## MODELLING HOURLY AND DAILY DIFFUSE SOLAR RADIATION USING WORLD-WIDE DATABASE

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God is He Who has created the heavens and the earth and sends down water (rain) from the sky, and thereby brought forth fruits as provision for you; and He has made the ships to be of service to you, that they may sail through the sea by His Command; and He has made rivers (also) to be of service to you.

And He has made the sun and the moon, both constantly pursuing their courses, to be of service to you; and He has made the night and the day, to be of service to you.

(Quran: Chapter 14; Verses 32, 33)

Dedicated to my Father, Prof (late) Munawwar A K Zobairi

#### ABSTRACT

Solar energy is an alternative to fossil fuels for more sustainable and reliable energy options; with a huge potential to meet many times the present world energy demand. Readily available solar radiation data is a key to design and simulation of all solar energy applications. Whereas, global radiation is a frequently measured parameter, diffuse irradiance is often not measured, and therefore needs to be estimated from robust, reliable models.

This research project aims to develop regional diffuse solar radiation models on both hourly and daily levels (using nine world-wide sites) for each of the following countries: India, Japan, Spain and UK.

Qualitative analysis is performed to investigate the bearing of sunshine fraction, cloud cover and air mass on the clearness index  $(k_t)$  -diffuse ratio (k) relationship, fundamental to presently proposed modelling.

This is followed by a quantitative assessment by developing a series of hourly models based on these parameters along with global radiation, and comparing the performance results with the conventional k-k<sub>t</sub> model. Eventually, after thorough statistical evaluation, optimal region-wise hourly models are recommended.

Daily radiation models are inherently different from their hourly counterparts and, nevertheless, are required for various other applications. Therefore, models for daily diffuse radiation are developed using daily sunshine fraction and daily-averaged cloud cover along with daily clearness index to estimate daily diffuse ratio. As in hourly modelling, all possible combinations of the parameters under focus are used to develop a set of models for each location. Statistical analysis similar to that in case of hourly radiation models is performed. This is followed by validating the daily models against other sites within a region to be able to safely propose region-based models for each of the four countries. It is revealed that uncertainty in measurements plays an important role in establishing the accuracy with which models can be used.

Through this work, important parameters for hourly and daily diffuse radiation models are established. The proposed models are believed to provide reasonable accuracy if used within a given region where diffuse solar radiation is not measured. A case study for the futuristic sustainable production of solar electricity for India is also included to demonstrate the application of solar radiation.

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Finally, I would like to thank my Mum from the deepest corners of my heart; for it is due to her that I am here, pursuing my PhD. She is the greatest source of my strength and encouragement behind this task.

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### DECLARATION

I hereby declare that the work presented in this thesis was solely carried out by myself at Napier University, Edinburgh, except where due acknowledgement is made, and that it has not been submitted for any other degree.

#### SAIMA MUNAWWAR (CANDIDATE)

Date

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### NOMENCLATURE

# Abbreviation and symbols

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AS	=	accuracy score		
AST	=	apparent solar time		
B <sub>n</sub>	=	beam normal hourly irradiation, W/m <sup>2</sup>		
CC	=	cloud cover		
CF		cloudiness factor		
DEC	=	earth's declination		
D	=	diffuse horizontal hourly irradiation, W/m <sup>2</sup>		
Dc		calculated diffuse horizontal daily irradiation, $W/m^2$		
Dm	=	measured diffuse horizontal daily irradiation, $W/m^2$		
E	-	extraterrestrial horizontal hourly irradiation, W/m <sup>2</sup>		
f	=	factor of standard deviation		
G		global horizontal hourly irradiation, W/m <sup>2</sup>		
k	=	hourly diffuse ratio		
K		daily diffuse ratio		
K <sub>b</sub>		direct transmittance index		
K <sub>d</sub>		diffuse transmittance index		
k <sub>t</sub>		hourly clearness index		
Kt		daily clearness index		
k	=	weighted mean of 'k' values		
m		air mass		
MBD		mean bias deviation		
n	=	number of data points		
P <sub>90</sub>	=	90 <sup>th</sup> percentile		
P <sub>10</sub>	=	10 <sup>th</sup> percentile		
Q1	=	first quartile		
Q <sub>3</sub>	=	third quartile		
QC	-	quality control		
R <sup>2</sup>	=	coefficient of determination		
RMSD	=	root mean square deviation		

Nomenclature

SD	=	sum deviation
SF	=	sunshine fraction (same convention for both hourly and daily)
SHA	=	solar hour angle
Skew	=	skewness
SOLALT	=	solar altitude
SOLAZM		solar azimuth
SS		sunshine duration
Yc	=	calculated value of dependent variable
Y <sub>m</sub>		mean of the dependent variable
Yo		observed value of dependent variable

### Greek

$\sigma_k$	=	standard deviations of 'k' values
ω		solar hour angle

### Prefix

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c		cubic relationship*
lin	=	linear*
q, quad	=	quadratic*

\* These conventions are used in all figures and tables.

# Subscripts

i	=	i <sup>th</sup> variable
i,max	=	maximum value of all 'i' variables

### **CHAPTER 1**

### **INTRODUCTION**

Energy is vital for human sustenance. Since the current research project is pertinent to utilization of one of the energy forms, it would be worthwhile to investigate and present a reliable picture of the global energy mix, current energy issues and challenges, prospects of renewable energy in general and potential of solar energy, in particular. The basics of solar radiation will also be reflected and the scope of the present project will be discussed herein.

#### 1.1 Energy

Energy, by definition, is the ability to accomplish work. It is an input or intermediate entity for any process of production or utilization which yields a final product.

#### 1.1.1 Energy and environment

Technically, it is by solar radiation that life is feasible on earth. It provides the ambient temperature, within which organisms comfortably survive. Part of the radiation sets up differences of temperature in the atmosphere and oceans in such a manner that the convective currents produce the winds, ocean currents and waves. Solar radiation also drives and maintains the hydrologic cycle by causing evaporation, precipitation and surface runoff. Sun- often taken for granted, is the source of light on earth, without which there would be perpetual darkness. Plants survive on solar energy by the process of photosynthesis, upon which animals and ultimately, humans rely. Even the most widely used energy resources today like fossil fuels, are an indirect result of trapped sun's energy over the time.

#### 1.1.2 Energy and civilization

Energy is an essential element in human life. It plays a crucial role in economic development and in a society's overall well being. With the evolution of civilization, man progressively gained access to larger amounts of energy. Apart from use of solar energy for drying purposes, with the invention of fire, a number of activities, like heating, cooking and

process heat for tool making may have started. The earliest evidence for fire-use dates back to 350,000-450,000 years ago (Sorensen, 2004). People lived in small tribes and it was only when villages and small cities emerged that fuel wood- the source for fire, became a traded commodity. The next advent of energy utilization, about 10,000 years ago, is generally considered to have been associated with taming of animals to form livestock and the introduction of agriculture. In the societies of the past, not only animal but human slaves were also exploited to perform mechanical work, thus barely affecting the average per capita energy usage. It is not surprising to note that throughout man's history, there have been individuals whose access to energy was largely limited to that converted by their own body. Until the 19<sup>th</sup> century, human progress was limited by the amount of work that people could do to feed themselves and their families (Buklin, 2003). In the 19<sup>th</sup> century the several orders of magnitude increase of the available energy sources changed the lifestyle dramatically. The 'relatively new' industrial revolution of a couple of hundred year's old, flourished when large amounts of coal became available as a fuel. Discovery of other fossil fuels, like oil and natural gas accelerated the growth in energy demand of the 20<sup>th</sup> century. With human settlement, there was also a fast emerging need to provide energy for in-land transportation (wind energy had been in use since the earliest of the civilizations for sailing overseas), besides other requirements for more systematic heating and cooking practices.

The development in the last century saw significant increase in energy consumption chiefly coming from the more developed nations. Modern society uses more and more energy for industry, services, homes and transport. This is particularly true for oil, which has become the most traded commodity, and part of economic growth is linked to its price. However, neither oil nor any of the other fossil fuels, such as coal and natural gas, are unlimited resources.

#### 1.2 Sources of Energy and their Current Status

Energy systems presently in use across the world can be divided into two main categories: conventional and non-conventional. While fossil fuels and nuclear power belong to the former, renewables fall under the latter category.

#### 1.2.1 Conventional, non-renewable energy resources

Historically, fossil fuels in its crude form i.e. wood and coal have been an extensive energy resource and wood, in particular, has served the human energy needs for thousands of years. During the industrial revolution fossil fuels saw their refined liquid phase i.e. oil, which is more efficient than their traditional solid phase counterparts (wood and coal). More recently world became familiarised with gaseous phase of fossil fuels that is even more efficient. Oil and gas, are still the dominant energy medium in the world. Currently, fossil fuels supply about 80% of world's primary energy (WBGU, 2003).

*Coal* is one of the most abundantly found, extensively used, relatively heavily polluting fossil fuel. The main constituent of coal is carbon and hydrogen, with traces of sulphur, oxygen and nitrogen. During the industrial revolution, coal was used for metallurgical processes, glass-making fuel for railroads, and in general for steam engine. By 1860, world production of coal reached 150 million tons (Dorf, 1981). The world produced 2732.1 million tons of oil equivalent of coal (bituminous, anthracite and sub-bituminous) in 2004 (BP, 2005). Coal remains the leading fuel in power generation sector. However, in near future natural gas, being a cleaner and more efficient fuel is likely to take up some of coal's share in electricity production.

*Oil* can be found in varieties of composition around the world, with common constituents of hydrocarbons ranging from C4 to higher order long-chained structures. Crude oil can exist in very different viscosities, sulphur content, percentages of alkenes, aromatics, naphthenic and asphaltenic hydrocarbons, heavy metals, etc. These differences in the nature of oil could be attributed to the conditions of formation and trapping in oil fields. The superior qualities and convenient transportation have made oil the preferred fuel since 1920. Today, oil faces little competition from other fuels in road, sea and air transportation. The transport sector is very vulnerable to any disruption of supply of oil for the fact that the entire infrastructure is built around a single fuel source (Buklin, 2003). Oil consumption growth in 2004 was the largest in volume terms since 1976. Global consumption grew by almost 2.5 million barrels per day (b/d), more than double the 10-year average rate, with consumption in all regions rising above the 10-year average rate on the back of a strong world economy. Both global oil production as well as consumption exceeded 80 million b/d for the first time in 2004 (BP, 2005). The past couple of years have evidently demonstrated the volatile nature of oil through doubling of oil prices and insecurity of

supply. Despite the world's increasingly heavy dependence on this leading energy resource, its depleting resources do not make oil a reliable choice for future.

*Natural gas*, consisting mainly of methane with traces of other hydrocarbons, oxygen and hydrogen, can be found with oil in associated gas fields or independently from oil as unassociated gas fields. In the past some gas has been generated from oil and some from coal. Natural gas has been in use for lighting and heating purposes for over a century. It is projected to be the fastest growing component of world primary energy consumption. Natural gas is seen as a desirable alternative for electricity generation in many parts of the world, given its relative efficiency in comparison with other energy sources, as well as the fact that it burns more cleanly than either coal or oil. The industrial sector accounts for 36 percent of the growth in world natural gas demand over the 2002-2025 period. World natural gas consumption reported at 2691.6 billion cubic metres, grew by 3.3% in 2004, compared with a 10-year average of 2.3%. International trade in natural gas increased by 9% in 2004. Pipeline shipments rose by more than 10% (BP, 2005). Some energy reviewers expect (SER, 2004), that natural gas will overtake oil as the most important energy resource in the world within the next 2-3 decades. Although it is cleaner and a more flexible natural fuel, natural gas is more difficult to transport than liquid or solid fuels.

*Nuclear energy* comes from large atoms as they break up (fission) or when two light nuclei fuse together to form a heavier one (fusion). While nuclear fission reactors are the primary contributors to this type of energy, research is also being done to overcome the challenges in establishing practically feasible nuclear fusion reactors. The first of the nuclear plants was set up in Obninsk, Russia in 1954. Nuclear (fission) power plants currently supply 6 % of world's global energy demands. Nuclear power consumption increased by 4.4% globally in 2004, after registering a rare decline in 2003, with the recovery in Japan accounting for 50% of the growth (BP, 2005). Known uranium reserves are more than adequate to cover the requirements of existing reactors during their lifetimes and beyond (SER, 2004). However, reactor safety, waste disposal and plant decommissioning are still matters of concern. Nuclear power's share of worldwide electricity is expected to decline as old plants are de-commissioned and only a few new ones built.

#### 1.2.2 Non-conventional, renewable energy resources

Renewable energy sources have also been important for humans since the beginning of civilisation. The sun is a working fusion reactor that already supplies more energy than humans could possibly need at anytime, provided if technologies can be developed to tap it efficiently. Another example is biomass which is used for heating, cooking and steam production —and hydropower and wind energy, for transport and later for electricity production.

In terms of *energy use per capita consumption* on a global level, biomass dominates the renewable energy sector. Next contribution is by hydropower followed by geothermal power, which only in part can be classified as renewable (since many reservoirs are being exploited at such high rates that would exhaust them over a period of decades). This is followed by wind and geothermal heat (used for district heating). Next, solar heat, tidal power and solar power contribute to the per capita consumption in that order. However, the fastest growing markets are of wind and solar power, with both currently adding 35% of installed power each year (Sorensen, 2004). Some of the most common renewable energy technologies and their current status in global energy mix will be reviewed in the following paragraphs.

*Hydroelectricity* is essentially generated when the potential energy of water stored at an elevation is transformed into kinetic energy by means of driving a turbine which in turns rotates the motor to produce electricity. Like most renewables, water power is indirectly derived from solar power. However, while other renewable resources are still in their embryonic stages, hydro power has gained global recognition as a major contributor to world energy supplies.

The first power station to supply electricity to general public set up in Surrey (UK) in 1881 was driven by hydropower (Laughton, 1990). The present-day hydroelectric plant has emerged as an end-product of 2000 years of technological advance, with significantly poor efficiency to the modern-turbo-generator spinning at 1500 rpm and producing electricity at efficiencies of 90% (Ramage, 1996). Today, hydropower is the largest and most important renewable resource and generates about 17% of the world's electricity. It is estimated that only 33% of the technically and economically feasible global potential of hydropower has been developed to date, although there are significant regional variations (SER, 2004).

Though small scale hydropower plants have gained much popularity, large hydropower schemes often face challenges due to their environmental impacts and long-term returns on investment.

World Energy Council claims in their *Survey of energy resources* (2004) that other nonhydro renewables are expected to make a growing contribution to global power generation, even if their total share is likely to reach only about 5% in 2030 (SER, 2004).

*Biomass* is essentially solar energy captured by green plants, during photosynthesis and stored as chemical energy usually in the form of carbohydrates and often as hydrocarbon molecules. Fuels derived from biomass are called biofuels. The UK Energy Technology Support Unit (ESTU,1991) defined biofuels as 'any fuel, either gaseous, liquid or solid, derived from organic materials, either directly from plants or indirectly from industrial, commercial, domestic or agricultural wastes. They can be derived from a wide range of raw materials and produced in a variety of ways.' (Ramage and Scurlock, 1996). Biomass can directly be used as biofuel such as combustion of firewood. In fact, until the seventeenth century this form of biomass was the only significant source of heat apart from sun. In 1980s it accounted for approximately 1 % of UK primary energy consumption, compared to over 90% in many of the world's poorer countries like Chad, Mali and Tanzania. (Laughton, 1990). In early 1990s, countries like Nepal and Ethopia, derived almost all their energy needs from biomass and percentages for Kenya, India and Brazil were about 75%, 50% and 25%, respectively. (Ramage and Scurlock 1996).

