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*Review Article*

# Solar Radiation: Models and Measurement Techniques

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In order to grasp the significance of the work accomplished by the author, it is necessary to keep abreast of the present developments in this field. The research work reported in the paper is an attempt to get knowledge to assess the solar energy potential for practical and efficient utilization in India. Our work is centered on estimating realistic values of solar (global and diffuse) radiation on horizontal and tilted surfaces using measured meteorological data and geographical and geometrical parameters for India.

## 1. Introduction

The sun is the driving force for all atmospheric processes. Solar radiant intensity is the expression of that input of energy upon the planet. Therefore, the ability to understand and quantify its value and distribution accurately is important in the initial understanding and modeling of any other thermodynamic or dynamic process in the earth-ocean-atmosphere system. Unfortunately, however, too little is known about the spatial and temporal distribution of incoming solar radiation. A more complete and precise description of that distribution will prove usefulness to many fields of study that rely on atmospheric energy input, such as agricultural [1], architectural [2], and engineering [3] planning. For these reasons, analysis of the solar radiation distribution in India—a state with a relatively high loading of input radiation and relatively high spatial and temporal variability—is both important and relevant.

## 2. Renewable Energy

From the beginning of 19th century, dwelling of fossil fuels is increasing continually toward the development of industrialization and modern life style. The fossil fuels are being used from domestic to industrial applications on the cost of pollution, health hazards, and ecology of earth. Excessive exploitation of conventional fuels directly and indirectly assist in global warming and many more factors which drive the planet towards dark future.

To overcome the dependency on conventional fuels, researchers and many organizations are working on alternative fuels, which should be commercially viable, easy to use, less pollutant, and must be abundant in nature. In this direction, renewable energies, like solar energy, tidal energy, wind energy, biofuels, and so forth, are more suitable than conventional sources of energy. These nonconventional forms are not only renewable but also maintain ecology and environment as they are ecofriendly and do not contribute to global warming and production of green house gases and so forth.

In context of India and developing countries, it is awful condition, because most of the Indian families exploit forest and fossil fuels for their domestic uses, which directly and indirectly not only affect growth of country but also health of user. Quest for energy security and sustainable development depend on the ability to get energy from renewable sources, and to use it optimistically to meet growing and diverse needs of India.

India is blessed with an abundance of nondepleting and environment friendly renewable energy resources such as solar, wind, biomass and hydro, and so forth. The Uttar-Pradesh, where solar energy and wind energy are profusely available throughout the year in comparison to the rest of India, has higher potential to exploit renewable energies for domestic and industrial applications.

## 3. Need for Renewable Energy

Increasing rate of energy consumption is essential for progress of our civilization and therefore main problem is how we produce energy. Extensive use of fossil fuels and nuclear energy has created bad impact on environmental, social, and sustainability problems. So we need such energy sources that will forever and can be used without pollution. Furthermore, conventional energy systems using fossil resources, especially old ones in numerous and small scale, are found to be major contributors to atmosphere pollution and greenhouse effect. In this sense the earth is already showing many signs of worldwide climate change (http://www.geosunnrg.com/) as follows.

(i) Average temperatures have climbed 1.4 degrees Fahrenheit (0.8 degree Celsius) around the world since 1880, much of this in recent decades, according to NASA's Goddard Institute for Space Studies.

(ii) The rate of warming is increasing. According to a number of climate studies, the last two decades of 20th century were the hottest in 400 years and possibly the warmest for several millennia. The UN'S Intergovernmental Panel on Climate Change (IPCC) reports that 11 of the past 12 years are among the dozen warmest since 1850.

(iii) The Arctic is feeling atmosphere pollution and greenhouse effect the most. Average temperatures in Alaska, western Canada, and eastern Russia have risen twice the global average, according to the multinational Arctic Climate Impact Assessment report compiled between 2000 and 2004.

(iv) Arctic ice is rapidly disappearing, and the region may have its first completely ice-free summer by 2040 or earlier. Polar bears and indigenous cultures are already suffering from the sea-ice loss.

