1211 W m^{-2}. The corresponding values of daily direct normal radiation, H_{bn}, are equal to 73.5 MJ m^{-2} and 109.0 MJ m^{-2}, and daily global radiation, H_g, are 36.0 MJ m^{-2} and 47.2 MJ m^{-2}, respectively. Such huge difference is explained in terms of geographical and meteorological conditions. For most of the area of the Northern Polar Zone, altitude (except for Greenland) can be considered to be equal to zero, while in the Southern Polar Zone altitude can be as high as 2800 m. Humidity in the summer time of the Northern Polar Zone usually is high while the Southern Polar Zone is regarded as "dry ice desert" and humidity there could be less than 1 %. The thickness of the ozone layer above the Northern Polar Zone is normal, while above the Southern Polar Zone it is considered to be depleted (i.e. "ozone hole"). Figs. 3 and 4 show that for any particular day (during summer times) solar altitude angle for North and South Poles remains constant, though with days, it changes within 0° to 23.45° range. Notwithstanding this fact, hourly and daily direct normal radiation values remain impressive. For North Pole I_{bn} is decreasing from 818 W m^{-2} (on 21 June) to 118 W m^{-2} on 20 September, while H_{bn} during this time is decreasing from 73.5 MJ m^{-2} to 10.6 MJ m^{-2}. And for the South Pole these figures are even more impressive: I_{bn} changes from 1211 W m^{-2} (on 21 December) to 646 W m^{-2} on 20 March, and the corresponding values of H_{bn} are 109 MJ m^{-2} and 58.2 MJ m^{-2}.

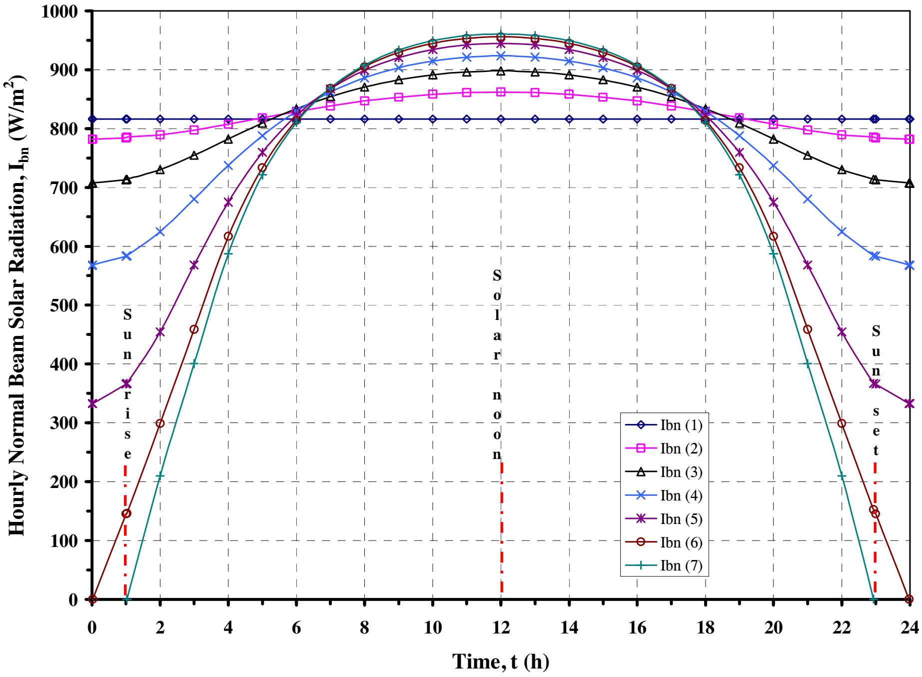


Fig. 5. **Variation of hourly normal beam solar radiation with time for the Northern Polar Zone on 21 June. Meteorological parameters used in the simulations are: *T* = 0 °C, *RH* = 80 % and *V* = 23 km. Subscripts (1) to (7) denote latitude ϕ = 89.9999°, 85°, 80°, 75°, 70°, 66.55° and 65°, respectively. Sunrise and sunset shown are for ϕ = 65°.**