Biomass power generation involves three basic thermo-chemical conversion technologies that use solid biomass as primary fuel, namely direct combustion, gasification and pyrolysis. In addition, the use of biogas (chiefly methane) produced from biomass via anaerobic digestion, has proved to be the most immediately available economic option, with sewage gas and gas from landfills being amongst the cheapest renewable sources. Since biomass is not as much a traded commodity, much of it being local and often with no fiscal transaction, the details of its consumption are either not recorded or considerable uncertainty is associated with the recorded figures. In fact, biomass contribution to the global energy mix is often underestimated as it doesn't account for ongoing consumption, particularly in the developing regions of the world. According to the SER (2004) – "biomass has the potential to become the world's largest and most sustainable renewable

energy source. To progress from this "potential" stage, both production and end-use technologies must be modernised."

*Wind* is often considered to be the most advanced of the renewables, after hydropower. Wind energy has been in use for thousands of years for milling grain, pumping water and other mechanical power applications. There are over one million windmills in operation around the world, principally for pumping water. While wind will continue to be used for such purposes, it is its capacity to generate pollution free electricity that has gained significant importance in present day world. Modern 'windmills' for generating electricity are called wind turbines to not only distinguish them from their other traditional use, but also because their function is similar to steam and gas turbines and yield the same endproduct i.e. electricity. There are two kinds of wind turbines in use, horizontal and vertical axis. Though fundamentally different in mode of operation, they both work on the principle of aerodynamic lift with the velocity of blades exceeding that of wind. With current technology, a wind power project is practically feasible at any place where the annual average wind speed exceeds about 5m/s (SER, 2004), economic feasibility naturally depending on the costs of other components of the plant. Wind turbines can either be landbased 'stand alone' systems or they can be installed as large 'wind farms' in shallow waters or on earth. Offshore projects spur the development of larger machines and wind turbines of up to 5 MW and are about to enter the market. The total world's installed generating capacity was 31, 398 MW and annual electricity output was 57,993 GWh at end 2002 (SER, 2004). However, the electricity systems with an increasing share of wind power in their fuel mix will have to face new challenges. Experience in those countries with a high share of wind in their electricity production (i.e. ~20% and above), demonstrates the problems of integrating an intermittent energy source into the grid and the implications this can have for the global power system performance, including the need for new concepts for power plant operation scheduling and system control. Despite all this, wind power is projected to become a significant contributor to global electricity supply in next 10 years (SER, 2004).

*Geothermal* energy results from heat stored in rock by earth's natural and continuous heat flow. Geothermal reservoirs consisting of porous or permeable rocks, can store enormous amounts of energy in the form of steam and hot water. The best geothermal fields are located within well-defined belts of geologic activity. There are four types of geothermal

resources capable of electricity generation: liquid dominated hydrothermal, vapour dominated hydrothermal, geopressured aquifers and enhanced geothermal systems (Hot Dry Rock, HDR). Geothermal resources can be exploited either by using naturally occurring fluids as the heat transfer medium or a more advanced method in which transfer medium is injected water. Hydrothermal resources, the only commercially used resources at the present time, can be used to generate electricity by traditional processes such as dry steam and flash steam systems and newer processes like, binary cycle and total flow systems, with some significant advantages. Many countries are believed to have potential in excess of 10 000 MWe which would fulfill a considerable portion of their electricity requirements for many years. Lower-temperature geothermal resources occur in many world regions. They can provide useful energy for space and water heating, district heating, greenhouse heating, warming of fish ponds in aquaculture, crop drying, etc.

Geothermal energy converting systems are able to provide electricity with an annual capacity factor of over 90%. During the early oil crises (1970s), intensive investigations led to the discovery of many geothermal reservoirs for electricity generation, some of which are in operation, while about 11 000 MWe of proven resources are not yet tapped. It was reported by the Geothermal Energy Association that geothermal power could serve the electricity needs of 865 million people, or about 17% of the world's population. It identifies 39 countries which could be 100% geothermal powered, mostly in Africa, Central and South America and the Pacific (SER, 2004). It is was recently reported that (Refocus, Jan/Feb 2006), geothermal was predicted to double its growth in 2005 and, according to the Geothermal Energy Association, will grow 50% in power production by 2010. Exploitation of geothermal energy is limited by economical and technical factors, rather than lack of resources. Although massive but relatively diffuse nature of this thermal energy poses problem to concentrate and harness it effectively.

*Solar* radiation, the earth's prime source of energy, is being increasingly utilised. This renewable form of energy will be covered under Section 1.6 in detail. Current status of various solar technologies will also be reviewed therein.

#### **1.3 Energy Challenges**

### 1.3.1 Limited resources and their vulnerability

According to 2003 figures, 80% of worldwide energy use is based on fossil fuels (WBGU, 2003). However, the risks associated with their use require prompt attention.

Fossil fuels stocks are rapidly declining around the world. The world burns as much oil in six weeks as it burned in one year in 1950 (Arthus-Bertrand, 2003). According to an article in Gaurdian (Monbiot, 2004), the state of the affairs of oil is as follows: "the world consumes six barrels of oil for every new barrel discovered. Major oil finds (of over 500m barrels) peaked in 1964. In 2000, there were 13 such discoveries, in 2001 six, in 2002 two and in 2003 none. Three major new projects are proposed to come on stream in 2007 and three in 2008. For the following years, none have yet been scheduled." Stress on existing reserves is increasing day by day due to increased demand. Research conducted at the University of Uppsala in Sweden in year 2003, claims that oil supplies will peak soon after 2010, and gas supplies not long afterwards, making the price of petrol and other fuels rocket with potentially disastrous economic consequences unless people have moved to alternatives to fossil fuels (Arthur, 2003). Other expert estimations have put the timing of the 'big oil rollover' (when oil production will start to decline around the world) between 2005 and 2020 (Magoon, 2000). According to BP (2005), the global reserve to production ratio of oil and gas is approximately 40 and 64 years, respectively. Although the reserve to production ratio of coal is almost five times that of oil, its serious environmental implications do not render it as a prospective energy resource.

Nuclear power due to its associated environmental and political concerns is not a likely candidate either to replace fossil fuels after the latter run out. Typically, majority of people in any country are against nuclear technology developments. There can be various reasons for inseparable apprehension associated with nuclear power, for example, the fear of radioactive outbreak, owing to accidents or lack of precautionary measures and external factors, like a potential threat to international security. In November 2003, Germany took major steps towards ending its nuclear power programme when it shutdown the first of its 19 atomic power stations. The shutdown followed an agreement signed with the industry in the year 2000 to close all the nuclear power plants by 2025. It was reported that several other European countries are preparing to follow Germany's lead, with both Belgium and Sweden announcing nuclear phase-out plans (Hardin, 2003).

Depleting fossil fuels and its numerous environmental problems, which will be covered in Section 1.3.2, are not the only concerns. The various components in energy infrastructures, for example, power plants, transmission lines and substations, and gas and oil pipelines are all potentially vulnerable to adverse weather conditions or human acts. During summer 2003, one of the hottest and driest European summers in recent years, the operations of several power plants, oil and nuclear, were put at risk owing to a lack of water supply to cool the condensers. World demand for fossil fuels (starting with oil) is expected to exceed annual production, very likely within the next two decades (SER, 2004). Shortages of oil or gas and heavy reliance on the same are deemed to initiate international economic and political crises and conflicts. Some of which will be addressed in Section 1.3.3.

Renewable sources of energy, on the other hand, are easily accessible and freely available to mankind. The intermittency is due to the nature of the source, which can be overcome with technological advancements or hybrid systems, as opposed to the factually and politically driven insecurity in supply of other resources.

If reform of the energy use and its sources doesn't take place in near future and the exploitation of conventional resources continues unabated, the world is likely to face a global energy crisis.

#### 1.3.2 Environmental concerns

During energy use, varied stresses are created on the natural environment, some of which have global implications like the global warming while others cause local impacts such as their effect on human health and ecology. Coal exploration and mining causes land degradation through subsidence and mine fires. The impact of mining on forest areas is of particular concern. Similarly, with onshore oil and gas production drilling waste fluids, drilling waste solids, produced water and volatile organics exhibit the potential to contaminate surrounding water bodies. Nuclear power also has serious reservations due to its associated radioactive emissions. Nuclear plants use uranium as a fuel to produce power. The mining and handling of uranium is very risky owing to potential radiation leaks. Besides, during the fission process, radioactive gases are produced which are to be contained in the operation of the plant. If these gases are released into the air, major health risks can occur. The third concern of nuclear power is the permanent storage of spent

radioactive fuel. This fuel is toxic for centuries and its handling and disposal is an ongoing environmental issue. Renewable energy sources, being clean and environmentally friendly, have a clear edge over the rest of energy systems.

The global environmental scene has changed dramatically over the last century. Climatic changes driven by human activities, in particular the production of Greenhouse Gas emissions (GHG), directly impact the environment. Energy sector has a key role in this regard since energy during its production, distribution and consumption is responsible for producing environmentally harmful substances.

Human activities are releasing greenhouse gases into the atmosphere.  $CO_2$ , one of the most important greenhouse gases, is produced when fossil fuels are used to generate energy and when forests are cut down and burned. Methane and nitrous oxide are emitted from agricultural activities, changes in land use, and other sources. Halocarbons (CFCs, HFCs, PFCs) and other long-lived gases such as sulphur hexafluoride (SF<sub>6</sub>) are released by industrial processes.

For the last 150 years, industry has been releasing CO2 into the atmosphere at a rate millions of times greater than the rate at which it was originally accumulated underground. Deforestation alone has been responsible for around 20 Gt of carbon since 1800. Table 1.1 shows the threatening status of CO<sub>2</sub> emission (Arthus-Bertrand, 2003). The mean global surface temperature has increased by 0.4-0.8 °C in the last century above the baseline of 14 °C (Sims, 2004). If nothing is done, global temperatures could rise by up to 6°C by 2100. The current rates of  $CO_2$  emitted by industrialised nations are typically in excess of their sustainable limits. Global warming and its associated climate changes are inflicting disastrous impacts on human health, economics and environment of the planet. Around the world, ice sheets and glaciers are melting at a rate unprecedented since record keeping began. Changes in the area and volume of the two polar ice sheets in Antarctica and Greenland are intricately linked to changes in global climate and could result in sea-level changes that would severely affect the densely populated coastal regions on Earth. Research undertaken by Australian scientists has revealed new evidences of global warming; suggesting that sea ice around Antarctica had shrunk 20% in the past 50 years. The change is important because sea ice - the area around the poles where seawater is

frozen into layers no more than a few metres thick - is regarded as a crucial indicator of climate change (Fickling, 2003).

Compared with the 304 Gt of carbon emitted since 1860 from the burning of fossil fuels, four times that amount is contained in the known reserves of oil, gas and mainly coal, that could be recovered in the near future, based on existing economic and operating conditions. Moreover, if the estimated and unconventional reserves (which includes oil shales, tar sands, coal bed methane, and deep geopressured gas) are fully exploited the net amount of carbon emitted would soar to 16 times that value until 1998 as shown in Table 1.2 (Sims, 2004).

If GHG emissions are unabated, natural catastrophes inflicting damage to ecology of the planet and its inhabitants are expected to occur more frequently and intensely in future. Physical infrastructure will be damaged, particularly by sea-level rise and by extreme weather events. Water resources will be affected as precipitation and evaporation patterns change around the world.

Organisations and institutions worldwide are, therefore, stressing on an immediate need to explore and develop other energy resources that are viable as well as environmentally friendly to avoid any further damage to global ecology.

### 1.3.3 Socio-economic and political impacts

The root cause for many of the world's current problems are issues associated with energy distribution, limited resources and environmental effects of various means of energy generation and usage.

According to World Health Organisation (WHO) as many as 160,000 people die each year from the side effects of climate change and the numbers could almost double by 2020 (Renewable Energy World, 2003). Economical losses as a direct result of climate change are also immense. Between the 1960s and the 1990s, the number of significant natural catastrophes such as floods and storms rose many-fold, and the associated economic losses rose by a factor of nine. Figures indicate that the economical losses as a direct result of natural catastrophes over five years between 1954-59 were US\$35 billion while between 1995-99 these losses were around US\$340 billion (Muneer et al, 2003).

The uneven distribution of primary energy resources, in particular oil, throughout the world, has led to profound economic and political implications. As the international trade of energy resources continues to expand, world's vulnerability to supply disruptions is also increasing. This energy insecurity has been responsible for shaping world politics to a large extent. Suez crisis in 1956 to 1970s oil crisis to the gulf War in 1990s to the more recent Iraq war of 2000s are some examples of major economic and political crises. Since the oil producing countries are generally weaker than the consuming nations, the latter are politically driven to dominate the former economically, politically - and if necessary, militarily, - to maintain access to oil (Alexander, 1996).

Access to electricity and other modern energy sources is a necessary requirement for the economic and social development of any country. It was projected by *The World Energy Investment Outlook* (WEIO, 2003) that if present trends continue, the world would need to invest \$16 trillion over the next three decades to maintain and expand energy supply. This number, much larger in real terms than the comparable figure for the past 30 years, is equivalent to 1 % of annual global GDP over the period. The average annual rate of investment is projected to rise from \$455 billion in the decade 2001-2010 to \$632 billion in 2021-2030. This compares with estimated energy investment of \$413 billion in 2000. However, such high projected rates of investment will still leave 1.4 billion people without access to electricity in 2030, only 200 million fewer than now (WEIO, 2003).

The electricity sector will account for more than 70% of the above mentioned figure of \$16 trillion, if the investments in the oil, gas and coal industries that are needed to supply fuel to power stations are included. World electricity demand will nearly double by 2030, and installed power generation capacity will increase from 3,498 GW in 2000 to 7,157 GW in 2030. In many countries investment in transmission and distribution will need to be even greater than that in power generation, in contrast to past trends. Asia will account for 36% of global electricity investment, of which a considerable amount will be attributed to India (Hulst, 2003).

### 1.4 The Global Energy Future trends

#### 1.4.1 Implications set by the ongoing conventional energy use

The demand for the provision of energy is increasing worldwide and will continue to rise as developing nations reach developed status and developed nations maintain their modernisation trends. Most predictions provide for the energy consumption growth of developed nations compounding at around 1% a year however for developing nations consumption is presently compounding at over 5% a year. In the Reference Scenario, energy demand is projected to grow on average by 2.9% per year between 2005 and 2030 (WEO, 2005).

According to postulations set in WEO (2005),

(1) Oil remains the single most important fuel, with two-thirds of the increase in oil use coming from the transport sector. The lack of cost-effective substitutes for oil-based automotive fuels will make oil demand more rigid.

(2) Natural gas demand grows faster, driven mainly by power generation. It overtakes coal as the world's second-largest primary energy source around 2015.

(3)The share of coal in world primary demand falls a little, with demand growth concentrated in China and India.

(4) The share of nuclear power declines marginally, while that of hydropower remains broadly constant.

(5) The share of biomass declines slightly, as it is replaced with modern commercial fuels in developing countries. Other renewables, including geothermal, solar and wind energy, grow faster than any other energy source, but still account for only 2% of primary energy demand in 2030.

In a reference scenario of existing policies, the world's energy needs would be more than 50% higher in 2030 than today. However, this trend is expected to raise many concerns, some of which (as addressed in WEO, 2005) are:

- Climate destabilising carbon-dioxide emissions would continue to rise, calling into question the long-term sustainability of the global energy system.
- The sharply increased dependence of consuming regions on imports from a small number of countries would exacerbate worries about the security of energy supply.

- Huge amounts of new energy infrastructure will need to be financed to sustain the growing demand.
- Many of the world's poorest people will still be deprived basic energy needs such as access to electricity, leave alone modern energy services.

In a scenario where governments around the world were to implement new policies, aimed at addressing environmental and energy-security concerns, fossil-fuel demand and carbondioxide emissions would be significantly lower. Nevertheless, global energy demand in 2030 would still be 37% higher than today (WEO, 2005).

The superimposition resulting from growing energy demand, depleting resources and the damage present energy systems are causing to the natural environment in many and diverse ways calls for a close monitoring of the energy situation. Ironically, as more and more energy is being produced, traded, transformed and consumed, energy dependency is increasing, and when greenhouse gas emissions are high on the international agenda, that it is becoming increasingly difficult to provide a timely and reliable solution to the 'foreseen' global energy situation. The way to repair the already inflicted damages of global warming and a rather safe escape from the anticipated threats is an immediate reform in the overall energy sector. There needs to be a global drive on two fundamental fronts; firstly to conserve energy and to increase the efficiency of existing energy resources, secondly to switch the energy systems from existing energy resources to renewables that are clean and environmentally friendly. Radical policy action and technological breakthroughs are the need of the hour.