(v) Glaciers and mountain snows are rapidly melting; for example, Montana's Glacier National Park now has only 27 glaciers versus 150 in 1910. In the Northern Hemisphere, thaws also come a week earlier in spring and freezes begin a week later.

(vi) Coral reefs, which are highly sensitive to small changes in water temperature, suffered the worst bleaching—or die off in response to stress—ever recorded in 1998, with some areas seeing bleach rates of 70 percent. Experts expect these sorts of events to increase in frequency and intensity in the next 50 years as sea temperatures rise.

(vii) The IPPC, in a 2007 report, claims that humans are "very likely" behind global warming. The report, based on the work of some 2,500 scientists in more than 130 countries, concluded that humans have caused all or most of the current planetary warming. Human-caused global warming is often called anthropogenic climate change.

(viii) Industrialization, deforestation, and pollution have greatly increased atmospheric concentrations of water vapor, carbon dioxide, methane, and nitrous oxide, all greenhouse gases that help to trap heat near Earth's surface.

(ix) Humans are pouring carbon dioxide into the atmosphere much faster rate than absorbing rate of plants and oceans.

(x) These gases persist in the atmosphere for years, meaning that even if such emissions were eliminated today, it would not immediately stop the global warming.

(xi) Some experts point out that the natural cycles in Earth's orbit can alter the planet's exposure to sunlight, which may explain the current trend. Earth has indeed experienced warming and cooling cycles roughly every hundred thousand years due to these orbital shifts, but such changes have occurred over the span of several centuries. Today's changes have taken place over the past 100 years or less.

## 4. Renewable Energy Future

Clearly, human kind has to set a different course in its need for energy, one that involves less intrusive sources such as solar, wind, and geothermal energy. There are energy sources that do not harm the planet and will never run out. The clock is ticking down but there is still time. Humankind has proven to be resourceful and prudent in the past. It needs to be again in the crucial areas of energy and the environment in order to assure sustainability for future generations (http://www.geosunnrg.com/).

## 5. Renewable Energy in India

India in 2006 had a population of 1.1 billion with a Gross Domestic Product of Rupees 33 trillion (728 billion US$) (http://indiabudget.nic.in/es2006-07/esmain.htm; 2006-2007). A breakup of India's primary commercial energy shows that more than 80% is supplied from fossil fuels. If we also consider traditional fuels and biomass, India's total primary energy consumption was about 20 EJ in 2004-2005 (an average of 18 GJ/capita/year). Figure 1 shows the share of different kind of energy sources in total India's primary energy supply (Government of India, Planning Commission; 2006). Fossil fuels account for about 64% of the total primary energy while traditional biomass accounts for about 33%. The India's population accounts for 17% of the world's total population; however, energy consumption is only 4% of the total world's primary energy consumption. The modern renewable energy accounts for only small portion of the total energy mix. India is the only country in the world that has a separate Ministry of New and Renewable Energy (MNRE), earlier known as the Ministry of Non-Conventional Energy Sources.

In view of the scarce fossil fuel reserves, energy security, and climate change concerns, it is expected that renewable energy will play a significant role in India's future energy mix. Figure 2 provides an overview of the different renewable energy sources. Renewable energy can be used for the entire spectrum of end-uses as given in Figure 3 [4].

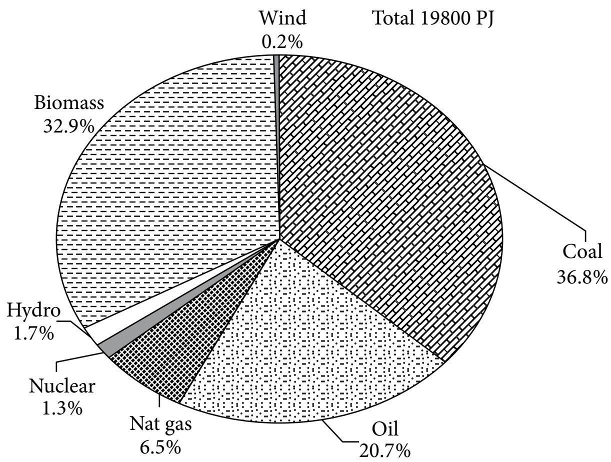


Figure 1: Primary energy production in India.

