Modeling and Analysis of Diffuse Solar Radiation in Jazan, Kingdom of Saudi Arabia

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Abstract: ***This study presents an analysis of diffuse solar radiation and diffuse fraction over the Jazan region in Saudi Arabia using historical solar radiation and meteorological data collected from 1983 to 2005. The investigation explores the influence of atmospheric turbidity, cloud cover, humidity, and seasonal variations on diffuse radiation levels. Multiple regression models were applied to derive empirical correlations based on clearness index and sunshine duration. Results indicate pronounced seasonal differences, with higher diffuse fractions during summer months due to increased dust storms and turbidity. The findings have practical implications for optimizing solar energy systems, particularly in regions with similar climatic patterns.***

Keywords: Diffuse solar radiation, clearness index, atmospheric turbidity, solar energy modeling and Jazan climate

1. Introduction

Jazan (17°30′ N, 42°30′ E) is a region in southwestern Saudi Arabia with a mix of rural, coastal, and industrial areas. It often has relatively good air-quality indicators compared to some other regions. There are several significant local sources of air pollution that affect the region. Understanding these sources is vital for proposing effective mitigation strategies and protecting public health.

The major Sources of Air Pollution in Jazan are, open burning of municipal solid waste, which releases particulate matter (PM), carbonaceous aerosols, and likely other harmful gases. Also, industrial emissions from Jazan economic city, including a refinery and power-generation facilities typically contributes to air pollution through emissions of sulfur oxides (SO_2), nitrogen oxides (NO_x), particulate matter, and possibly heavy metals, depending on the processes.

A significant portion of air pollution, as reported by households, originates from dust and natural sources, resuspended soil, and wind-blown particles. Also, transportation (Traffic Emissions) contributes NO_x, CO, PM, and other emissions.

Therefore, this work studies how these pollution sources reduce solar radiation in Jazan’s atmosphere.

In a planetary scale, 17 % of solar radiation is absorbed by the atmosphere, 30% is reflected by the constituents of the atmosphere, and 53 % reaches the surface of the earth, 31% of it as direct solar radiation and 22 % as diffuse radiation. Diffuse solar radiation is that solar radiation received from the sun after its direction has been changed by reflection and scattering by the atmosphere. It has no fixed direction at any instant. It is scattered in all directions. Evidently a portion of this radiation reaches the surface of the earth. In addition to the absorption and diffusion of solar radiation by the usual constituents of the atmosphere, aerosol particles and water (liquid and solid) also absorb and cause diffusion of solar radiation quite significantly. Wider adoption of solar energy necessitates accurate and reliable data on solar radiation.

Diffuse fraction k_d is the ratio of diffuse solar radiation to total global solar radiation on a horizontal surface. It ranges from ~0 (very clear, mostly direct beam) to ~1 (very cloudy/all diffused). It depends on cloud conditions, atmospheric turbidity (dust/aerosols), and solar position.

Previous studies estimated diffuse solar radiation using the clearness index and sunshine duration S/S_0using Page and Collares method.

In this work, we study how diffuse fraction can be estimated for Jazan, Saudi Arabia.

2. Methodology

In this work, we use the monthly average values of global solar radiation (H), extraterrestrial solar radiation values (H_0), Diffuse (D) solar radiation, sunshine hours (S), maximum possible hours (S_0) and clearness index (Kt) during the period (1983-2005) for Jazan.

The clearness index (Kt) is defined as follows:

$$Kt = H / H_0 \quad (1)$$

Correlations to which the measured data are fitted are:

$$D / G = a + b (Kt) \quad (2)$$
$$D / G = a + b (Kt) + c (Kt^2) \quad (3)$$
$$D / G_0 = a + b (Kt) \quad (4)$$
$$D / G_0 = a + b (Kt) + c (Kt^2) \quad (5)$$
$$D / G = a + b (S/S_0) \quad (6)$$
$$D / G= a + b (S/S_0) + c (S/S_0)^2 \quad (7)$$
$$D / G_0 = a + b (S/So) \quad (8)$$
$$D / G_0 = a + b (S/S_0) + c (S/S_0)^2 \quad (9)$$
$$D / G = a + b (P) \quad (10)$$
$$D / G = a + b (T) \quad (11)$$
$$D / G = a + b (RH) \quad (12)$$
$$D / G = a + b (Cl) \quad (13)$$
$$D / G = a + b (WS) \quad (14)$$