#### 1.4.2 Role and prospects of renewable energy

A secure, sufficient and accessible supply of energy is very crucial for the sustainability of modern societies. World public opinion and experts' views are increasingly voicing the urgent need to fundamentally transform present energy systems onto a more sustainable basis. A major contribution to this transformation can be expected to come from renewable energy resources.

Renewable energy sources are indigenous resources having the potential to provide energy services with zero or almost zero emissions of both air pollutants and greenhouse gases. They have now been acknowledged as a vital and plentiful source of energy that can indeed meet many times the present world energy demand with appropriate technology. Renewables can enhance diversity in energy supply markets, secure long-term sustainable energy supplies, and reduce local and global atmospheric emissions. They can also provide commercially attractive options to meet specific needs for energy services (particularly in developing countries and rural areas), create new employment opportunities, and offer possibilities for local manufacturing of equipment. As the time progresses, most of the energy demands are likely to come from developing economies. This compliments the fact, that many of such countries are blessed with abundance of renewable energy. Although biomass has been the most popular choice, hot and sunny climates of these regions offer tremendous scope for solar applications. Electricity generation using renewable sources holds significant prospects for rural and remote areas that are very often 'grid cut-off'.

The renewable energy sector is now growing faster than the growth in overall energy market. Concerns encompassing the use of both fossil fuels and nuclear power are beginning to drive the energy sector, globally, to strive towards alternative energy. This is evident not only at technological but also legislative level in several regions of the world. There are various commissions and institutional bodies on both national and international platforms designated for renewable energy promotion and development and whose member states are committed towards the cause. Many have set future targets, such as the EU's target of 12% primary energy needs to be met by renewables in 2010 and 20% by 2020. Also, several oil and gas industry giants are heavily investing in research and installation of alternative energy projects. This indicates there subtle but prudent shift towards renewable energy sector. Renewables account for a considerable portion of market share in both developed and developing world. Some long-term scenarios postulate that renewables could reach up to 50% of the total share of mid-21<sup>st</sup> century with appropriate policies and new technology developments as shown in Fig. 1.1 (Powerline, 2000).

However, one of the technical issues associated with renewable technology is the requirement of conventional energy back-up implying large investments, and also cancellation of emission reduction acquired by turning to the renewable source in the first place. Accommodating intermittent generation and integration to the grid are other such practical concerns. Most experts accept that significant infrastructural changes are needed to accommodate contributions from intermittent renewables beyond the critical 20% level (Refocus, Jan/Feb 2006). However, like everything evolves so will the present monolithic
system to a more adaptable and less centralised successor. Growing diverse needs, emerging technologies and associated concerns are expected to give way to a more flexible energy mix that can accommodate diverse generators from micro-power systems to massive grid-connected renewable complexes.

## Hydrogen as an energy carrier

It is interesting to note that way back in 1923 Haldane prophesied the production of hydrogen in UK by renewable energy means. He writes thus, "The country will be covered with rows of metallic windmills working electric motors which in their turn supply current at a very high voltage to great electric mains. At suitable distances, there will be great power stations where during windy weather the surplus power will be used for the electrolytic decomposition of water into oxygen and hydrogen. These gases will be liquefied, and stored in vast vacuum jacketed reservoirs, probably sunk in the ground. In times of calm, the gasses will be recombined in explosion motors working dynamos which produce electrical energy once more, or more probably in oxidation cells." (Haldane and Daedulus, 1923).

Renewable energy can be stored in the form of hydrogen fuel to meet the energy demand during its intermittency. Hydrogen is deemed to be both a primary fuel and an 'energy carrier' (as is electricity today) of the future, by many. Its development is also expected to be supported by its potential for transforming transportation and stationary energy systems (SER, 2004).

The transition of world energy system to hydrogen - the simplest and most abundant element in the universe - as a fuel is quite logical and becomes clearer when one takes a look at historical energy production sequence. Each successive transition from one source to another - from wood to coal, from coal to oil - has entailed a shift to fuels that were not only harnessed and transported more economically, but also had a lower carbon content and higher hydrogen content. It is also evident that at each step greater energy density is being achieved. The third wave of decarbonisation is now at its threshold, with natural gas use growing fastest, in terms of use, among the fossil fuels. The fourth wave, the production and use of pure hydrogen, is certainly on the horizon. Its major drivers are technological advances, renewed concern about the security and price of oil and gasoline, and growing pressure to address local air pollution and climate change.

## **1.5** Solar Energy: The Fuel of the Future

Although there is much controversy, contradiction and scepticism surrounding the estimates and potential of various energy resources, there is a common consensus on the potential of sun amongst all world energy experts in that the sun is the *ultimate* source of energy for all the life forms. It is also the originator of all other sources of energy that exist on the face of this earth.

The annual solar energy reaching the earth's surface is estimated between 2.9-3.2 million EJ. Therefore, the energy from the sun is nearly 7000 times the global energy consumption in year 2005 of about 463 EJ/yr (Nielsen, 2005). The energy content of the total non-renewable energy resources is approximately 325,300 EJ (oil, 8 690 EJ; gas, 17 280 EJ; uranium, 114 000 EJ; coal, 185 330 EJ) and of other major renewables is estimated at 1 960 EJ (hydro, 90 EJ; wind, 630 EJ; photosynthetic storage/ biomass, 1 260 EJ); a very small fraction of annual solar radiation (SER, 2004).

The potential of solar energy varies geographically along with other factors. Nevertheless, even the lowest estimate (of 1575 EJ/yr- SER, 2004) is more than three times the current global primary energy consumption. This disproves the myth that economic applications of solar energy should only be restricted to the sunniest regions. If the annual average horizontal surface irradiance, of approximately 170 W/m<sup>2</sup>, is integrated over 1 year, the resulting 5.4 GJ that is incident on 1 m<sup>2</sup> at ground level is approximately the energy that can be extracted from one barrel of oil, 200 kg of coal, or 140 m<sup>3</sup> of natural gas.

Solar power is one of the most promising renewables. It is more predictable than wind energy and less vulnerable to changes in seasonal weather patterns than hydropower. Whereas generation of power from hydro, wind and geothermal sources is limited to sites where these resources exist in sufficient quantities and can be harnessed, solar energy can produce power at the point of demand in both rural and urban areas.

The energy content of solar radiation can either be used directly or converted into other energy forms useful in our daily lives- light, heat, electricity, fuels and other applicationsby solar technologies. Some applications, like photovoltaic and solar thermal collectors are more popular; others are less known, like solar detoxification or solar distillation. Nevertheless, each solar application has a significance of its own. It is these diverse ways in which solar energy can be used that make it an attractive and important option to power different energy systems in all countries of the world. (Figure 1.2 illustrates some typical solar energy applications).

## 1.5.1 Solar thermal Systems

Solar thermal systems can be used to supply heat for domestic hot water and space heating in residential, commercial and institutional buildings, for swimming pool heating, solar-assisted cooling, solar-assisted district heating, for industrial process heat and other miscellaneous purposes. The most important developments are in the installation of solar water heating (<100 deg C) which have proved to be efficient and reliable. Some of the solar thermal application techniques include glazed collectors (flat plate and evacuated tube), unglazed collectors (for heating swimming pool water), air collectors and so forth.

About 140 million m<sup>2</sup> of solar thermal collector area are in operation around the world, and the annual newly installed area is more than 10 million m<sup>2</sup>. The total installed capacity is thus approaching 100 GW<sub>th</sub> – more than the global wind power electric capacity (Philibert, 2005). China is the world lead market, with an installed capacity of one third of the world's total, almost exclusively, evacuated tubular collectors. In some countries, city regulations that require installation of solar thermal collectors to supply hot water for buildings have accelerated the growth in solar thermal installations. (SER, 2004).

## 1.5.2 Solar thermal power generation

Solar thermal power plants use direct solar radiation which can be concentrated onto a smaller area and collected by a range of concentrating solar power (CSP) technologies. The concentrated energy is generally utilized either by placing photovoltaics (usually of high efficiencies) at the concentration area or using the heat to create steam and run a turbine. These technologies rely on lenses and mirrors to do the concentrating and recent advancements in production techniques and materials, particularly the development of cheap plastic fresnel lenses, have driven the costs of CSP down to a very competitive level, both compared to regular photovoltaics as well as traditional power generation sources and other renewables like wind. Today, total installed CSP capacity is 364 MW. Most of this power (354 MW) is from the nine California SEGS (solar electricity generating systems)

power plants, connected to the Southern California grid. One long-term scenario foresees that by 2040, CSP's contribution would be at a level of almost 630 000 MW (SER, 2004).

The future of thermal power generation holds great commercial promise and a broad spectrum of interesting new opportunities. Among these possibilities are 24 hour solar-only power generation thanks to the thermo-chemical energy storage, the re-formation and synthesis of high-value fuels and fine chemicals, the thermal and/or thermo-chemical production of hydrogen, and the detoxification of hazardous wastes (Luzzi and Lovegrove, 2004).

## 1.5.3 Solar Photovoltaic

Solar cells are semi-conductor devices converting sunlight to electric current by excitation of photon. They power anything from lanterns in remote villages; to watches, calculators, laptops, parking ticket machines, solar home systems, and grid-connected roof-top arrays. There are a vast number of applications for photovoltaic technology ranging from autonomous systems to grid-connection. Owing to the modularity of PV technology, power can be generated on a few milliwatts to hundreds of megawatts scale. To achieve a more practical and economic method of power generation 'hybrid' systems, combining two or more technologies, such as PV, wind turbines, diesel generators or micro-hydro generators, are often used. A typical PV system has five main components, PV module (an array of solar cells), batteries, charge controllers, inverters and back-up generators. Figure 1.3 shows an example of PV installation at Napier University over a 160m<sup>2</sup> surface of a southeast facing wall which is capable of running 80 computers at the University's Jack Kilby Computer Centre.

The *International Energy Agency* identifies four primary applications for photovoltaic power of 40 W or more:

- off-grid domestic systems- supplying power to households and villages that are unconnected to the grid;
- off-grid non-domestic systems- to power commercial applications far from the grid such as telecommunications, water pumping, warning lights and environmental data recording;
- grid-connected distributed PV systems- to power a building or other load that is also connected to the grid;

grid-connected centralised systems- designed to provide an alternative to conventional centralised power generation or to strengthen utility distribution systems.

While photovoltaic (PV) power generation is still the most expensive solar technology, costs are falling and its versatility enables it to find many stand-alone applications. Because of the cost of transmission lines and the difficulty of transporting fuel to remote areas, developing countries are increasingly turning to solar energy as a cost-effective way to supply electricity. With a third of the world's population still without electricity, usage of solar PV modules will increase significantly as the demand for electricity spreads throughout the world. By end-2004 a cumulative total of about 2.6 GW of PV power had been installed globally (IEA PVPS countries), with about 770 MW installed during 2004. Most of this capacity represents grid-connected distributed and centralized systems, offgrid residential, commercial and industrial building installations. A large share (94%) of this growth in capacity accounted from installations in Japan, Germany and the USA, in that order. In terms of installed capacity per capita, Germany now leads the way at 10 W per capita, followed by Japan, Switzerland and the Netherlands at 9 W, 3 W and 3 W per capita respectively (IEA- Photovoltaic Power systems Programme, 2005). World photovoltaic cell and module production increased in 2004 to 1195 MW representing a massive 57% increase on that in 2003. (Refocus, Sept/Oct 2005). Although PV is a fast growing sector, its share remains very small in the renewable energy market, compared to other resources such as wind.

Photovoltaic arrays on satellites and spacecrafts provide electric power for onboard equipment and communication with control centres on earth. Space photovoltaics are different than their terrestrial equivalents. Space solar power are complex systems which comprise of the following components: solar cells, cover-glasses, metal inter-connectors, array substrates, deployment and tracking mechanisms, power storage and electric power distribution. For almost all of the space age, PV has been a prominent factor in successful operation of thousands of satelleites performing a wide variety of activities. Likewise in future, PV power will continue to make major contributions to many space missions. A NASA aircraft using photovoltaics is shown in Fig. 1.4.

# 1.5.4 Solar cooking, detoxification, desalination and other miscellaneous applications

*Solar cookers* are an ideal option, particularly in developing countries blessed with solar energy and where women and children suffer severe health problems owing to the traditional biomass use in inefficient cook-stoves and poorly ventilated kitchens. Resorting to solar cooking methods, may also help restore the deteriorating forest cover and soil fertility due to indiscriminate use of firewood. Solar cookers can be classified into four main categories: concentrator cookers, solar ovens, box cookers and indirect (combined) solar cookers. Although, these cookers vary in construction and the different ways of concentrating solar radiation, their underlying principle is the same i.e. focusing sun's ray onto a darkened (usually, black-coated) cooking pot. Although, this technology is not very favourable world-wide, solar cookers have found wide applicability in some countries like India, particularly proven successful in community cooking for hostels, temples and asylums.

Where medium to high solar radiation is available, *solar detoxification* is useful for treating water contaminants with several hundreds of milligrams per litre of non-biodegradable contaminants and for disinfecting water. This process has proven promising for the treatment of contaminated water, air and soil. The basic chemical reaction behind photo-catalytic detoxification process is: the near-ultraviolet part of solar spectrum photo-excites a semiconductor catalyst (usually, TiO<sub>2</sub>) in the presence of oxygen which generates oxidising species- either bound hydroxyl radical or free holes. These species attack the oxidisable contaminants, thus producing a progressive breaking of molecules yielding CO<sub>2</sub>, H<sub>2</sub>O and dilute organic acids (Malato-Rodriguez, 2004). Although its development presents difficulties, treatment of industrial waste water seems to be one of the most promising fields of application of solar detoxification. This technology is yet to be developed on a commercial scale.

*Solar distillation* is the process which involves purification of water using solar heat by evaporation and condensation. When this method is used to purify saline water, the process is called *solar desalination*.

*Solar evaporation* and *dehumidification*. Using sun's energy to dry agricultural products has been most commonly used for its inexpensiveness and convenience. Another sun

drying application is the evaporation of sea-water to yield salt. Traditional sun drying has its own demerits, like irregular and slow drying rate, high moisture retention especially in humid areas and contamination with dust and insects, etc. These problems can be counteracted with the use of mechanical dryers. Solar dryers usually employ high air flow rates at low temp over long periods of time. Such slow drying of fruits and vegetables preserves the flavour and quality of produce, thereby making solar drying advantageous over fossil fuel dryers, which usually employ lower air flow rates at higher temperatures for faster drying. There are several types of solar dryers in use, broadly classified as passive and active systems with sub-categories of direct or indirect method under each.

A *solar pond* is a unique large-area solar collector that uses water as working material for three functions: collection of solar radiant energy and its conversion into heat, storage of heat (up to approx 100 deg C), and transport of thermal energy out of the system.

Solar energy has the potential to play a very important role in providing most of the heating, cooling and electricity needs of the world, and assist in solving our environmental problems at the same time. Much of this potential is underestimated, mainly because we do not see widespread commercial solar applications. However, some of the new emerging developments in solar technology are likely to change the situation. One of such examples is, nanoscale antennas for direct conversion of sunlight to electricity with potential conversion efficiencies approaching 80–90% (Goswami et al, 2004).

*Building-integrated photovoltaic (BIPV)* is a rapidly emerging field among various other solar energy applications. Some critics are of the view that since solar energy is a 'dispersed' source, PV needs significant land use on its own. Since, urbanisation and commercialization has led to vertical expansion of cities, owing to horizontal space restrictions, PV installation seems to be a greater concern. However, this argument is misleading as solar systems can intelligently be integrated in buildings without using additional space. While walls and windows of high-rise buildings can serve as solar collectors, roof-tops are the ideal candidates for lateral buildings. Buildings are complex energy systems capable of capturing and delivering solar power to perhaps the largest extent. In industrialized countries, 35-40% of total primary energy consumption is used in buildings, for lighting, water heating and thermal comfort (space heating or cooling). However, if the energy used in manufacture materials and the infrastructure to serve

building, were taken in account, buildings' share rises to around 50% of total primary energy consumption (SER, 2004).