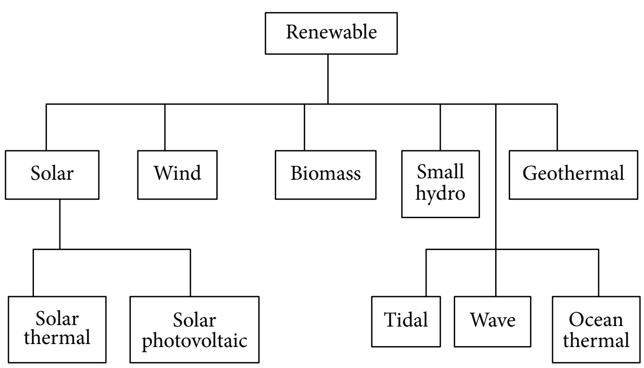


Figure 2: Schematic of renewable energy options.

## 6. Modeling Techniques

In the literature, there exist several methods for modeling solar radiation components (global, beam, and diffuse) on the ground of parametric models and decomposition models. Parametric models like Iqbal, Gueymard and ASHRAE models [5–7], require detailed information of atmospheric conditions. Meteorological parameters frequently used as predictors include the type, amount, and distribution of clouds or other observations, such as the fractional sunshine, atmospheric turbidity, and perceptible water content [8]. On other hand, decomposition models usually use information only on global radiation to predict the beam and sky components. These relationships are usually expressed in terms of the irradiations which are the time integrals of the radiant flux or irradiance. Decomposition models which are based on the correlations between the clearness index $k_t$ (it is the ratio of global to the extraterrestrial solar radiation) and the diffuse fraction $k_d$ (it is the ratio of diffuse to the global solar radiation), diffuse coefficient $k_D$ (it is the ratio of diffuse to the extraterrestrial solar radiation) or the direct transmittance $k_b$ (it is the ratio of beam to the extraterrestrial solar radiation) as an example Orgill and Hollands, Erbs et al., Reindle et al. and Liu and Jordan models [9–12] developed to estimate direct and diffuse radiations from global radiation. Instead

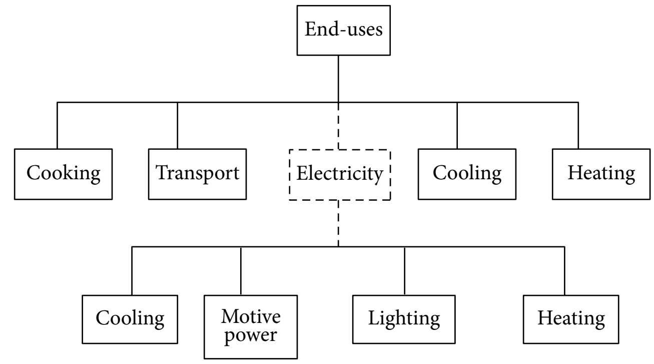


Figure 3: Energy end.

of these two methods nowadays empirically method [13–15] and the artificial neural network method (which constitutes a widely accepted novel approach offering an alternative way to synthesize complex problems) can also be used for the determination of global and diffuse components of solar radiation [16, 17].

## 7. Measurement Techniques of Radiation

To asses the availability of solar radiation at different locations, measurements of global radiation, diffuse radiation, beam radiation, sun shine hours, bright sun shine hours, maximum and minimum temperature, humidity, pressure, visibility, wind speed and direction, gust speed, water precipitation, and air mass are very important parameters.