Where, a, b and c are empirical constants, while P is the atmospheric pressure, T is the ambient temperature, RH is the relative humidity, while Cl is the cloudy cover. The measured data for Jazan are used in linear and multiple linear regression analysis to obtain correlations between Jazan data. The correlations obtained are then used to estimate diffuse solar radiation (D) for Jazan. Calculated values of D are then compared with the measured data.

The accuracy of estimation of D is tested by calculating the mean bias error (MBE), root mean square error (RMSE) and the mean percentage error (MPE). Generally, low values of RMSE and MPE are desirable. Positive MBE shows over estimation while negative MBE indicates under estimation. The MBE, RMSE and MPE are defined as in the following equations:

$$MBE = \left[\sum\left(D_{di,c} - D_{di,m}\right)/n\right] \quad (15)$$

$$RMSE = \left\{\left[\sum\left(D_{di,c} - D_{di,m}\right)^2/n\right]\right\}^{\frac{1}{2}} \quad (16)$$

$$MPE = \left[\sum\left(\frac{D_{di,m} - D_{di,c}}{D_{di,m}} \times 100\right)\right]/n \quad (17)$$

Where $D_{di;c}$ and $D_{di;m}$ are the calculated and measured values of D and n is the number of observations.

3. Results and Discussions

Long-term monthly-average values of global (G) and diffuse (D) solar radiation were analyzed for Jazan over 1983–2005, combining measured radiation components with derived clearness index and turbidity parameters.

Fig 1 shows the monthly average values of global and diffuse radiation for Jazan, where, the global solar radiation ranged between (7.78-5.01 kWh m^{-2} day^{-1}). Also, the diffuse solar radiation ranged between (2.06- 1.08 kWh m^{-2} day^{-1}), where maximum values were observed in July, and minimum values occurred during the winter months for both components.

Clearness index (Kt) average values about 0.63, highest in winter/spring and lowest in summer due to dust storms effect. This data confirms that Jazan experiences strong seasonal radiation variability, with high summer insolation but also higher atmospheric turbidity at that time see Fig 2. Also, the meteorological parameters monthly average values are shown in Fig 3.

Therefore, correlations between the values of D/G and D/G_0 against Kt, and S/S_0 besides some meteorological parameters such as P, T, RH%, Cl and WS has been done for jazan, using first and second order correlation table 2.

After that calculating the diffuse fraction has been done from the correlation equations where a good agreement between the measured and calculated valued as illustrated in Figure 3.

An important factor influencing the values of Kd in jazan, Linke turbidity values, which range from (2.7 in winter to 5.7 in summer), Also the Ångström turbidity coefficient which has values ranges between (0.204 in summer to 0.123 in winter). These values classify the Jazan atmosphere as more turbid during summer, largely due to dust-storm activity. Higher turbidity increases scattering, which enhances the diffuse portion of solar radiation, explaining seasonal changes in Kd.

The good correlation between meteorological parameters against Kd comes from the high relative humidity and cloud cover in winter which reduce global radiation through increased scattering and absorption. Global radiation correlates directly with air temperature but inversely with relative humidity and cloudiness. These relationships emphasize the importance of atmospheric transparency in determining diffuse fractions.

Overall, the diffuse fraction in Jazan is moderate, consistent with its humid-coastal climate and seasonal dust effects. The atmosphere is clearer for most of the year (relatively low K_d), but summer dust increases diffuse radiation noticeably, raising K_d values. This seasonal pattern matches regional analyses showing diffuse fraction modulated by clouds and aerosol dust loading over Saudi Arabia.