According to one estimate, about 8-10 million buildings are constructed globally each year. These buildings can be dealt with an intelligent and modular design approach from the very start, where every choice is 'decisive', involving multi-disciplinary teams to develop new forms of integration of solar technologies. This allows for buildings to be designed and built yielding 30-70% improvements in energy efficiency, with construction costs 2-10 % higher (SER, 2004). Such approaches towards 'energy efficient' and 'energy-saving' buildings are initiating a revolution in the building construction industry. They have the potential to become main driver for application of technologies to produce solar heat and electricity, thus contributing to the energy budget of buildings, in particular, and to world's energy use in general. Since buildings do not exist in isolation, this approach can further be extended to blocks of buildings, leading to unconventional, yet practically achievable, concept of *solar cities*. The Japanese Cosmotown Kiyomino SAIZ, a complex of 79 homes each equipped with a roof-integrated 3 kW PV power generation system, is one such example (SER, 2004).

The solar revolution in building industry is a gradual process and needs a push through new regulations and building codes that make energy saving, new energy-efficient measures and solar technology incumbent upon the constructors and contractors, whose interest, unfortunately, may not lie in energy reforms.

Solar energy's intermittent nature is a constraint to its growth in worldwide usage, until reliable and low-cost technology for storing solar energy becomes available. Thermal storage for solar heat and chemically charged batteries for off-grid PV systems are presently the most widely used solar energy storage systems. The most likely long-term candidate for solar energy storage is hydrogen. This is evident from hundreds of prototypes and demonstration systems currently in operation around the world that use the intermittent solar source to produce hydrogen and then continuous power (SER, 2004). Buildings are already the largest human fabric intercepting solar radiation and, therefore, potential drivers for the development of solar energy use. Visible changes are taking place in particular with passive solar heating, cooling and daylighting designs. Roofs and walls are becoming the potentially largest area in which photovoltaic and thermal systems to collect solar radiation can be integrated.

Annual growth of solar energy for hot water and electricity production increased at more than 32% per annum in the period 1971–2000, although from a very low base. However, the contribution of solar radiation to the world total primary energy supply is still bare minimum, at about 0.04% (SER, 2004). The overall challenge to using solar energy is, however, increasingly not so much technological as cultural and political. Only strong public policy and political leadership can move forward the application of solar and other renewables.

A long-term scenario based on the energy efficiency and energy intensity policies postulates that by 2100 oil, gas, coal and nuclear, should cover less than 15% of world energy consumption while solar thermal and photovoltaic should cover about 70%. Those policies will deeply transform the building, industry and transport sectors, increasing their reliance on renewable energy resources (SER, 2004).

The energy delivered by sun is both intermittent and subject to diurnal and seasonal variation. Also, there are a number of other factors, like the tilt and orientation of the surface application, surrounding elements, geographic and climatic parameters that play an important role in the output energy of any solar system. Therefore, preliminary design analysis taking in account all these key inputs is essential to a solar installation. For this reason, understanding the *solar radiation data*, the physical drivers and influential parameters required in its assessment needs critical attention and forms the core aspect of this project.

#### 1.6 The Solar Radiation Data

## **1.6.1** Solar radiation basics

The sun is a sphere of intensely hot gaseous matter with a diameter of 1.4 million kilometres, interior temperatures of 15 million degrees Kelvin and a pressure of 70 billion times higher than earth's atmospheric pressure. At such high temperature and pressure, sun is a natural house of several fusion reactions (hydrogen atoms combining to form helium atoms as one of the most important) that emanates tremendous amount of heat in the form of radiation. The sun has been producing energy at the rate of  $3.9 \times 10^{26}$  W for around five billion years, and will continue to do so for several more billion.

Radiation expands outward from the sun at the speed of light (300,000 Km/sec). Given the earth-sun distance of 150 million kilometres it takes 8 minutes for solar radiation to reach earth's surface. The energy intercepted by the earth over a period of 1000 years (or one year) is equal to the energy emitted by the sun in just 14 seconds (or milliseconds) (Nielson, 2005). Solar Radiation spreads over a wide spectrum of wavelengths, from the 'short-wave' infrared to ultraviolet. The pattern of wavelength distribution is critically determined by the surface temperature of the sun.

The amount of solar radiant energy falling on a unit surface area per unit time is called *irradiance*. The integral of irradiance over any convenient stated period of time is called *irradiation*. The average extraterrestrial irradiance or flux density at a mean earth-sun distance, known as *solar constant*, has a currently accepted value of 1367 W/m<sup>2</sup> with an uncertainty of the order of 1%. Due to the earth's rotation, asymmetric orbit about the sun, and the contents of its atmosphere, a large fraction of this energy does not reach the ground. Solar radiation data just outside of earth's atmosphere can be predicted with high precision, as it fundamentally depends on astronomical geometric parameters. It is the surface prediction that is more difficult owing to the atmospheric interactions, varying cloud cover and differing soil surfaces (ESRA, 2000).

Solar radiation plays a crucial role in affecting earth's weather processes. Earth-sun geometry is also an important concept as it helps determine the seasonal irradiation which has a direct impact on building and solar system designs. Notes on such geometrical parameters like, solar azimuth, solar elevation, declination, etc. can be found in the Glossary provided in Appendix A of the thesis.

The radiation received at the earth's surface consists of direct and diffuse (scattered plus reflected) short-wavelength radiation and long-wavelength radiation from sky and clouds, originating as thermal emission or by reflection of thermal radiation from ground. When sun's rays hit the atmosphere, the portion of the light that is scattered comes to the earth as *diffuse irradiation*. *Direct*(or *beam*) *radiation*, often called sunshine in layman terms, is the radiation which has not experienced scattering in the atmosphere, so that it is directionally fixed, coming from the disc of the sun. In practice, this includes a certain amount of *circumsolar diffuse radiation*. The sum total of diffuse and direct irradiance is called global or total irradiance. Glossary of the above parameters is also provided in Appendix A.

The interception of solar radiation by arbitrary surfaces is a function of their solar geometry and a determinant of their microclimatic interaction, i.e. the energy exchange between the surface and the surroundings. To maximize amount of solar radiation received on a surface, it must be tilted towards the sun. Likewise, orientation of the surface is very important. Both optimum tilt and orientation depend on the time of the year with the former additionally depending on the latitude.

## 1.6.2 Solar data: its use and significance

The basic need for knowledge of the quantity of radiation that can be received and transformed into useful energy at a given time or during a given time interval at a given geographical place or region led to the need for measuring and maintaining solar radiation data.

Solar data recording began in 1957 and since then many meteorological stations across the globe have gathered considerable data on solar radiation. Solar radiation data provide information on how much of the sun's energy strikes a unit surface of area at a location on earth during a particular time period, over the course of days, months and years. They are available in several forms. A typical database comprises of global, direct and diffuse solar irradiance, duration of sunshine and complementary data like cloud cover, atmospheric turbidity, humidity, temperature, etc. There are a number of aspects important in the understanding and use of solar data: geographic information of the site; whether the measurements are instantaneous (irradiance) or cumulative values (irradiation) over a period of time (usually hour or day); the time stamp and period of measurement; the parameters (e.g. global, diffuse or direct) being measured; the instruments used; the receiving surface orientation (usually horizontal, sometimes inclined at a fixed slope, or normal to the beam radiation); and if averaged, the period over which they are averaged (like, monthly averages of daily radiation) (Duffie and Beckmann, 1980).

For the development of any solar energy project, site-oriented and long-term solar radiation data is needed right from resource assessment to design of the system to evaluation and optimisation of its performance and short-term prediction of solar radiation for operational feasibility. Such data is extremely vital in a number of field applications, such as the following:

*Climatology:* solar radiation data is required for meteorological monitoring around the world. Knowledge of the solar irradiance components under varying atmospheric and surface conditions is an integral part of studies of global energy budget and is required to be fully understood for application in such diverse fields as global climate prediction and remote sensing (BP, 2003).

*Illumination:* day lighting design concepts require knowledge of solar radiation incident on the walls, apertures and other external building surfaces.

Architectural and energy-conscious building designs: solar data is useful in determining optimum building configurations, orientations and air-conditioning systems in order to minimize the energy load. Likewise, heating and cooling systems can be sized in accordance with the effects of sun's exposure through window orientations and sizes on the energy consumption of a building. Engineers and architects can use this information, combined with desired levels of natural lighting and building aesthetics, to formulate the final building design. Because energy costs are a significant expense in building ownership, an energy-efficient design can significantly reduce the life-cycle cost of a building.

*Solar energy resource assessment:* solar radiation data also help determine the best geographic locations for implementing solar energy technologies. Other factors being equal, a site receiving more solar radiation will be economically and technically more feasible.

*Solar energy technologies:* space and water heating, thermal photovoltaic, detoxification process, etc. require solar data for their design and effectuation. A common factor in all such applications is the end-use product. Generally, it is a direct function of the amount of solar radiation received and the conversion efficiency.

*Simulation of solar power plant:* prospects of solar electricity can be evaluated by matching the profile of the available solar radiation throughout the day with the load profile of the proposed site. If the solar power surpasses the load at any point of time it can be stored. The amount of solar radiation received changes throughout the day and year due to weather patterns and the changing position of the sun, and solar radiation data reflect this

variability. By knowing the variability, we can size storage systems. This stored energy can later be retrieved with the help of proven technologies to meet the energy demand during night time and cloudy periods. An application of this work is demonstrated at a later stage in the thesis (Chapter 7).

*Agricultural research:* solar data helps in the study of crop growth models and evapotranspiration estimates in the design of irrigation systems.

## 1.6.3 Need for solar radiation data modelling, in particular, diffuse radiation

In a period of rapidly growing deployment of solar energy systems, solar resource assessment, or in other words acquisition of solar data, is imperative. It allows assessment of a solar system's performance in relation to the technicalities, local geography and energy demand. This in turn helps to assess the feasibility and practical value of the solar energy application.

However, irradiance measurement-networks or meteorological stations do not always provide sufficient geographically time-site specific irradiance coverage (SER, 2004). Quite often, solar energy projects are not backed up by the long-term measured solar database required at the place of interest, mainly due to the capital and maintenance costs that measuring instruments incur. Consequently, they need to be estimated from alternative information available at the site or a near by location. This is where solar radiation modelling plays an important role.

Another scenario, pertinent to the present research topic is the common availability of global radiation at most of the sites world-wide, but no records on either diffuse or direct components. The solar radiation data recorded at the meteorological stations is generally measured on a horizontal surface. However, most of the solar energy applications involve tilted surface for optimal performance. The irradiance falling on it cannot be calculated unless both direct and diffuse components of global irradiance are known.

The portion of total solar radiation that is diffuse is about 10% to 20% for clear skies and up to 100% for cloudy skies. In north-western Europe, on average over the year, approximately 50% of the solar radiation is diffuse and 50% direct. Both are useful for most solar thermal applications. While direct radiation can be focussed to generate very

high temperatures, diffuse radiation provides most of the 'day lighting' and hence, is vital to building industries. Diffuse radiation is also used in analysing the energy balance of the atmosphere and in photo-biological processes. Despite their utility, both diffuse as well as direct irradiation, are not measured as frequently as their global counterpart. This is a very common situation worldwide. In UK alone, only 9 out of 84 meteorological stations recording hourly global irradiation, measure direct and diffuse irradiation. See Table A1 attached in the appendix extracted from *Solar Radiation and Daylight Models* (Muneer, 2004). This calls for a need to estimate diffuse radiation from more frequently measured radiation components and weather elements. Once, diffuse radiation is estimated from global radiation, direct component can be calculated as a difference of the two. The estimated radiation can thus not only serve the locations lacking solar data but also provide to fill the gaps in the meteorological data even where it is measured.

## 1.7 The Present Research Project

## **1.7.1 Problem statement**

*Diffuse solar radiation modelling:* To study and analyse the bearing of sunshine fraction, cloud cover and air mass on  $k-k_t$  regression relationships of hourly radiation and sunshine fraction and cloud cover on daily radiation, for the primary purpose of proposing improved diffuse irradiation models.

## 1.7.2 Aims and objectives

The aim of the project can thus be summarised as follows:

(1) To study the influence of sunshine fraction (SF), cloud cover (CC) and air mass (m), if any, on diffuse radiation by using the k (diffuse ratio) –  $k_t$  (clearness index) relationship (qualitative analysis).

(2) Following the analysis undertaken in (1), to develop a series of regression models based on all possible combinations of k<sub>t</sub>, SF, CC and m and to evaluate these models using various statistical tests and comparative indices (quantitative analysis).

(3) To select and recommend the most appropriate models with optimum number of variables for a given site such that the gain in accuracy outweighs the model intricacy.

(4) To propose region-wise models by striking a balance between generalizing a model and accuracy of prediction.

(5) To demonstrate the application of solar radiation data with reference to energy production.

The work is to be demonstrated for a number of worldwide locations with varying climates and topography and both hourly as well as daily radiation models are to be developed. The site-specific models are also to be analysed to find out if they possess any appreciable correlations between different locations.

## 1.7.3 Outline of the thesis

Chapter 1 gives the introduction to the thesis with a bird's eye view. It starts from a very broad subject of energy, narrows down to renewable energy further to solar energy and then further still to the core topic of solar radiation. It also provides the background, statement and objectives of the present research problem.

Chapter 2 deals with literature review covering the following topics: (a) techniques of measurements, measurement uncertainties and quality assessment of data, (b) available solar radiation models in general and diffuse radiation models in particular and finally, (c) the various statistical means commonly used for comparison and evaluation of models.

Chapter 3 deals with information on presently used database. It also gives an account of data compilation of hourly and daily values and quality control to obtain ready-to-use filtered data sets.

Chapter 4 involves qualitative investigation of presently chosen parameters of sunshine fraction, cloud cover and air mass on clearness index and diffuse ratio relationship. It is in this chapter that the relative effect of each parameter on diffuse radiation is established prior to their inclusion in regression models.

Chapter 5 presents the modelling procedure for hourly diffuse radiation using the three parameters of sunshine fraction, cloud cover and air mass, besides global radiation. The models are inter-compared by the means of various statistical indicators and comparative indices, briefly described therein. Finally, the optimum models are selected and proposed.

Chapter 6 deals with developing daily diffuse radiation models by using daily sunshine fraction and daily averaged cloud cover as additional parameters apart from daily global radiation. The models are evaluated using the same statistical means as in Chapter 5,

however, this chapter also includes a strongly-founded validation strategy to propose region-wise daily diffuse irradiation models.

Chapter 7 demonstrates the potential for solar  $H_2$  economy in an Indian perspective for year 2025. The study presents economic feasibility of the proposed electricity network for six major Indian sites based on the available solar radiation data.

Chapter 8 draws up important conclusions from each aspect of the presented work and also discusses the potential for future work.

The structure of the thesis is pictorially shown in Fig. 1.5.

## 1.8 Summary

This chapter provided elaborate introduction to energy, its various components, associated issues and challenges, current and future status. Significance of renewable energy resources was established and various such forms discussed. Solar Energy was addressed in detail as this forms the basis of present project. Solar radiation and underlying fundamentals were briefly discussed. The need for solar radiation data was discussed and the need for modelling such data was also emphasised. This was followed by stating the research problem, its aims and objectives and finally, structure of the thesis.