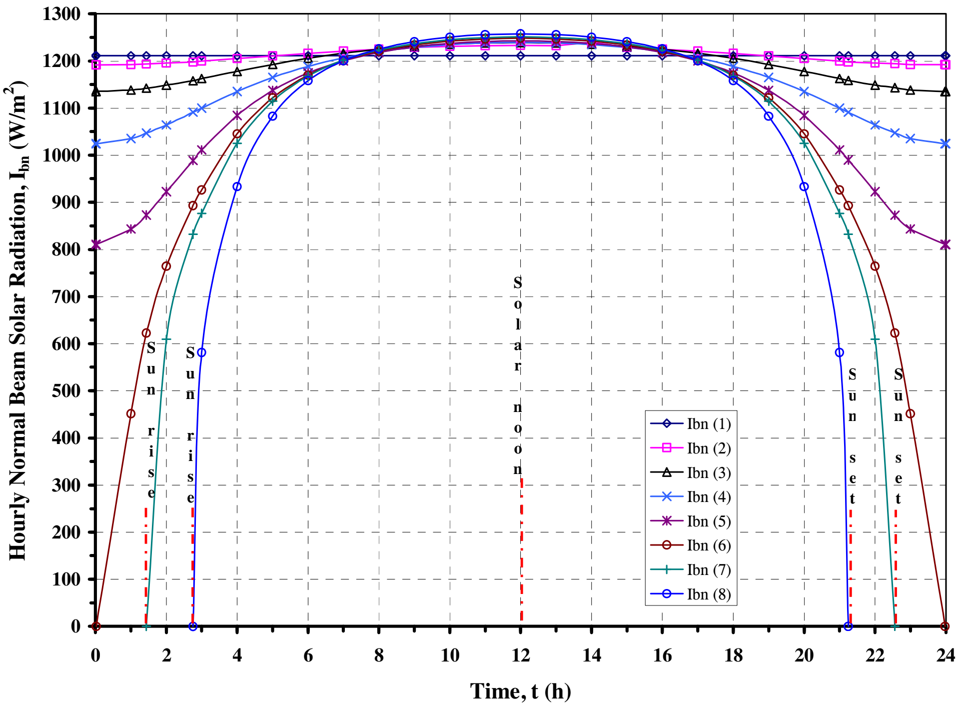
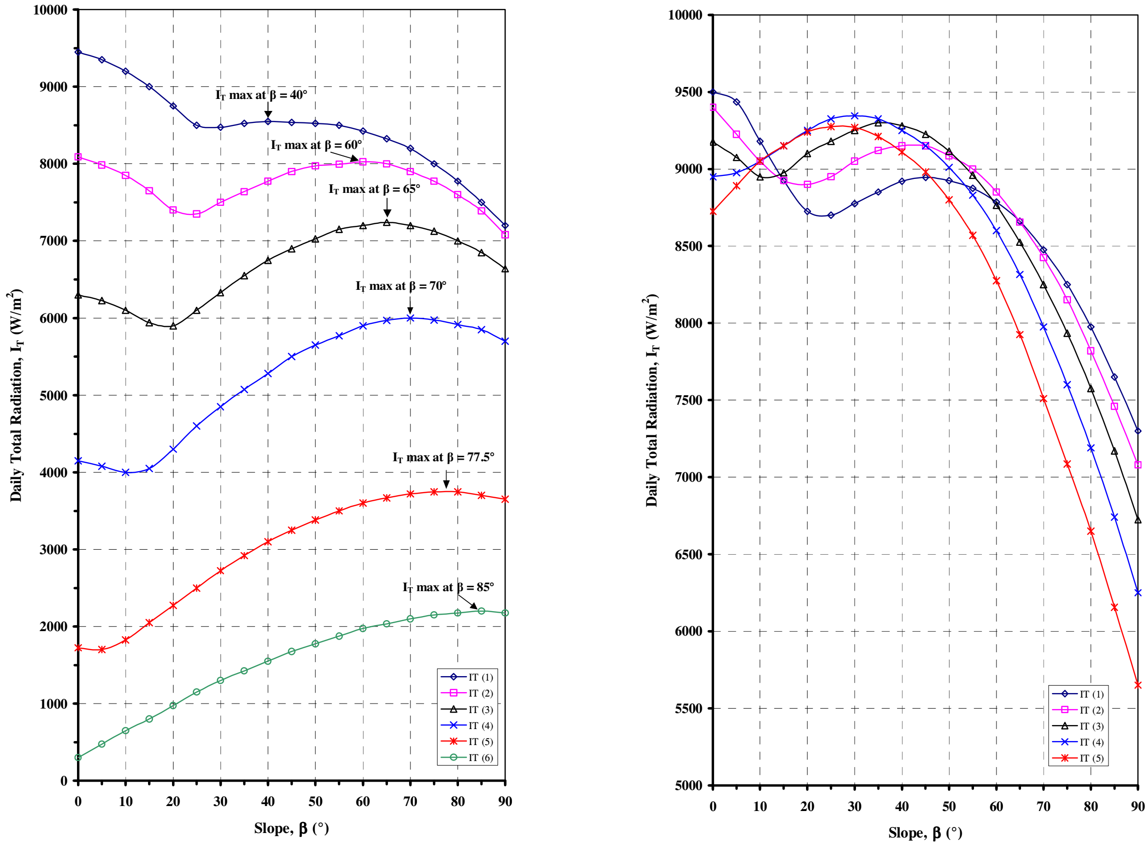