To measure the abovementioned parameters we require a big laboratory and group of skilled fellows. Although it is a difficult task to maintain and run such a laboratory but the quality and reliability of data of the site then can only be ensured. However there is a wide network of Indian meteorological department which provides wide variety of data that includes radiation and meteorological and pollution data. But the radiation data are scared. World Radiation Centre also provides data of global, beam, and diffuse radiation of cities of the world.

The direct measurement of solar radiation and its components (direct and diffuse) is done in two basic ways as well. The values are measured either by using ground-based instrumentation as pyranometers, or remotely with satellites. These methods are often used in combination to validate one another [18–20]. In general, pyranometer data from adequately maintained instruments provide an accurate description of the solar radiation values in the immediate area. It has been suggested that extrapolation of daily values beyond the discrete point represented by the location of the pyranometer can result in the misrepresentation of the extrapolated areas. Suckling [21] found that, for areas in the Tennessee Valley Authority region, permissible extrapolation distances of daily solar radiation values were ~200 km, but that these distances may vary by season. However, Younes and Muneer [22] claimed that "...for a given location that is, farther than 50 km from the measurement station the use of the respective measurement station's data is obsolete in the assessment of solar energy applications." In his study of solar radiation variability in San Diego County, California, Aguado [23] suggested that the relative proximity of two points to the coast further complicates the abilities of researchers to extrapolate beyond the discrete points at which solar radiation was measured.

Global and diffuse solar radiation can be measured with the help of a thermoelectric pyranometer. Basically pyranometer is consisting of a thin-blackened surface supported inside a relatively massive well-polished case. When solar radiation falls on this surface, the temperature of the surface rises until its rate of loss of the heat by all causes is equal to the rate of gain of heat by radiation. This rise in temperature sets up a thermal e.m.f. which is measured on a recording millivoltmeter or recorder. Each pyranometer is calibrated and a certificate is provided by the manufacturer. For quality data of solar radiation pyranometer have to be calibrated at regular intervals and required proper maintenance.

Instrument used for measuring the intensity of direct solar radiation, that is, beam radiation is called pyrheliometer. The Ångström compensation pyrheliometer is a standard instrument for the measurement of direct solar radiation, in which the sensor is fixed at the lower end of a tube provided with a diaphragm so that when the tube is directed towards the sun, the sensing surface is normal to the line joining the sun to the receiver, and only radiation from the sun and a narrow annulus of the sky is received by the sensor. The alignment is done by means of a sighting device called the diopter.

In pyrheliometer the absorption of the radiant energy by a blackened metal strip, exposed to the sun's ray, is determined by measuring the electric current necessary to heat an identical shielded strip to the same temperature. Since both strips are mounted similarly and are at the same temperature and the heat exchange of the strips with surroundings is identical, the rate of generation of heats in shielded strip due to electric current is equal to the rate of absorption of radiant energy by the exposed strip. The equivalence or otherwise of the temperature of the two strips is determined by two fine thermocouples attached to the back of the strips, connected in series with a sensitive galvanometer. The current through the shielded strip is determined with an accurate digital milliammeter. The advantage of the instrument is that the equilibrium current through the shielded strip is not affected by change in the rate of heat loss from the strips, provided that the changes affect both the strips equally.

Such an instrument in theory is an absolute instrument as all the relevant factors required for the calculation of the radiation intensity can be measured:

let $I$ = the intensity of direct solar radiation in watts/cm$^2$

$A$ = area of the strip

$\alpha$ = absorption of the strip

$i$ = heating current in amperes.

Then we have $I \cdot A \cdot \alpha = R \cdot i^2$

$$I = (R \cdot i^2)/(A \cdot \propto) = K \cdot i^2 \text{ watts/cm}^2,$$

where $K = R/(A \cdot \propto)$ is a constant for the instrument and depends upon resistance, length, breath, and absorptance of the strip. The constant of the instrument is actually determined by comparison with other standard instrument with constant traceable to the group of standards maintained at the World Radiation Centre in Switzerland.