Fig. 1.1 Historical and future trends of energy systems (reproduced; source: Powerline, 2000)



Fig. 1.2 General applications of solar energy (Courtesy: NREL publication: 'Shining on')







Fig. 1.3 Napier University's PV installation (a) PV façade (left) (b) Inverters set-up, (topright) (c) Inverter displaying the PV output (bottom right)



Fig. 1.4 Spacecraft utilizing solar photovoltaics (Courtesy: NASA, <u>http://planetquest.jpl.nasa.gov/SIM/sim\_index.cfm</u>)



Fig. 1.5 Schematic flow chart illustrating the chapter-wise thesis layout

Country	Emissions of carbon equivalent in kg	Factor by which present emissions			
÷	per person per year	exceed sustainable level			
	(base 2000)	(of 500 kg per person per year)			
US	6718	13.4			
Germany	3292	6.6			
France	2545	5.1			
India	247	0.5			

Table 1.1 Status of carbon emissions (Arthus-Bertrand, 2003)

Table 1.2 Atmospheric carbon emissions (GtC) from fossil fuel use since 1860 compared with remainingknown and unconventional reserves and resources on a global scale (Sims, 2004)

Status of reserves		Gas	Coal	Totals
Known reserves		87	1111	1307
Estimated reserves		180	2606	2944
Unconventional reserves	446	297	-	743
Cumulative emissions	713	564	3717	4994 <sup>*</sup>
Emissions from				
1860-1998		43	152	304

\* Potential emissions from exhaustive consumption of fossil fuels

## CHAPTER 2

## **REVIEW OF THE RELEVANT LITERATURE**

In context of the present research project, modeling of solar radiation data has three core aspects. Carrying out solar radiation measurements or acquiring the measured data forms the first aspect. It also includes processing and filtering to obtain 'clean consistent datasets'. The second aspect deals with the modeling methodology itself. Third aspect involves comparison and evaluation of the performance of models, so as to propose the 'best' model. This chapter is accordingly sub-divided into three sections. The first section 2.1 reviews the existing techniques of measurements and quality assessment of data. Next, section 2.2 provides a comprehensive yet summarized coverage of many important solar radiation models available in literature. Section 2.3 reviews the various statistical means employed by the model-developers and investigators to assess the model performance.

## 2.1 Measurement and Processing of Solar Data and other Meteorological Parameters

## 2.1.1 Brief history of solar radiation measurement

Solar radiation has been a subject of interest throughout history. The earliest investigation of the sun and its properties was, most probably, that of Galileo Galilei (1611) following the famous invention of telescope. Since then, much of the seventeenth century, some of the eighteenth century and whole of the nineteenth century saw various discoveries and explanation of now well-known concepts such as: spectral character of light, law of refraction, phenomenon of diffraction, light's speed, wave theory of light, polarization of light, electromagnetic theory of radiation, the colour of sunlit sky, radiation scattering, polarization's wavelength dependence, solar radiation absorption by water vapour, etc.

Among the earliest inventions in radiation instrumentation is the electrical compensation pyrheliometer by Knut Ångström (1899), which is still used as standard

for absolute radiant energy determinations in many countries of the world (Coulson, 1975). Later, Anders K Ångström using the same principle as his predecessor constructed an instrument, what is now known as pyrgeometer, to measure nocturnal long-wave atmospheric radiation. Some examples of the pre-World War II solar radiation measuring instruments under the pyrheliometer and pyranometer categories, respectively, are:

Water-flow type, the silver-disk type (currently used for reference), Eppley, Linke-Feussner, Yanishevsky and Michelson pyrheliometers. Modified versions of the latter four are still operational, the basic designs of which were developed prior to 1940.
Kimball-Hobbs, Moll-Gorczynski and Robitzsch and Bellani pyranometers.

Since 1945, many advances have taken place in instrumentation technology and new improved versions have been introduced. Incorporation of temperature circuits in Eppley type instruments, use of thermopiles to replace the conventional resistance strips in Ångström-type pyrheliometers, redesign of collimator tube for pyrheliometers, sealing the enclosed air space and installation of black discs at the receiver of pyranometers are to name a few. Computerized data loggers / electronic data acquisition has revolutionized the traditional time-consuming methods of data-handling.

*Note:* Most of above section's review is a summary of the work: 'Milestones in Radiation Research', Chapter 1, Sec 1.3 of Coulson (1975).

## 2.1.2 Solar radiation instruments (radiometers)

Solar radiation measurements can broadly be classified as: *ground-based* measurements carried out at specific locations on earth and measurements derived from geostationary *satellites* which measure the energy reflected by the system (earth/atmosphere) in different wavelength bands (ESRA, 2000). Since the input radiation of the models developed under this project is the 'ground-source', the foregoing literature review only focuses on ground-based measurements.

Routine measurements of diffuse, global and direct radiation on a horizontal surface are carried out by an agency, such as the national meteorological office. Generally, this is also a body responsible for maintaining and monitoring a network of all the meteorological stations within a country. Some of the commonly employed instruments for measuring the different radiation components will briefly be discussed here. Main thrust will be laid on the instruments used to measure the descriptors/parameters involved in the present research project.

Every radiation instrument needs a *detector* or *sensor*. They can be broadly classified into four main types: *calorimetric*, *thermomechanical*, *thermoelectric* and *photoelectric*. Description of each type can be found in Garg and Garg (1993).

*Pyrheliometer*- measures the direct solar radiation  $(W/m^2)$  at normal incidence. It comprises of a narrow cavity tube known as collimator with an optimum aperture of about 6 ° to completely include sun's disc in the field of view excluding much of the scatter radiation at the same time. It uses a fast-response multi-junction thermopile detector placed inside the collimator. Pyrheliometer is usually attached to a suntracking equatorial mount driven by electricity. Figure 2.1 shows a few types of pyrheliometer.

Pyranometer- measures the global (diffuse and direct, together) solar radiation  $(W/m^2)$ , received from the whole hemisphere. This hemisphere is usually the complete sky dome. The instrument consists of a flat, blackened thermopile detector mounted on a base covered by a hemispherical glass dome. Figure 2.2 is a picture of CM11 type-pyranometer. A 'spherical pyranometer' or a pyranometer in a tilted position, to additionally measure the ground reflected radiation, can also be used. Here, the working principle of a pyranometer, in general, and of CM 11, in particular, is given as described by Muneer (2004). The detector responds to the total power, unselective to the spectral distribution of the radiation absorbed. The heat generated by the absorption of radiation by the black disc flows through a thermal resistance to the heat sink. The resultant temperature difference across the thermal resistance of the disc is converted into a voltage, which can be read by computer. Double glass construction of the CM11 minimizes temperature fluctuations from the natural elements and reduces thermal radiation losses to the atmosphere. The glass dome requires periodical cleaning to remove the debris that often gets collected over the time. The presence of silica gel crystals in the body of CM 11 pyranometer prevents moisture accumulation.

*Pyranometer with a shading device-* measures diffuse solar radiation  $(W/m^2)$ , by use of a fitted shade ring or disk shading the sun's direct radiation. Also known as shadow band, the former is a stationary device (with respect to east-west axis), aligned or set parallel to the earth's polar axis. It needs repeated adjustment to account for variation in sun's declination angle. A pyranometer with a shade ring is shown in Fig. 2.3. Occulting disk on the other hand is sun-synchronous i.e. tracks along with the sun and therefore, more expensive. It provides more accurate estimation of diffuse radiation because, it doesn't block off the portion of diffuse radiation as shade ring does.

Based on features like sensitivity, stability, linearity, etc., the World Meteorological Organisation-WMO (1965) classified the pyrheliometers in standard, first and second class category and pyranometers in first, second or third class. Since all of the developed pyranometers require calibration with respect to a primary radiation standard, none of them could be classed as standard (Coulson, 1975). Table 2.1 enlists the classification largely based on Coulson (1975) but with a slightly updated version from Garg and Garg (1993).

Global, direct and diffuse irradiation components are related to each other by the following fundamental equation:

$$G = D + B_n \sin SOLALT$$
(2.1)

Solar altitude can easily be calculated by temporal (time, day, month) and geographical (latitude) knowledge. Thus, theoretically if two of the three radiation components are measured the third can be evaluated using Eq 2.1.

Measurement of beam (direct) normal irradiance is an expensive affair. The collection of pyrheliometric data can be very expensive not only in terms of equipment costs but also the high level maintenance costs that this type of instrument incurs. According to one estimate, the direct equipment cost of a pyreheliometer itself is almost six times the expense of alternate collection methods, e.g. shaded pyranometer measurements (Muneer, 2004). However, even though used world-wide, lesser expensive alternatives such as above, compromise on the accuracy of radiation measurements compared to that obtained from pyrheliometers.

Besides the two main types of radiation instruments discussed above, following instruments are also used to measure solar radiation.

*Albedometer-* measures both global solar radiation as well as reflected radiation, yielding albedo value as an output. This instrument is generally installed several metres above the surface to ensure precise measurement.

*Pyrgeometer*- measures long-wave radiation. The dome is mirrored in a way to reflect maximum possible short-wave radiation from the sun and has filters which allow only infrared radiation (3-50 micro m) to pass. It is often used in combination with a shading to ensure the exclusion of direct solar radiation.

*UVmeter-* as the name suggests, measures the ultra-violet part (UV-A: 0.351-0.400 micro m or UV-B: 0.280-0.315 micro m) of the spectrum measurable at earth's surface.

All the above-listed instruments fall under the category of broadband instruments. Some examples of spectral instruments are: sky scanners, sunphotometers, multi-filter shadow band radiometers, rotating shadowband spectrometers, spectroradiometers, interfreometers and grating spectrometers (Gueymard and Kambezidis, 2004).

## 2.1.3 Measurement of bright hours of sunshine

Sunshine has a direct impact on the components of solar radiation. Daily and hourly records of amount of sunshine not only are useful in various regression models for radiation estimation, but they also aid in the design and simulation of many solar energy application systems.

The duration of bright sunshine is the time during which the sun's disk is visible in a given period of time. The most simple, inexpensive and widely used instrument for registering the hours of bright sunshine is Campbell Stoke's sunshine recorder. It was adopted as a standard of reference known as the 'Interim reference sunshine recorder-IRSR' by WMO (the World Meteorological Organisation) in 1962 and recommended to be used as reference for all future sunshine records (Garg and Garg, 1993). The principle behind this instrument is the use of a glass bowl which burns a track of the

sun on a registration paper if sun is shining with sufficient intensity. A threshold value of 120 W/m<sup>2</sup> is implemented artificially to meet a WMO convention which aims to keep data measured with different types of instruments homogenous (ESRA, 2000). Figure 2.4 illustrates pictures of Campbell Stoke's sunshine recorder. Although the sunshine recorder is an economic and robust device, there are a few well-known errors associated with its use, such as:

- Intermittent sunshine over burns the paper which consequently results in over estimates of sunshine duration
- Owing to the threshold sensitivity, the recorder doesn't register a burn on the paper below a certain level of incident radiation, leading to underestimation.
- Regardless of the clear and cloudless day, the burn doesn't commence until 15-30 min after sunrise and doesn't cease about the same period after sunset (Muneer, 2004). This 'lapse' varies with season and also to a certain extent with location.
- The performance of the glass sphere deteriorates with weather conditions and insufficient maintenance thereby giving in inaccurate results.

Using a 120 W/m<sup>2</sup> direct solar beam as a threshold distinction between sun and no sun, Forgan (2004) showed that a difference of more than one hour per day, relative to the historical records produced by the Campbell Stokes Sunshine Recorder, can be made with daily mean sunshine duration uncertainties on the order of 0.5 hours. Many weather stations have now switched from paper-based to electronic sunshine loggers. As a result, ambiguities associated with over-burn, underestimation of sunshine hours and moisture deposition on the registration paper in the conventional type of instrument are no longer a concern (Gul et al, 1998). Delta-T, a Cambridge (UK)-based company developed a new instrument- BF3 sensor that measures the horizontal global and diffuse irradiance along with sunshine duration all from a single stationary sensor. Its chief advantages are: neither requires any sunshine card nor shade-ring, the electronic outputs are compatible with electronic data loggers and works at any latitude (Muneer, 2004). BF3 sensor has been tested by Wood et al (2003) who concluded that it yields reliable radiation measurement and sunshine hours within the WMO accuracy requirements.

Marving- Marvin is another sunshine recorder falling under the same category as Campbell Stoke's, which uses heat of direct solar radiation for activation. Further two classifications based on the principle involved are: photochemical and photoelectric type sunshine recorders. Jordan, Pers and McLeod fall under former, whilst Foster sunshine switch is an example of latter. Details of these instruments can be found in Coulson (1975).

## 2.1.4 Cloud cover measurements

Diffuse radiation is highly sensitive to the presence of clouds (Halthore, 1999) and hence, cloud information is an important determinant for solar radiation. Traditional cloud cover observations are taken at a great number of stations as there are no instruments involved. Cloud cover is visually observed by dividing the sky vault into 8 regions- 4 azimuthal quadrants and 2 zenithal elevations. Using this framework, the observer decides whether each sky region contains clouds and thus reports cloud cover in octas on a scale of 0 to 8, where 0 denotes clear sky and 8 denotes overcast sky. The US standard is to convert octas in tenths before reporting. Moreover, cloud cover is also reported for three cloud altitudes: low, middle and high clouds (Perez et al, 2000).

In mid 1990s the US National Weather Service began switching an increasing number of stations to automated cloud cover measurement system. This technique of cloud measurements uses a ceilometer (Fig. 2.5) that detects the presence and altitude of clouds directly overhead (Perez et al, 2000). Celiometer sees only a narrow region at the sky's zenith and, as pointed by Muneer (2004) for laser technique, works on the assumption that what passes overhead is representative of the whole sky. Nevertheless, it provides a time continuous stream of data as opposed to the single spot reading of the cloud amount in previous method. Within the UK, cloud cover is measured at night using laser cloud based recorders. Another technique often used to collect night-time cloud information i.e. height and amount is the estimation by trained human observers using a spotlight and alidade, as was the case with data used in CIBSE Guide J 2002 (Muneer and Fairooz, 2002). The height of the cloud can be evaluated (by trigonometry) when a spotlight is made to shine vertically upwards illuminating a spot on the cloud base and the observer uses an 'alidade' located some distance away to measure the angle of the spot (Muneer, 2004).

Cloud cover reporting is free from instrumentation misalignment and calibration error. However, it is subject to perspective errors (Barker, 1992). Cloud cover is known to be subjective and doesn't give an explicit indication weather the sun was obscured during the period. Under broken cloud, for instance, with the sun shining through, global irradiance exceeds the corresponding clear-sky receipt, as both direct and diffuse components are augmented by reflection off the clouds (Muneer, 2004). More so, Perez et al (2000) demonstrated in their study of cloud cover observations carried out at several US airports and stations, that human observation of cloud cover is not free from bias; the bias tends to be greater in the observations carried at larger airports.

Clouds can also be estimated using satellites. However, such information is fairly incomplete as it only accounts for the top-layer of the clouds as seen from above the earth.

# 2.1.5 Uncertainties and errors associated with solar radiation measurements2.1.5.1 Calibration uncertainty

Calibration is an integral part of any measurements. For that reason, the World Meteorological Organization (WMO) at the Physical Meteorological Observatory, (Davos, Switzerland), established the World Radiometric Reference (WRR) using a group of "absolute cavity" pyrheliometers (ACP) in 1983. Also known as active cavity radiometer (ACR), they 'are based on measurement of electric current and voltage to produce power equivalent to heating of a 'cavity' trap detector that is equivalent to the power absorbed when trapping solar radiation' (Myers, 2005), thus providing absolute irradiance calibration.

Field instruments, pyranometers and pyrheliometers, are calibrated against these working reference cavity radiometers. The net uncertainty in the reference irradiance direct beam component measured with a working reference ACP is 0.45% (of which 0.35% is the overall uncertainty in the WRR scale plus 0.1% transfer uncertainty from laboratory use to outdoors calibration) or  $5 \text{ W/m}^2$  at 1000 W/m<sup>2</sup> direct irradiance. The diffuse radiation component during an outdoor calibration requires characterizing the responsivity of a reference pyranometer for the shaded measurement. To

determine this responsivity, pyranometers are calibrated by the shade/unshade technique wherein the pyranometer is alternatively shaded and unshaded to obtain by difference of total and diffuse irradiance, the vertical component of direct-normal irradiance, which is then compared to the corresponding value measured by an ACP (Halthore, 1999). Procedures for acquiring shade/unshade calibration data are described in the American Society for Testing and Materials Standard E-913 (Myers, 2005). In general, a pyranometer should have the following characteristics: (a) The calibration factor must be independent of temperature, and (b) It should not be wavelength-selective (Garg and Garg, 1993).