Table 2: Regression constants of Eqs. (2) to (14) corresponding values of R^2, RMSE, MBE and MPE

Correlations	Degree of correlations	a	b	c	MBE	RMSE	MPE (%)	R²
D/G & Kt	First	0.275	-0.0043	-	-0.002	0.014	-0.991	0.652
	Second	0.242	0.0099	0.0011	-0.003	0.009	-0.871	0.760
D/Go & Kt	First	0.178	-0.002	-	-0.002	0.002	-0.923	0.574
	Second	0.146	0.0116	0.0013	-0.001	0.013	-1.003	0.840
D/G & n/N	First	1.232	-1.265	-	0.003	0.011	-0.92	0.792
	Second	0.216	1.217	-0.362	0.002	0.007	-0.04	0.883
D/Go & n/N	First	0.932	-2.341	-	-0.004	0.003	-0.012	0.745
	Second	2.123	0.9821	-0.873	0.003	0.015	-0.009	0.873
D/G & P	First	0.198	-0.0012	-	0.003	0.018	-0.453	0.511
	Second	0.211	0.0018	-0.0098	-0.004	0.009	-0.678	0.723
D/G & T	First	0.275	-0.0043	-	-0.005	0.012	-0.340	0.752
	Second	0.242	0.0099	-0.0011	-0.001	0.014	-0.033	0.860
D/G & RH%	First	0.231	-0.0023	-	-0.001	0.016	-0.865	0.475
	Second	0.342	0.0078	-0.0045	0.002	0.001	-0.954	0.698
D/G & Cl	First	0.112	-0.011	-	-0.001	0.003	-1.10	0.621
	Second	0.114	0.0231	-0.021	-0.002	0.005	-0.078	0.782
D/G & WS	First	0.156	-0.0053	-	-0.005	0.018	-1.011	0.567
	Second	0.132	0.0067	-0.0025	-0.003	0.009	-0.996	0.756

4. Conclusions

Understanding Kd variability is important because diffuse fraction affects solar-system performance (e.g., PV orientation, tilted-surface radiation modeling).

Jazan shows strong solar resource potential but with seasonal diffuse fraction variability shaped by dust, humidity, and cloud cover.

Higher diffuse fractions occur during less clear skies, typically during wetter months or when relative humidity/cloud cover increases.

Lower diffuse fractions indicate clearer conditions and dominate in dry summer months.

In general, all models show the same qualitative seasonal trend, but quantitative differences matter for precise energy system design.

Broader Saudi solar resource studies show that southern cities like Jazan tend to have somewhat higher diffuse fractions average reported in one regional assessment compared with northern areas due to increased humidity and atmospheric scattering near the Red Sea. This highlights that diffuse radiation significantly contributes to total solar energy in Jazan region, which is important for PV system design (where diffuse energy still contributes to power output).

Empirical models approximate measured values reasonably but must be chosen based on available data and desired accuracy.

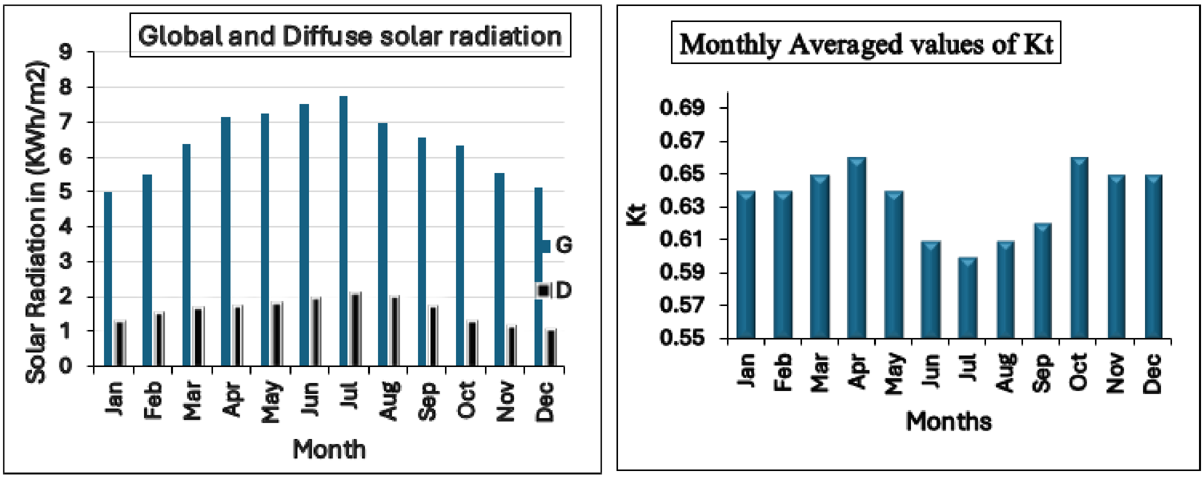

Figure 1: Monthly means values of global, direct and diffuse solar radiation and clearness index.