For a study of the intensity of solar radiation in different regions, Scott glass filter OG1, RG2, and RG8 are used. The transmission of the filters is given below:

OG1 transmits from 0.525 $\mu$ to 2.800 $\mu$

RG2 transmits from 0.630 $\mu$ to 2.800 $\mu$

RG8 transmits from 0.700 $\mu$ to 2.800 $\mu$.

## 8. Estimation of Radiation

It is generally accepted that models for solar radiation prediction are necessary, because in most cases the density and number of solar radiation measuring stations cannot describe the necessary variability [24]. It is then understandable that new models and improvements to existing modeling techniques are continually proposed which intend to improve estimates of solar radiation values with the use of more readily available meteorological variables [22, 25, 26].

*8.1. Estimation of Solar Radiation on Horizontal Surface.* Ångström [27] proposed first theoretical model for estimating global solar radiation based on sunshine duration. Page [28] and Prescott [29] reconsidered this model in order to make it possible to calculate monthly average of the daily global radiation $\overline{H}$ (MJ/m$^2$ day) on a horizontal surface from monthly average daily total insolation on an extraterrestrial horizontal surface as per the following relation:

$$\frac{\overline{H}}{\overline{H}_0} = a + b\left(\frac{\overline{s}}{\overline{s}_0}\right), \quad (1)$$

where $\overline{H}_0$ is the monthly average daily extraterrestrial radiation (MJ/m$^2$ day), $\overline{s}$ is the monthly average daily bright sunshine hours, $\overline{s}_0$ is the maximum possible monthly average daily sunshine hours or the day length, and $a$ and $b$ are constants.

Although a number of correlations included more parameters and have been developed by different workers [12, 30–32], one has been found to be very convenient, applicable to a large number of locations, and is the most widely used correlation [15, 33–37].

Solar radiation coming through the atmosphere is partially absorbed or reflected by its constituents (aerosol particles cause diffuse radiation) which actually reduces the beam component and affects the performance of energy systems. Therefore, knowledge of diffuse irradiation on a horizontal surface is also important in designing the various energy utilization systems. Many researchers have presented empirical correlations to estimate daily diffuse radiation. Two of the most widely used correlations are due to Liu and Jordan [12] and Page [28] to which the irradiation data fitted are given as

$$\frac{H_d}{H} = a + b\left(\frac{H}{H_0}\right), \quad (2)$$

where $H_d$ is daily mean diffuse radiation and $H/H_0 = K_t$, the clearness index.

A third type approach has been proposed by Iqbal [38] to find a correlation between $H_d$ and the ratio of bright sunshine ($S$) to the day length ($S_0$) given as

$$\frac{H_d}{H} = c + d\left(\frac{S}{S_0}\right), \tag{3}$$

where $c$ and $d$ are the constants.

Gopinathan [30] used the above models, estimated the radiation, and suggested that the applicability of the correlations to locations in various parts of the word is to be tested. Therefore, an extensive work has to be done in this area [25, 39–41]. Recently some others researchers [13, 14, 42–51] have also reported new developments in solar energy.

Orgill and Holland [9], Erbs et al. [10], and Collars-Pareira and Rabl [31] have all related the diffuse fraction of global radiation to an index of the atmospheric clarity on hourly basis. Elminir [47] examined the correlations of Orgill and Hollands [9] and Erbs et al. [10] and recommended then later for computing hourly diffuse fraction. Ahmad and Tiwari [52] presented modified version of ASHRAE [7] model for New Delhi station. Katiyar [53], Gueymard [54], Jacovides et al. [55], Katiyar et al. 2010 [36, 37], and Chen et al. [56] have also reported new developments in solar energy, which could be used to estimate long-term global, direct, and diffuse radiation.

*8.2. Estimation of Solar Radiation on Tilted Surfaces.* Most of the solar energy systems of interest redesigned with tilted collected surfaces. Therefore, it is necessary to have knowledge about the availability of solar radiation on tilted surfaces.