## 2.1.5.2 Sources of error

Absolute measurements do not exist! Some of the common sources of error are: lack of maintenance either of instruments or data recording equipments, calibration errors and sometimes unsuitable instruments (ESRA, 2000).

## Equipment-related errors

There are some inherent features of the equipments that also contribute towards errors. For example, one of the major causes of errors in pyranometer measurements is the *cosine effect*. This is the sensor's response to the angle at which radiation strikes the sensing area. The more acute the angle of the sun, i.e. at sunrise and sunset, the greater will be the error (at altitudes below 6 °). Cosine error is typically dealt with through the exclusion of the recorded data at sunrise and sunset times. The azimuth error is the result of imperfections of the glass domes and in the case of solarimeters, the angular reflection properties of the black paint. This is an inherent manufacturing defect which yields a similar degree of uncertainty as the cosine effect. As for the temperature response, CM11 pyranometers have a much less elaborate thermostatic control. They rely on two glass domes to compensate for large temperature swings. The spectral selectivity of the pyranometers is dependent on the spectral absorptance of the black paint and the spectral transmission of the glass. The overall effect contributes only a small error percentage to the measurements. Each sensor possesses a high level of *stability* with the deterioration of cells resulting in approximately  $\pm 1\%$ change in the full-scale measurement per year. Pyranometers with all-black receivers are barely in thermal equilibrium outdoors. Thermal energy exchange between the absorbing sensor, dome and sky, results in a net negative *thermal offset* in the

thermopile voltage signal. Myers (2005) noted in his article, that this offset is sitedependent, depending on the thermal environment for the climate where the equipment is installed. The effect of thermal offset is more pronounced at night-time due to nocturnal radiative cooling. Exclusive to diffuse radiation measurement is the *shadow band error*. Shadow band/ring not only obscures the sun throughout the day, but also obscures some portions of the sky amounting to a correction of 4% of diffuse irradiance. On the other hand, a shadow 'disc' blocks mainly the sun and the aureole; about 2% correction in this case (Halthore, 1999).

#### **Operational errors**

Care should be taken to avoid operational errors resulting from incorrect levelling and orientation of sensors, as well as improper screening of the vertical sensors from ground-reflected radiation. There are a number of well-recognized operational errors, some of which are demonstrated via clearness-index versus diffuse ratio plot in Fig. 2.6 (*Courtesy*: Muneer, 2004). Others are pertaining to the surroundings, like building structures blocking the sensor's view or electric fields in the vicinity of cables, mechanical loading on cables, etc. Processing errors, such as incorrect diffuse shade ring correction factor, inaccurate programming of calibration constants, are among others.

*Note:* Description of first five equipment-related errors and all of the operational errors listed above was extracted from Muneer (2004).

## 2.1.5.3 Measurement uncertainties

Drummond (1956) estimates that accuracies of 2-3% are attainable with first class pyranometers for daily summation. For individual hourly summation this is in excess of 5% even with carefully calibrated equipment (Muneer and Fairooz, 2002). Coulson (1975) infers errors associated with routine observations to be well in excess of 10%. In case of isolated poorly maintained equipment but those part of regular network, monthly averaged errors of 10% or more may be prevalent. Halthore (1999) observed from his experience of pyranometers, that the uncertainty in measurement of diffuse irradiance is  $\pm 5$  W/m<sup>2</sup> at the 75% confidence limit and  $\pm 8$  W/m<sup>2</sup> at the 95% confidence limit, much larger than measurements using ACRs which differ from each other typically by about 1 W/m<sup>2</sup> in a measurement of 1000 W/m<sup>2</sup>. Geiger et al (2002) quoted the WMO published figures for the achievable relative uncertainty at 95% confidence level: 3%, 8% and 20% in case of hourly sums and 2%, 5% and 10% for daily summation for operational parameters of high, good and moderate quality, respectively (Muneer, 2004). Myers (2005) reported the possible range of measurement errors or uncertanities between +25 and -100 W/m<sup>2</sup> in pyranometeric data, and  $\pm$  25 W/m<sup>2</sup> in pyrheliometeric data occurring under clear-sky conditions.

## 2.1.6 Proposed methods to improve the quality of data

The measurement uncertainties and errors resulting in unknown or questionable quality of data make it incumbent for the measured data sets to go through a quality assessment procedure prior to their use for modelling. Many such quality control algorithms for filtering the solar data have been proposed in the past, some of which will be reviewed in Section 2.1.6.1. Section 2.1.6.2 following that, will address the shadow band error and review the various methods proposed in the literature for shadow band correction to rectify the measured diffuse radiation data.

## 2.1.6.1 Quality assessment of the data

*Reindl et al (1990)* - They proposed a series of filters to exclude the following spurious data:

- A day with even one missing hourly data (either global or diffuse)
- Diffuse ratio; k (diffuse/global radiation) >1
- Beam transmittance index (beam/extraterrestrial radiation) >1
- k < 0.90 when  $k_t < 0.20$  (overcast sky), and
- k > 0.80 when  $k_t > 0.60$  (clear sky)

*US NREL (1993)* - The three solar radiation data elements - global horizontal, diffuse horizontal, and direct normal - are quality assessed using SERI QC, a procedural and software package developed by the National Renewable Energy Laboratory (NREL). Below is a summary of key features obtained from the web link provided with the reference.

SERI QC defines ranges of acceptable data, depending on whether one, two, or all three hourly data elements are present. Ranges are defined based on dimensionless parameters normalized with respect to extraterrestrial radiation, where K<sub>t</sub> and K<sub>d</sub> are

the clearness index and diffuse transmittance, respectively, as defined elsewhere in the thesis, and  $K_n$  is the ratio of direct normal radiation to extraterrestrial direct normal radiation. Depending on the circumstances, SERI QC performs one-element, two-element, or three-element tests.

- First, it performs a one-element test by defining a range of acceptable values between minimum and maximum values of K<sub>t</sub>, K<sub>d</sub>, or K<sub>n</sub>, depending on the element being tested, based on three air mass regimes and the month of the year.
- Second, if the zenith angle (at the middle of the hour) is less than or equal to 80°, and all three of the elements are present, SERI QC performs a three-element test by defining a range of acceptable values so that the equation  $K_t = K_d + K_n$  is satisfied within an arbitrary error limit of  $\pm 0.03$ , which accounts for measurement uncertainties.
- Third, if the data pass the three-element test (or only two elements passed the one-element test), SERI QC performs a two-element test by defining a range of acceptable values within boundaries empirically determined for three different air mass regimes for each month using data collected at the site.

After all SERI QC tests are completed, flags are assigned to the data. The SERI QC flagging system permits the assignment of uncertainties that are dependent on the nature of the test performed (one, two or three components) and the distance by which the data point exceeds expected limits.

SERI QC has some demerits, like: for some seldom occurring conditions, data depicting real conditions may reside outside the boundaries and be flagged as bad data. Likewise, bad data can also be flagged good by SERI\_QC. For overcast sky conditions, SERI\_QC does not detect an improperly adjusted shadowband because  $K_n = 0$  and  $K_t = K_d$  within its arbitrary error limit.

*CIE automatic quality control (1994)* - The Commission Internationale de l'e'clairage (CIE) has proposed quality control tests for radiation as well as illuminance. Briefly summarising, it comprises of five levels of test;

- The first is to set rough boundary limits for global and diffuse irradiance and direct irradiance to be less than the extraterrestrial irradiance
- Second level tests ensure consistency by utilizing the redundancy between the three solar radiation components, or the diffuse to be less than the global plus 10% allowance for shade ring correction, where beam irradiance is not measured.
- Third test is related to the north, east, south and west global irradiance and illuminance.
- Fourth level test allows inter-comparisons between irradiance and illuminance.
- Fifth level test compares the zenith luminance with either diffuse irradiance or illuminance.

CIE recommends automated testing to be performed when solar elevation and the global irradiance are greater than 4 ° and 20  $W/m^2$ , respectively (Younes et al, 2005).

*ESRA (2000)* - All daily totals of solar radiation data were controlled using the following steps:

- Solar radiation values had to be less than extraterrestrial values, sunshine duration values had to be less or equal the corresponding astronomical value.
- Solar radiation values had to lie within the range of the expected clear-sky extreme values considering the influence of the atmospheric layer.
- Values of solar radiation parameters had to be in a specific range compared with nearby station values with allowance for spatial variability.
- Basic relationships between different radiation components should be fulfilled.
- Variation of the relative terms G/E of the Angstrom regression should lie within a defined range.

*QC for Page model (1997, 2000)* - The Page model is based on the work undertaken for the production of the European Solar Radiation Atlas (ESRA, 2000) and the CIBSE Guide on weather and solar data (Page, 1997). Page sets the overcast and clear-sky irradiance as the upper and lower limits for diffuse irradiation. For global

radiation, the upper limit is set by the global clear-sky model, details of which are provided by Muneer (2004).

*Muneer and Fairooz quality control procedure (2002)* - The Muneer and Fairooz (2002) quality control procedure is a four levels test with emphasis on two components of radiation, namely, global and diffuse. It is based on tests recommended by CIE and Page irradiance model.

• First test partly adopts CIE's first level of quality control, i.e.  $0 < G < 1.2 E_n$  (2.2)  $0 < D < 0.8 E_n$  (2.3)

where,  $E_n$  is the normal incidence extraterrestrial irradiance, 1367 W/m<sup>2</sup> (solar constant).

- Second test includes consistency between diffuse and global, and between global and horizontal extraterrestrial irradiation.
- Third test is based on established and expected diffuse ratio clearness index regression envelope such that the diffuse radiation data conforms to the limits set out by this envelope of 'acceptance'.
- Fourth test: a check on diffuse irradiance is established by comparing its value with corresponding values under very clear and heavily overcast regimes as set by Page (1997).
- Fifth level test is a final measure of check on diffuse and global irradiance by investigating the Linke turbidity values; for example, a value less than 2.5 or greater than 12 requires closer inspection of the corresponding data.

In reference to the graphical procedure used in the third level test of Muneer and Fairooz QC procedure, Younes et al (2005) have proposed an envelope of acceptance based on a new standard deviation procedure. Their procedure essentially categorises diffuse ratio – clearness index in bands of k<sub>t</sub>. Outliers are identified as data points lying outside the envelope defined by  $\overline{k} \pm 2\sigma_k$  boundaries for any given k<sub>t</sub> band.

Muneer (2004) noted that there is a need to fill-in the 'holes' within the dataset produced as a result of discarded erroneous data during the filtering process . Unless this procedure is undertaken, the time series would be incomplete and simulation programmes in particular are prone to hick-ups with such problems. Gaps identified within the dataset may either be filled by the generation of irradiation data from wellestablished models using synoptic data such as sunshine or cloud cover, or by data averaging techniques such as that proposed by Rymes and Myers (2001).

There are some other web-based test procedures and tools for quality assessment of solar radiation in literature such as that by Geiger et al (2002), and Molineaux and Ineichen (2003) (reader is referred to Muneer, 2004 for further information). A data set of solar radiation values that has passed the QC procedure, nevertheless, must be examined for its uncertainty that is transferred from a measuring sensor to the actual measurement. (Gueymard and Kambezidis, 2004).

## 2.1.6.2 Shadow band correction

Shadow band for diffuse radiation measurement is an economical option but unfortunately also shades a portion of the sky. This shading induces underestimation of diffuse radiation thus significantly affecting measurement accuracy. It is noted by Muneer (2004) that shading can lead to a maximum error of up to 24% in the true diffuse irradiance value and hence a correction factor needs to be used. Drummond (1956) developed a simple model for this correction factor based upon solar geometric calculations, which can be applied anywhere in the world. He calculated the proportion of the sky area that is subtended by the shadow band 'f', from which the correction factor can be deduced by the means of following equation:

 $C_D = 1/(1-f)$  (2.4)

Drummond concluded that this geometric correction factor is sufficient for uniform or isotropic sky conditions but that an additional correction of up to 7% and 3% should be applied under cloudless and overcast/cloudy sky conditions, respectively. His correction factor, however, does not take into account the circumsolar radiation blocked by the shadow ring, which is by definition anisotropic with respect to the hemisphere as viewed by the horizontal surface. Kudish and Ianetz (1993) presented the following review of various studies in literature that consider it necessary to apply an anisotropic correction factor, in addition to the geometric correction factor. Painter (1981) measured diffuse radiation by using an occulting disk and shadow ring
pyranometer simultaneously. He observed that the magnitude of the anisotropic correction factor varied significantly with season and therefore correlated it with the declination angle and ratio of the diffuse radiation as measured by the shadow ring to the global radiation. Painter's results, as reported by him, were specific to conditions of his experiment; particular to the shadow ring pyranometer, specific latitude and for the general prevailing state of sky and atmospheric turbidity. Ineichen et al (1984) determined the shadow band correction factor by means of two simple models; one was based on isotropy of diffuse radiation and the other on the diffuse radiation density as a function for solar altitude. Kasten et al's (1983) anisotropic correction factor was a linear function of three parameters, namely, the diffuse ratio (obtained after applying isotropic correction to diffuse radiation), the solar declination, and the extinction coefficient for beam transmission. Stevens (1984) developed a simple model of sky radiance as the sum of a uniform background and circumsolar component. Stanhill (1985) and Kudish and Ianetz (1993) applied Steven's model to determine the shadow ring correction factors to diffuse sky radiation measurements at Quidron on the Dead Sea, and Beer Sheva, Israel, respectively. The former found the correction factor under anisotropic conditions to vary between 14 and 30%. The latter authors reported a variation range of 2.9 to 20.9% for the monthly average hourly anisotropic correction factor and that from 5.6 to 14% for geometric correction factor (Kudish and Rahima, 2005).

LeBaron et al. (1990) developed a model using four parameters. One of the parameters is Drummond's correction factor and the other three are, zenith angle, and two dimensionless indices for sky's clearness and brightness- one as a function of cloud conditions and the other as a function of cloud thickness or aerosol loading, respectively. Thus, the LeBaron model takes into account both isotropic and anisotropic conditions, characterized by the latter three parameter, to determine the correction factor. Battles et al (1995) model is based upon multiple linear regression equations employing the four parameters used in LeBaron et al's approach. In Battles model, the values of LeBaron's sky clearness index determines which equation to be applied for calculating the correction factor i.e., each equation is applied only if this parameter falls within a corresponding given range. Muneer & Zhang (2002) relatively recently developed a model based upon an anisotropic sky-diffuse distribution theory. The sky distribution is two dimensional, a function of any given

sky patch geometry (altitude and azimuth) and the position of the sun. The diffuse radiation (D) is obtained from the zenith radiance and two parameters corresponding to the radiance distribution indices for the two sky quadrants containing the sun and opposed to the sun. Their correction factor is given as:

$$C_{M-Z} = 1/(1 - F/D)$$
 (2.5)

where, F is defined by a complex empirical equation using declination, latitude, solar hour angle and view angle of the shadow ring subtended at the diffuse irradiance sensor. According to Muneer and Zhang their model represents a compromise between simplicity of an isotropic model and complexity of a two-dimensional model, besides the robust nature and general applicability.

#### 2.2 Radiation Modelling

The need for modelling the solar data was highlighted in Chapter 1. This section reviews some of the major landmark models (correlations or regressions, as one may call it) in the history of solar radiation.