Fig. 6. **Variation of hourly normal beam solar radiation with time for the Southern Polar Zone on 21 December. Meteorological parameters used in the simulations are: *T* = -10 °C, *RH* = 0.03 %, *V* = 115 km and Sh = 12 h. Subscripts (1) to (8) denote latitude ϕ = -89.9999°, -85°, -80°, -75°, -70°, -66.55°, 65° and 60°, respectively. Sunrise and sunset shown are for ϕ = -65° and -60°.**

Such high values for I_{bn} and H_{bn} for the South Pole are attributed to high altitude (up to 2800 m), low humidity (less than 1 %) and high visibility because the atmosphere is free from aerosols and ozone layer. All these parameters reduce relative air mass of the atmosphere, e.g. at South Pole even for zenith angle $\theta_Z = 90^\circ$ (for half the Sun disc under the horizon) air mass is 15.12 while the same parameter for North Pole is 21.30. Figs. 5 and 6 also reveal very interesting facts. In the Northern Polar Zone on 21 June diurnal profile of instantaneous direct beam radiation is different for different latitudes. For the North Pole itself it is a straight line (I_{bn} remains constant), however for the rest of the latitudes the diurnal profiles are represented by complicated curves. On 21 June in the whole of the Northern Polar Zone there are no sunset and sunset. Only at the Northern Polar Circle ($\phi = 66.55^\circ$) the Sun's disc once in a day touches the horizon (sunset and at the same time sunrise moment). Due to specific diurnal profiles of instantaneous direct beam radiation, daily direct normal radiation, H_{bn}, do not differ very much for different latitudes: for $\phi = 90^\circ$, H_{bn} = 73.5 MJ m^{-2}; for $\phi = 85^\circ$, H_{bn} = 74.1 MJ m^{-2}; for $\phi = 80^\circ$, H_{bn} = 73.3 MJ m^{-2}; for $\phi = 75^\circ$, H_{bn} = 70.3 MJ m^{-2}; for $\phi = 70^\circ$, H_{bn} = 64.9 MJ m^{-2}; for $\phi = 66.55^\circ$ (Northern Polar Circle), H_{bn} = 58.8 MJ m^{-2}. If we move further away from the North Pole H_{bn} would be decreasing significantly, e.g. for $\phi = 65^\circ$, H_{bn} = 56.4 MJ m^{-2} and for $\phi = 0^\circ$ (at Equator), H_{bn} = 33.8 MJ m^{-2} (for Kisumu station, Kenya). For the Southern Polar Zone on 21 December the values of I_{bn} and H_{bn} are more striking: for $\phi = -90^\circ$, H_{bn} = 109.0 MJ m^{-2}; for $\phi = -85^\circ$, H_{bn} = 109.2 MJ m^{-2}; for $\phi = -80^\circ$, H_{bn} = 107.5 MJ m^{-2}; for $\phi = -75^\circ$, H_{bn} = 104.1 MJ m^{-2}; for $\phi = -70^\circ$, H_{bn} = 98.9 MJ m^{-2}; and for $\phi = -66.55^\circ$, H_{bn} = 89.4 MJ m^{-2}. All I_{bn} and H_{bn} values discussed above are for completely cloudless weather. Of cause, the values of H_{bn} with days are getting less and less until they would become zero at Polar Night. It has been shown by Nijegorodov et al. [9] that the duration of light time in the year is the same for all latitudes. For example, at the Equator ($\phi = 0^\circ$) every day has 12 light hours and 12 night hours, and for the Poles one half of a year has only light days and the next half has only night days. Hence, for the Equator and at the Poles the duration of light and night time in a year is the same, i.e. 365/2 days. And this is true for all latitudes. So it would be interesting to compare the amount of solar energy available at the Equator and the North and South Poles. Since the number of sunshine hours for the North and especially South Pole are not known (at least for the authors), we considered that all days at the Equator and at the Poles are completely cloudless. The results of the simulations are as follows. For the whole summer time (from 21 March to 21 September) at the North Pole the total direct normal beam radiation is equal to 10585 MJ m^{-2}, for the whole year at the Equator it is 13059 MJ m^{-2} and for the whole summer time (21 September to 21 March) at the South Pole the total direct beam radiation is 17885 MJ m^{-2}. The result is astonishing: solar radiation is much more available at the South Pole than at the Equator. The result would almost be the same for all latitudes during summer at the South Pole ($\phi = -90^\circ$). All the above discussion relates to direct normal radiation, which can be intercepted using tracking devices. However, total solar radiation on the absorber plate, which is fixed at constant angle of tilt, depend on the value of the slope. The dependence of the daily total beam radiation (in W m^{-2}) upon the slope at the North Pole, but for different dates is shown in Fig. 7(a). On 21 June, maximum daily total beam radiation would be intercepted at $\beta = 0^\circ$. For 21 July there are two maxima; at $\beta = 0^\circ$ and at $\beta = 60^\circ$. For the rest of the dates, optimum slope is shifted towards 90°. For example, on 6 September a collector installed at $\beta = 77.5^\circ$ (to the south) will intercept 3700 W m^{-2}, that is approximately two times more radiation than for the case when $\beta = 0^\circ$. The dependence of the total solar radiation upon the slope on 21 June at different latitudes for Northern Polar Zone is shown in Fig. 7(b). For latitudes $\phi = 90^\circ$, 85° or 80° it is better to use $\beta = 0^\circ$. For $\phi = 75^\circ$, $\beta = 35^\circ$; for $\phi = 70^\circ$, $\beta = 30^\circ$; and for $\phi = 65^\circ$, $\beta = 25^\circ$. The tendency in the dependence of total daily solar radiation upon the slope observed in Fig. 7 is applicable to the Southern Polar Zone; only the slopes would be negative (i.e. the collector should face north) and the values of daily total radiation are much higher.