The total amount of radiation incident on an inclined plane ($H_t$) is composed of beam ($H_b$), sky-diffuse ($H_s$), and ground reflected ($H_r$) components:

$$H_t = H_b + H_s + H_r. \tag{4}$$

The daily beam radiation received on the tilted surface can be expressed as

$$H_b = (H - H_d)\, r_b. \tag{5}$$

Under isotropic conditions, the global radiation on inclined surface can be written as

$$\begin{aligned} H_t = {} & (H - H_d)\, r_b + \frac{1}{2} H_d (1 + \cos\beta) \\ & + \frac{1}{2} H\rho (1 - \cos\beta), \end{aligned} \tag{6}$$

where $\rho$ is the ground albedo, $\beta$ is the surface slope from the horizontal (degree), and $H$ and $H_d$ are monthly mean daily total and diffuse radiation on horizontal surface, respectively.

The estimation of solar radiation on tilted surfaces has been made by different authors. Recently, Mefti et al. [57] gave the hourly solar radiation model for inclined surfaces using sunshine duration data. An extensive work has to done in this area [13, 14, 58–63].

## 9. Present Trends in Correlation

Ångström-Prescott correlation has served as a basic approach to estimate global radiation for long time. Simplicity of Ångström-Prescott equation has dominated over its several demerits. Coefficients in Ångström-Prescott equation are site dependent. Yeboah-Amankwah and Agyeman [64] believed that "$a_1$" and "$b_1$" are time dependent and so developed a differential Ångström model with a set of coefficients which vary with time. Sahin and Sen [65] proposed a method to dynamically estimate the coefficients. These works do not include radiation damping process when solar rays pass through the atmosphere. Some researchers [66, 67] are employing a damping structure to calculate global solar radiation in clear sky. Their models consider physical process in detail, so the effect of latitude, elevation, and other factors are taken into account automatically. However damping spectrums are very irregular and hence numerical integration is indispensable. To overcome all these difficulties Yang et al. [68] proposed a "Hybrid model" which considers the physical process but still maintains the simplicity of the Ångström equation. The author tested their hybrid model with data of Japan and found that it needs greater turbidity when applied to urban areas due to air pollution; otherwise, global radiation may be estimated. Also, the estimation under completely cloudy sky is still difficult. Hybrid model assumed that global radiation has linear relationship with effective beam radiation and diffuse radiation as well as fractional sunshine time. Yang and Koike [69] also proposed a model to calculate solar radiation from upper air humidity. This could be used to predict numerical weather prediction (NWP).

Lingamgunta and Veziroglu [70] proposed a universal relationship for estimating clear sky insolation. This relation predicts annual mean daily clear sky insolation and is a function of latitude and altitude only. The author claimed that relation (the author called it as Lingamgunta-Veziroglu relation) predicts radiation that fairly accurate over conventional methods.

Suehrcke [71] proposed an entirely new relation between relative sunshine duration and global radiation. This relation, unlikely Ångström-Prescott equation, is nonlinear and it does not require any empirical constants. The local atmospheric conditions are considered through the value of the average daily clear index. Further fractional sunshine can be calculated from Suehrcke relation, and Suehrcke's sunshine radiation relationship has been verified by Driesse and Thevenard [72] using a global data sheet.

Recently there have been emphases [73–76] on empirical correlation using satellite images. Most estimation of daily global radiation values from satellite images requires the useof models which allow us to calculate these values from a small number of images per day (usually three). Different methodologies have been developed in this regard.

Atmospheric pollutants and aerosols absorb and scatter shortwave solar radiations. The interactions have resultant impacts on atmospheric radiative energy transfer and balance. If the pollution increases, then diffuse component of global solar radiation will also increase. Spectral and diffuse radiation study of global solar radiation has now gained importance as reflected in recent literature [77–79]. There has been another area of modeling gaining importance which is estimation of solar radiation potential using artificial neural network [16, 60, 80–82].

## 10. Conclusion

This paper presents a brief account of the general introduction, principle, experimental technique, measurements of solar radiation data, and review of literature of solar radiation models and describes present trend of solar energy modeling which is of major interest to solar energy engineers, architects, designing building, and thermal devices for optimum and efficient utilization of this nonconventional energy resource.