Irradiance can be divided into two categories: short-wave and long-wave. While global and of course, its two components, fall in the former category, infra-red irradiance is an example of latter. Short-wave irradiance can further be perceived as broadband or spectral, and, therefore, modelled accordingly. Although, a quick review of spectral models will be helpful herein, since this project strictly deals with modelling of broadband radiation only, emphasis is laid on the latter. In the present study all the measurements involved are ground-based, therefore, the review would largely be focussed on models and modelling techniques developed for ground-based measurements. However, for the purpose of knowledge, a brief summary of satellitebased models will also be included. While a detailed description would be provided in the following sub-sections, a general classification of solar radiation models is presented in Fig. 2.7 with special emphasis on the different types of broad-band radiation models available in literature. In general, model complexity increases from left to right; involvement of greater number of parameter or complex phenomenon in case of broad-band models and spectral breakdown and high resolution requirement in spectral-type models. Satellite based models, being inherently different, although

cannot be branded under the same flag, nevertheless, have other challenges and complexities associated with them. However, in reference to the terrestrial or groundbased models, generally accuracy of models increases with model intricacy from left to the right side across the figure. Presently proposed diffuse radiation models can be located within the models' classification as highlighted in Fig. 2.7. It is worthwhile to note here, that often a model incorporates the attributes of more than one category. Therefore, the above classification should be seen more on a continuum rather than discrete basis.

It is to be noted that the word radiation, from hereon, would be used to refer to the radiation measured (or predicted) on a *horizontal* surface, unless otherwise stated.

In the past innumerable radiation models have been proposed. Many researchers have tested and modified them over the time. Very broad classification of such models leads to two general types:

(1) Models that estimate either diffuse or direct or both from the knowledge of global radiation alone;

(2) Models using meteorological parameters, with or without global radiation, to estimate the different solar radiation components.

# 2.2.1 Estimation of solar radiation components from global radiation

This class of models is commonly known as 'decomposition models of global into diffuse and direct/beam irradiance'. Models have extensively been developed based on inter-correlations between ratios such as K<sub>t</sub>: clearness index (global/extraterrestrial horizontal radiation), K: diffuse ratio (diffuse/global radiation) or K<sub>d</sub>: diffuse transmittance index (diffuse/ extraterrestrial radiation), and/ or K<sub>b</sub>: hourly beam transmittance index (direct/extraterrestrial radiation). Note that small lettered k(s) specifically refer to hourly radiation values, whilst capital lettered K has been used for general reference in this section and also for daily values.

#### 2.2.1.1 Diffuse ratio- clearness index regressions

One of the most common and popular estimation techniques in literature and for practical use in solar resource assessment has been the use of global radiation to estimate diffuse radiation. In this regards, the first regression model based on K-K<sub>t</sub>

was proposed by Liu and Jordan (1960). Since then, this correlation relationship has evolved over the time and its coefficients have been modified for different locations and also different time scales, i.e. monthly-average, daily or hourly radiation models.

# Monthly-average radiation

Page (1961) using data from 10 widely-spread sites in the 40° N to 40° S latitude belt derived a linear relationship between monthly-average K and K<sub>t</sub>. Following Page's approach, many linear type monthly-average K- K<sub>t</sub> models have been proposed in the literature. Erbs et al (1982) proposed third degree polynomial regression for monthly diffuse fraction.

#### Daily radiation

The pioneering work of Liu and Jordan (1960) involved development of a regression between daily clearness index and daily diffuse ratio using data from one location, Blue Hill, MA. In the same study, they also used a statistical distribution of global irradiation to develop a regression between monthly-average diffuse and global irradiation. Later, other researchers, like Choudhary (1963), Stanhill (1966), Tuller (1976) used the Liu-Jordan relationship for New Delhi, Gilat and four Canadian locations respectively. They came to the common conclusion that the diffuse ratio showed a significant departure (being higher than the modelled) from that suggested by Liu and Jordan. Both Choudhary and Stanhill attributed this deviation to the presence of higher dust content in the respective locations. In his study, Tuller found individual trend for each location, attributing it to the latitude effect. Collares-Periera and Rabl (1979) used pyroheliometer data from five US locations and found their results closer to those of Choudhary and Stanhill than that of Liu and Jordan (1960). They concluded that this discrepancy of Liu and Jordan is due to reliance on uncorrected measurements of diffuse radiation (shade ring misalignment). Muneer and Hawas (1984) developed a regression based on 3 years data from 13 Indian stations between diffuse fraction as a third order polynomial of clearness index. They also concluded in their study, that no single regression (from the above mentioned) is applicable to all regions as each region has its own characteristics. Rao et al (1984) developed polynomial regressions based on daily data from Corvallis, Oregon. Saluja and Muneer (1985) developed a linear regression between daily diffuse fraction and

daily clearness index, based on 3 years data for five diverse locations in the UK. Within the same study, they also proposed a single regression for the country, asserting that there is no latitude effect. Lalas et al (1987) using data from Greek islands, proposed a linear regression on a daily basis. Oliveira et al (2002) proposed fourth degree polynomial and linearly varying diffuse fraction as a function of clearness index on daily and monthly average basis, respectively for the city of São Paulo in Brazil. Paliatsos et al (2003) found that a linear K- K<sub>t</sub> model to be optimum for diffuse radiation estimation in Balkan Peninsula (Greece).

A common methodology underlying most of the daily diffuse estimation models is to propose a piece-wise regression. This is achieved by developing piecewise fits to K- $K_t$  data for overcast, partly-cloudy and clear sky. Mathematical representation would, thus, be:

For overcast skies, the regression is generally given in a linear form (with some models assuming a constant value in the overcast regime):

$$K = a_0 + a_1 K_t, \qquad \text{for } K_t < K_{ta} \tag{2.6}$$

where, symbols have their usual meanings and  $K_{t\alpha}$  is a value (visually or empirically determined from the specific data in question) beyond which, partly cloudy conditions prevail.

For partly cloudy skies, a third-order (sometimes, fourth-order) polynomial in K<sub>t</sub> is generally used:

$$K = b_0 + b_1 K_t + b_2 K_t^2 + b_3 K_t^3, \qquad \text{for } K_{ta} < K_t < K_{tb}$$
where, K<sub>tb</sub> is a value corresponding to the advent of clear skies. (2.7)

Finally, for 'clear sky' conditions, a constant value is the widely-accepted choice:

$$K = c_0, \qquad \text{for } K_t > K_{tb} \tag{2.8}$$

Some of the authors of similar approach have also extended their work to propose single regression-polynomial that best fits the data.

One of the exceptions to this polynomial relationship between diffuse fraction and clearness index is model proposed by Bartoli et al (1982) given by a single empirical equation with fixed constant values and exponential power of  $K_t$ .

$$K = a + (1 - a) \exp[-bK_t^c / (1 - K_t)]$$
(2.9)

where, the parameters take the following values: a=0.154, b=1.062 and c=0.861.

#### Seasonal models

Some researchers have also investigated and reported seasonal variations for daily regressions, e.g., Tuller (1976), Collares-Periera and Rabl (1979), Erbs et al (1982), Rao et al (1984), Vignola and McDaniel (1984), Chandrasekaran and Kumar (1994) for a tropical site (Madras) and by Jacovides et al (1996) for Cyprus data.

#### Hourly radiation

Orgill and Hollands (1977) followed the Liu and Jordan approach in correlating the diffuse ratio to clearness index except on an hourly basis. Their study was based upon four years data from Toronto (Canada). Bugler's (1977) model correlates the hourly diffuse ratio to the ratio of hourly global radiation and the estimated clear sky radiation. Erbs et al (1982) used 65 months of data from 5 locations in USA to develop regression between diffuse ratio and clearness index, for hourly, daily as well as monthly average data. They proposed a fourth degree and a third degree polynomial for daily and monthly average diffuse ratio, respectively. Muneer and Saluja (1986) developed regression for hourly diffuse fraction, following their work for daily data from the same 5 UK locations. They found a third degree polynomial to be the optimum to relate diffuse ratio as a function of clearness index. They also investigated the effect of fractional possible sunshine and solar altitude and concluded that although the latter showed some what relevance, the former had no bearing on the regression. Newland (1989), using data from Macau, developed a fourth-order polynomial regression for daily diffuse fraction and a linear one for monthly average. De Miguel et al (2001) reproduced CLIMED1-1997 (daily regression) and CLIMED2-1997 (hourly regression) models for Mediterranean region. These models are essentially third degree polynomial fits for partly cloudy sky, and either constant

or linear regression for overcast and clear sky regimes. They concluded that solar altitude plays a significant role on diffuse fraction and should be taken in account in future.

### 2.2.1.2 Diffuse transmittance index - clearness index regression

Iqbal (1980) used data from three Canadian and two French sites to develop a regression between hourly diffuse transmittance index (ratio of diffuse/ extraterrestrial radiation), instead of diffuse ratio, and hourly clearness index (ratio of global/extraterrestrial radiation). He found the models to be site-specific and concluded that they cannot be generalised. He recommended that the range of solar altitudes higher than 40 ° should be investigated.

# 2.2.1.3 Direct transmittance index – clearness index regressions

Maxwell (1987) developed regressions between  $K_b$  (direct transmittance index) and  $K_t$ , including solar elevation dependence, where  $K_b$  is computed as a function of air mass along with clearness index. Perez et al (1990-b) enhanced the use of global radiation to improve estimation accuracy within the DISC model (Maxwell's quasiphysical model), by using a zenith-angle independent clearness index and also by utilizing time variability of global radiation. Such additional descriptors, as suggested by Perez, could overcome the two limitations posed by solar elevation dependence of clearness index and its inability to account for abrupt changes in sky conditions from one hour to the next. Once the normal beam irradiance has been estimated from these models, diffuse irradiance is calculated as the difference between global irradiance and the product of normal beam irradiance and the solar altitude (as given in Eq. 2.1).

# 2.2.2 Estimation of diffuse radiation from beam/direct radiation

# 2.2.2.1 ASHRAE model

ASHRAE (1972) model calculates the intensity of beam normal irradiation which is further used to calculate hourly beam and diffuse radiation on a horizontal and tilted surfaces, but only for clear cloudless days.

$$I_{bn} = A \exp(-B/\cos\theta_z) \tag{2.10}$$

 $I_d = CI_{bn}$ 

(2.11)

where,  $I_{bn}$  is the beam normal radiation,  $I_d$  is the diffuse radiation,  $\theta_z$  is zenith angle and A, B, C are mean monthly values of empirically chosen constants determined from experimental data for USA.

Muneer and Hawas (1983) tuned the ASHRAE model coefficients with respect to the cloudless data from Indian locations as they found disagreement between the ASHRAE values from the original model and measured data, significantly more for diffuse radiation than global. Likewise, in another study, Nijegorodov (1996) adjusted the ASHRAE empirical constants to predict solar radiation components for the African region of Botswana, Namibia and Zimbabwe.

**2.2.2.2 Direct transmittance index - diffuse transmittance index regresssion** Ianetz et al (2001) attempted to correlate  $K_d$ , the ratio of the daily diffuse to the daily extraterrestrial radiation as a function of  $K_b$ , the ratio of the daily beam to the daily extraterrestrial radiation in the form an empirical monthly regression equation for Beer Sheva and Sde Boker (Israel).

$$K_{d} = a[\exp(bK_{b} + cK_{b}^{2})]$$
(2.12)

where, a, b and c are monthly values of empirically determined coefficients.

#### 2.2.3 Estimation of solar radiation from meteorological parameters

The models based on  $k_t$  are convenient to use as they only require one measured input variable i.e. global radiation. However, their major drawback is the fact that the variation in diffuse fraction cannot be explained/ accounted by the clearness index alone. There are other factors that play an important role in its characterisation. This section will review some of the well-known models in literature that utilize other parameters as well to estimate the radiation components, diffuse radiation in particular.

# 2.2.3.1 Estimation of solar radiation from sunshine fraction

Sunshine duration has a strong bearing on solar radiation as is evident from a number of regressions in the literature.

The very first type to fall in this category is the estimation of global radiation from fractional possible sunshine demonstrated by the famous Angström (1924) formula using a simple linear model:

$$\frac{H}{H_o} = a + b \left( \frac{S}{S_o} \right) \tag{2.13}$$

where, a and b are the two constants and  $H/H_0$  and  $S/S_0$  are the ratios of meteorological irradiation and sunshine variables at a location, respectively. These constants are determined empirically and can assume a wide range of values depending on the local and seasonal variations, like cloudiness, effect of snow albedo, atmospheric constituents, latitude etc. If these constants cannot be estimated from measured data for the specific location, they can be inferred from regressions established at neighbouring locations, e.g. the approach used by Palz and Greif, 1996. (Driesse and Thevenard, 2002).

Due to the wide spatial and temporal coverage of sunshine records and relatively less frequent global radiation measurements, such relationship has found immense use in the past. The commonly used equation is that proposed by Page (1961) which estimates the monthly-average global radiation from daily hours of bright sunshine and day length.

$$H = H_0 \left(a + b \frac{n}{N}\right) \tag{2.14}$$

where, H and  $H_0$  are the monthly-average daily terrestrial and extraterrestrial radiation, n is the average daily hours of bright sunshine and N is the day length.

There are several types of models (linear, quadratic, third degree polynomial and logarithmic) in literature for estimating the global radiation from extra-terrestrial irradiance and measured and theoretical daily sunshine duration. Almorox and Hontoria (2004) used these models, along with an exponential model for data from 16 meteorological stations in Spain to estimate monthly average daily global radiation. They found that the third degree models performed better than the others, however, suggested the linear model as optimum.

One of the very initial attempts investigating the relative importance of cloud and other atmospheric constituents on scattering of direct radiation was made by Stanhill (1966) by comparing the diffuse fraction with local measurements of 'cloudiness index hours of bright sunshine' and observations of amount of cloud cover. Iqbal (1979) developed linear and second order empirical equations which correlate monthly average daily values of diffuse and direct radiation with the fraction of maximum possible sunshine hours, based on three Canadian locations. The diffuse fraction is expressed as a first order function; whereas, both diffuse and direct transmittance indices are second order functions of fractional sunshine. Abdalla and Feregh (1988) predicted diffuse radiation by two methods i.e. regression of diffuse fraction with clearness index and with fractional sunshine. They found a good agreement between the two. Soler (1990) investigated the dependence of monthly average hourly diffuse radiation on daily sunshine fraction for Uccle, Belgium. Following Iqbal's approach, similar regression equations have been developed to obtain monthly-average daily solar radiation from fraction of maximum possible sunshine hours for different locations by several authors, for example, estimation of diffuse radiation by Barbaro et al (1981), diffuse and global by Jain (1990) and global, diffuse and direct solar radiation by Castro-Diez et al (1989), Ahmad et al (1991) and Tiris et al (1996). El-Sebaii and Trabea (2003) proposed second order regression between diffuse transmittance index and sunshine fraction to estimate monthly average daily diffuse for four locations in Egypt and an overall regression for the country to predict annual averages of diffuse radiation.