(a) (b)

Fig. 7. Variation of daily total solar radiation with slope for: (a) the North Pole for different dates, where subscripts (1) to (6) denote 21 June, 21 July, 6 August, 21 August, 6 September and 20 September, respectively; (b) the Northern Polar Zone on 21 June, where subscripts (1) to (5) denote latitude ϕ = 85°, 80°, 75°, 70° and 65°, respectively. Meteorological parameters used in the simulations are: T = 0 °C, RH = 80 % and V = 23 km.

In reality the values of total solar radiation presented in Fig. 7 could be higher because in Polar Zones, ground albedo can be as high as 0.8 – 0.9, instead of the 0.2 used in the simulations. The simulations results showed that the thickness of ozone layer does not affect very much the total solar radiation on the horizontal surface, because O_3 absorbs only the ultraviolet component of solar radiation. The simulations for the South Pole (Fig. 2) were done for a case when O_3 layer is zero. If however, O_3 layer would be normal then the value of the mean daily total solar radiation, H_T, would decrease by 2.0 %. The effect of carbon dioxide is such that with the increase in CO_2 in the atmosphere, the amount of solar radiation absorbed by the air is increasing, while the amount of solar radiation reaching the surface of the Earth is decreasing. However, since the ground albedo at polar zones is high, most of the solar radiation reaching the Earth's surface is reflected into the air and a big part of it would escape to space. Hence, the increase in CO_2 in the atmosphere at polar zones would hardly cause serious climatic change. On the other hand pollution which can decrease the value of the ground albedo, is more critical because it can initiate the melting of glaciers.

3. Conclusion

The results of simulations of solar radiation components in the Northern and Southern Polar Zones allow concluding:

1. That the values of hourly and daily direct normal solar radiation depending on the number of sunshine hours, could be high in the Northern Zone and amazingly higher in the Southern Zone. Hourly direct beam normal radiation at the Northern Polar Zone could be up to I_{bn} = 950 W m^{-2} and daily value up to H_{bn} = 74.2 MJ m^{-2}. Corresponding values of direct beam radiation for the Southern Polar Zone are I_{bn} = 1248 W m^{-2} and H_{bn} = 109.2 MJ m^{-2}.
2. Utilisation of direct beam normal radiation requires tracking systems, which are not easy to maintain at remote areas, especially if it is for large scale use, that is why at Polar Zones it is better to use PV-arrays installed at constant optimum slope.
3. Optimum slopes in Polar Zones vary from $\beta = 0^\circ$ (for Poles) up to 90° (Northern Polar Zone) and -90° (Southern Polar Zone).
4. In future, utilisation of solar energy using PV-arrays, which would cover about 1 % of the Northern Polar Zone (say, some part of Greenland) and less than 1 % of the Southern Polar Zone, could partly ease mankind's electricity needs.

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