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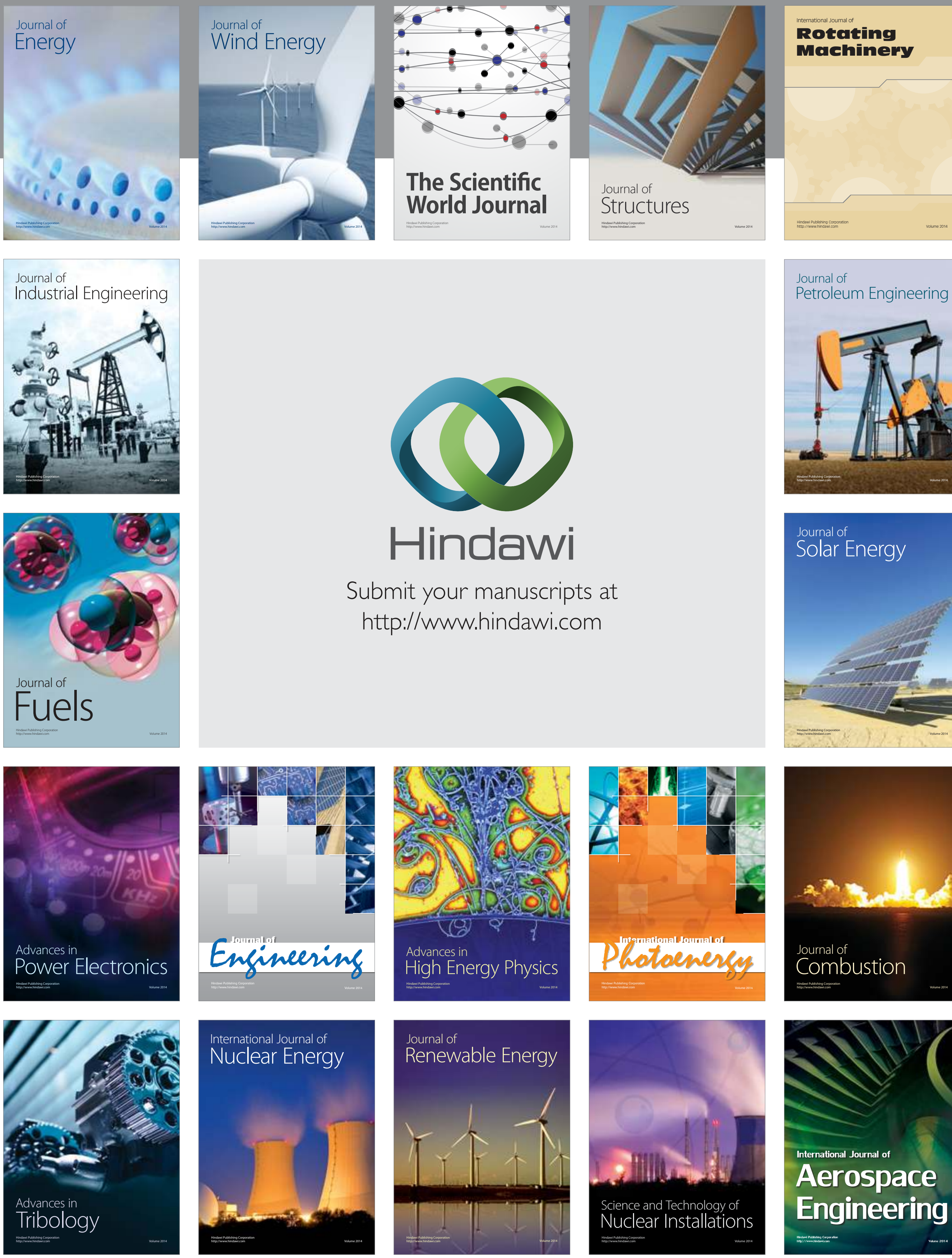
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