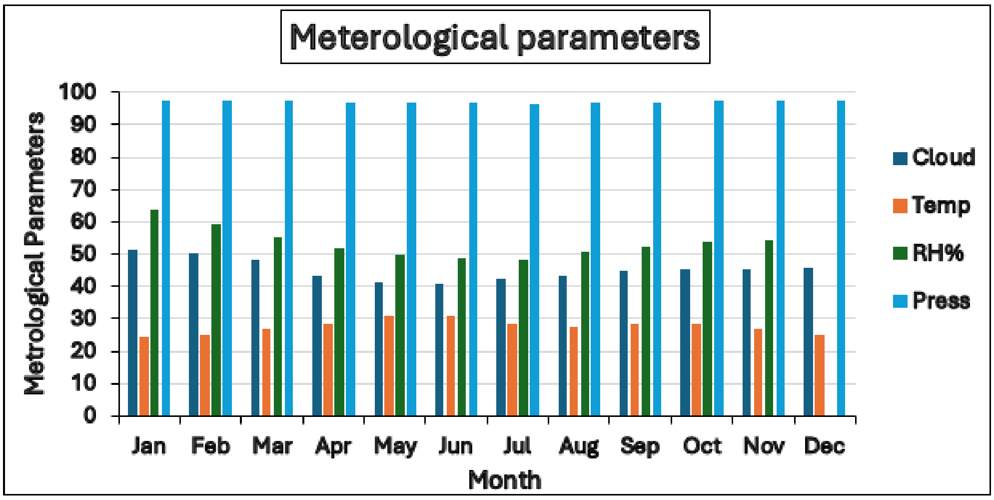

Figure 2: Monthly mean values of Meteorological parameters.

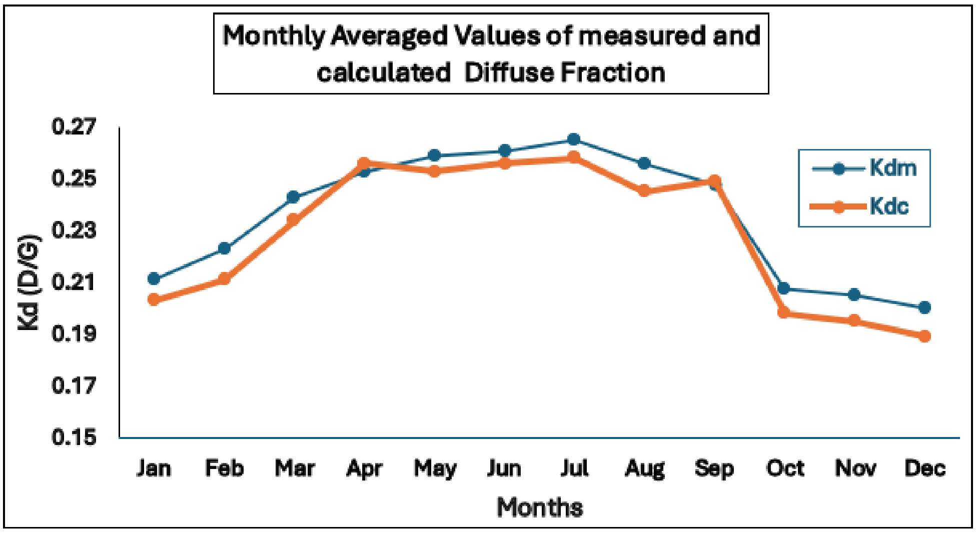

Figure 3: Comparisons between measured and calculated Kd values.

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