**2.2.3.2** Additional descriptors used with clearness index for radiation models Although, there is a considerable amount of work gone in development and modification of Liu-Jordan type models in the literature, authors (Perez et al, 1990, Olmo et al 1996) have indicated in the past that regressions based on  $k_t$  alone can yield high errors in hourly diffuse radiation estimation. This can be explained by the fact that for a given  $k_t$  a wide range of diffuse fraction values are encountered, owing to the great variety of sky conditions that lead to the same  $k_t$ . Therefore, a diffuse radiation model with global radiation as its unique input parameter is less likely to perform accurately because of its physical limitation to account for the different conditions in terms of its direct and diffuse content. Consequently, there is a need to incorporate additional descriptors for estimating diffuse radiation. This can be

achieved by a more physical interpretation of the phenomenon involved, or by empirical detection of effective variables (González and Calbó, 1999). The effect of solar altitude on diffuse fraction models was stressed by Bugler (1977) and Iqbal (1980), Skartveit and Olseth (1987) and Reindl et al (1990). According to Erbs et al (1982), the models obtained from hourly value k-kt regressions do not produce good results because the hourly values of global solar-radiation are very sensitive to the cloud type, which is generally not included in the regression. Hollands and Crha (1987) developed a model for the radiative process in the atmosphere to study the relationship between diffuse fraction and clearness index. Their model took into account the radiation scattering phenomenon between two atmospheric layers by using parameters such as ground albedo, transmittance of the upper layer of the atmosphere and scattering albedo of the lower layer. Hollands and Crha models were based on 20-year data from Toronto and Winnipeg (Canada). Reindl et al (1990) used data from five locations in the US and Europe to assess the influence of climatic and geometric variables on the hourly diffuse fraction and concluded that the regressions show seasonal and location dependence. They proposed a regression based on clearness index, solar altitude, ambient air temperature and relative humidity which yielded reduced error in estimation compared to correlating solely with clearness index. Vazquez et al (1991) showed a clear qualitative but physically correct description of the scattering, absorption and air mass influence on the diffuse to global regressions. They concluded that variation in absorption caused by air mass, or by changes in absorbing constituents, do not affect the basic shape of the  $k_d-k_t$ relationship, but rather accounts for seasonal variability and for variations as a function of solar altitude. Perez et al (1992) proposed a revised version of their model (Perez et al 1990-b) that additionally uses the hourly dew point temperature, apart from the inter-hourly variability of solar global irradiance. Skartveit et al (1998) proposed an improved version of their diffuse fraction model by including hour-tohour variability index (Skartveit and Olseth-1992) and regional surface albedo as input parameters in addition to hourly solar elevation and clearness index. They defined the variability index (similar to Perez's; 1990-b) as the root mean squared deviation between the 'clear sky' index of the hour in question and, respectively, the preceding and the succeeding hour. Skartveit et al concluded that regional surface albedo significantly affects the diffuse irradiance, particularly under a cloudy sky. Gonazalez and Calbo (1999) normalized clearness index by making it air mass

independent and then used it to compute three variability parameters. The use of one or more of these variability parameters, however being time-intensive i.e. requiring knowledge of data at five minutes (or shorter) intervals, according to them improved the diffuse fraction estimation.

Olmo et al (1996) studied the performance of the global to direct/diffuse conversion models in the literature (Orgill and Hollands (1997), Erbs et al (1982), Maxwell (1987), Skartveit and Olseth (1987), Reindl et al (1990) and Perez et al (1991)) before and after the eruption of Mount Pinatubo. They concluded that the empirical models present a dependence on the database used for their development. They further concluded that this is true for the simpler Liu- Jordan type models as well as those that include additional variables such as solar elevation, inter-hourly variability or other meteorological parameters.

# 2.2.3.3 Estimation of diffuse radiation using various other parameters

Page (1986) developed a clear sky radiation model as part of the work undertaken for the development of European Solar Radiation Atlas, to estimate diffuse (or direct) irradiance as a function of solar altitude and air mass 2 Linke turbidity factor, after incorporating the standard corrections for mean solar distance and air mass adjustment for station height. Piece-wise regressions of diffuse radiation for overcast  $(k_t < 0.3)$ , intermediate  $(0.3 < k_t < 0.8)$  and clear skies  $(k_t > 0.8)$  similar to the earlier work on Liu-Jordan type models, have been proposed based on clearness index, solar elevation, ambient temperature and relative humidity (Reindl et al, 1990, Chendo and Maduekwe, 1994). Gopinathan and Soler (1996) and Soler et al (1999) proposed a regression between monthly mean hourly diffuse to global radiation (k) with monthly mean hourly clearness index  $(k_t)$ , mean monthly hourly sunshine fraction  $(s/s_0)$ , and monthly mean solar elevation at mid hour for four locations in Spain and UK, respectively. They concluded in their study that the diffuse radiation estimation can be improved by adding solar elevation or sunshine fraction along with k<sub>t</sub>, yielding best results when all three variables are used. Gul and Muneer (1998) proposed a diffuse fraction model as a function of clearness index and product of precipitable water and air mass for several locations in UK. They claimed that their model outperformed the previous models, like, Maxwell's (1987), Reindl et al's (1990) and Muneer and Saluja's (1986). There also is a model in literature, by Coppolino (1981) that

correlates monthly average diffuse radiation as a exponential function of fractional sunshine and solar elevation, used by Bashahu (2003) for his comparative models analysis. Monthly average diffuse fraction was correlated with monthly average sunshine fraction and monthly average value of water vapour content in the work of Garg and Garg and Hussain (1984) (Bashahu, 2003). Diffuse radiation has also been shown to depend on atmospheric turbidity by various researchers, which in turn varies with air mass origin as demonstrated by Rapti (2000). He investigated the effect of seasonal variations on air mass content (like, heavy water content owing to humidity, or continental dust content owing to winds) in a Mediterranean location and correlated it with diffuse radiation accordingly.

Several authors have demonstrated the dependence of diffuse radiation on one or more of the variables such as surface albedo, bright sunshine hours, precipitable water, the atmospheric turbidity, solar elevation, cloud cover, apart from the well known global irradiance (Bashahu, 2003). Some investigators also attempted at correlating the diffuse ratio with sunshine fraction along with clearness index. Gopinathan (1988) computed the monthly mean daily diffuse radiation from clearness index and percent possible sunshine. Al-Hamdani et al (1989) developed a multilinear regression equation for daily diffuse fraction as a function of clearness index and fractional sunshine duration to estimate for Baghdad, Iraq. Later Al-Riahi et al (1992), same co-authors as above, developed similar model to estimate hourly diffuse radiation.

# 2.2.3.4 Cloud cover models

Cloudiness is one of the most influential parameters for diffuse radiation since it accounts for scattering of solar radiation to a large extent. The fact that cloud observations are undertaken at a large number of stations as they usually require no measurements, led to the development of cloud radiation models (CRM). Rangarajan et al (1984) fitted a cubic regression equation for monthly mean values of the fraction of the sky covered by clouds of all types and duration of bright sunshine. They computed the sunshine duration from cloud cover data and from the cloud derived sunshine data, monthly mean values of global and diffuse solar radiation were computed. Gul et al (1998) (who have also presented a brief review of such models in literature) extended the work of Kasten and Czeplak (1979) for UK, where the latter

in their study of continuous hourly data (10 years) from Hamburg, showed that the ratio of global irradiance for any given cloud amount (N octa) to global irradiance under a corresponding cloudless sky ( $G_t/G_{t,0}$ ) is independent of solar elevation ( $\gamma$ ). The equations for calculating  $G_{t,0}$  and determining global irradiance for a given cloud amount are therefore, respectively represented as:

$$G_{t,0} = (A\sin\gamma - B) \tag{2.15}$$

$$\frac{G_t}{G_{t,0}} = 1 - C \left(\frac{N}{8}\right)^D \tag{2.16}$$

Linear equations correlating monthly average diffuse transmittance index to daily average cloud cover ( $\overline{N}e$ , in eighths) have also been proposed. In his comparative analysis of various models, Bashahu (2003) used two such models of the following form:

$$\overline{K}_d = a_7 + b_7 \frac{\overline{N}e}{8} \tag{2.17}$$

$$\overline{K}_d = a_8 + b_8 \left( 1 - \frac{\overline{N}e}{8} \right) \tag{2.18}$$

El-Metwally (2004) proposed several empirical models for estimation of global radiation from daily mean of cloud cover, minimum and maximum temperature and extraterrestrial radiation.

There are a great many models for estimation of solar radiation in general as discussed in the foregoing text. The models for estimation of diffuse radiation reviewed so far are summarised in Table 2.2. Since the current area of research is essentially to deal with modelling of diffuse radiation, it was considered worthwhile to give a general overview of the diverse and extensive research in this area. Other models used to estimate global and direct radiation are purposely not included in the table. Due care has been taken to encompass all the important diffuse radiation

models available in the literature; however, it is acknowledged that not all of these models could be compiled herein. Efforts were made to ensure that the originators of each model have been listed in the table. It is worthwhile to note that all the listed models are representative or specific to the site where they are developed, with rare cases of generalisation of results for a region/country. All proposed k versus k<sub>t</sub> models are piece-wise regressions as discussed in Section 2.2.1.1. Since, there are numerous models under this category; sub-divisions are made on temporal basis of model estimates.

# 2.2.3.5 Atmospheric transmittance models (ATMs)

Some models are based on parameterizations of transmittance and absorption functions for basic atmospheric constituents, like, scatteres: air molecules (Rayleigh scattering), aerosols (Mie scattering) and absorbers: water vapour, many other gases, dust and clouds. These models are known as atmospheric transmittance models. They can be broadband or spectral based. The latter are more conveniently termed as radiative transfer models.

A typical example of broadband ATM is the Meteorological Radiation Model (MRM) developed by Gul et al (1998). It requires data such as dry- and wet- bulb temperature along with sunshine fraction to produce hourly solar radiation components for both overcast and clear skies. The MRM for non-overcast conditions evaluates hourly diffuse to beam ratio (DBR) as an exponential function of direct transmittance index (kb). The beam/direct irradiance is calculated as a product of hourly sunshine fraction (SF) and five transmittances due to Rayleigh and Mie scattering, mixed gases, ozone and water vapour.

$$DBR = 0.285k_b^{-1.00648} \tag{2.19}$$

$$G_b = (SF)G_0\tau_r\tau_\alpha\tau_g\tau_o\tau_w \tag{2.20}$$

Each transmittance index is further given by an empirical equation, where the coefficients need to be determined by fitting the data. A major drawback of this model is the large number of coefficients specific to individual locations that need to be

calculated. For overcast conditions, the diffuse irradiance is assumed equal to global radiation and modelled in accordance with studies undertaken by Dave (1979) and Bird and Hulstrom (1981) (Gul et al, 1998). Another type of model in this category is the REST (Reference Evaluation of Solar Transmittance) model proposed by Gueymard (2003). Its basic functional form is similar to other models, except that the total NO<sub>2</sub> absorption is taken into account through a specific transmittance, T<sub>n</sub>. In the same research paper, Gueymard evaluated several other broadband ATMs based on theoretical tests and concluded CPCR2, MLWT2, REST and Yang to be the best performers. Alam (2006) studied the performance of three of these four models, namely, CPCR2, REST and Yang models at four Indian locations and found REST model in good agreement with the measured data than the other two.

#### Spectral models

It is believed that many biological, chemical and physical processes are wavelength sensitive. However, due to technical difficulties in monitoring such spectral selective processes and prohibitive costs associated with spectral measurements, several researchers have proposed the use of mathematical models that include a description of the spectral characteristics of the incident radiation to predict the performance of a system. The underlying approach is to solve the equations of radiative transfer not only wavelength by wavelength but also layer by layer in the atmosphere. There are various such models in literature often designed specifically for their end-use application. Two of the most common models are: SPECTRAL and SMARTS (Simple Model of the Atmospheric Radiative Transfer of Sunshine). Bird (1984) introduced a model SPECTRAL and later modified it as SPECTRAL2 (Bird and Riordan, 1986) which is still useful for very rapid estimates of the clear-sky direct, diffuse and global irradiance on horizontal or tilted surfaces, for 122 wavelengths between 300 and 4000 nm. Gueymard (1995) proposed and modified SMARTS (Gueymard, 2001) model that can be used to predict clear-sky direct, diffuse and global irradiance incident on any horizontal or tilted surface at 2002 wavelengths from 280 to 4000 nm, as well as illuminances, luminous efficacy, UV action spectra, circumsolar irradiance and broadened irradiances. These models are largely limited to clear-sky conditions; however they can also be empirically modified to predict spectra under cloudy conditions to certain extent as claimed by the developers of the models, referenced elsewhere (Gueymard and Kambezidis, 2004). Spectral models are

complex models that require rigorous calculations and extensive look-up tables and therefore, have restricted use in those applications only that require spectral resolution. The model equations have not been included herein, however if the reader is interested the above references and Chapter 5 (Gueymard and Kambezidis, 2004) of *Solar Radiation and Daylighting Models* (Muneer, 2004) can be referred for details.

## 2.2.4 Satellite-based models

The amount of solar radiation reaching the earth's surface exhibits large spatial variations mainly due to geographical and climatological differences. It is not feasible to establish solar radiation monitoring networks at a density proportionate to this spatial complexity. As a result, solar radiation models have also been developed based on the data from metrological satellites. These satellites provide wide geographical coverage with high spatial resolution. Modelling techniques range from being totally subjective to those employing some of the most sophisticated radiative transfer codes (Hay, 1993). Perez et al (2002) developed "a model based on monitoring the dynamic range for satellite image pixels and assigning irradiance values corresponding to the relative brightness of the pixels. This cloud index acts as a quasi-linear modulation of a clear sky model. The modulating function was fitted to ground-based measurements grouped together with the data normalized by extraterrestrial irradiance." (Vignola et al, 2005).

However, there are a variety of problems faced by the users of satellite data to estimate solar radiation on earth's surface (Hay, 1993). One such issue was noted by Vignola et al (2005) when they compared the satellite-based model with ground based measurements; the former's inability to distinguish between the frost on the ground and low lying fogs and/or clouds on clear winter days. They concluded that ground based measurements are needed to augment the satellite data for comprehensive modelling. Also, the estimated diffuse radiation from their model was found to be sub-quality compared to the measured data. Besides, the technicalities, it is generally difficult to accomodate the satellite-based models within the existing earth's radiation and energy budget (Hay, 1993).

#### 2.3 Statistical Measures used for Evaluation of Models

Evaluation, testing, comparison and validation are essential steps to deduce the performance on any model. There are numerous examples in history of solar radiation model evaluation by statistical means. Different authors have preferred to use different statistical indicators. This section attempts to provide a wholesome coverage of such statistical evaluators particularly, in reference to the models reviewed in Section 2.2.

The most widely used statistical indicators in literature are the RMSE/ RMSD (root mean square error/deviation) and MBE/MBD (mean bias error /deviation), numerically expressed as follows:

$$RMSE = \left(\frac{1}{n}\sum_{i=1}^{n}{d_{i}^{2}}\right)^{1/2}$$
(2.21)  
$$MBE = \frac{1}{n}\sum_{i=1}^{n}{d_{i}}$$
(2.22)

The RMSE provides short-term performance of a model by allowing term by term comparison of the actual deviation between the estimated and measured value. Smaller value indicates better performance of the model. The MBE, on the other hand, helps in assessment of a model's long-term performance of a model. It provides information on existence of systematic over or under-estimation tendencies, depending if it takes positive or negative value, which in turn depends on the formula used to define it. Nevertheless, the smaller the absolute value, the better the model performance.

Badescu (1988) noted that dimensional values of these indicators do not allow comparison of models tested under various meteo-climatic conditions. He reported that the two most popular methods in literature to adimentionalize the evaluators have been those of Page et al (1979) and Davies et al (1984).

The Page et al root mean square and mean bias errors are represented, respectively as:

$$RMSE_1 = \left[\frac{1}{N}\sum_{i=1}^n \left(\frac{G_i - F_i}{F_i}\right)^2\right]^{1/2}$$

(2.23)

$$MBE_{1} = \frac{1}{N} \sum_{i=1}^{n} \frac{G_{i} - F_{i}}{F_{i}}$$
(2.24)

The Davies et al root mean square and mean bias errors respectively are:

$$RMSE_{2} = \left[\frac{\sum_{i=1}^{N} (G_{i} - F_{i})^{2}}{N}\right]^{1/2} / \frac{\sum_{i=1}^{N} F_{i}}{N}$$
(2.25)

$$MBE_{2} = \frac{\sum_{i=1}^{N} (G_{i} - F_{i})}{N} / \frac{\sum_{i=1}^{N} F_{i}}{N}$$
(2.26)

where,  $G_i$  and  $F_i$  are computed and measured values, respectively.

Barbaro et al (1981) used dimensionless RMSE (similar to one proposed by Page) to estimate the degree of accuracy of the model fit. They termed it as "relative standard error of estimate". Coefficient of determination ( $R^2$ ) and error histograms have also been used to assess the model performance by authors, such as Muneer and Saluja, 1986.

Each indicator has its drawbacks which will be addressed in model evaluation sections of Chapter 5 and 6 in detail. With the view that each test by itself may not be an adequate indicator of a model's performance, Stone (1993) introduced a statistical indicator 't-statistic' which if used additionally with MBE and RMSE, provides more reliable and explanatory results. It "allows models to be compared and at the same time can indicate whether or not a model's estimates are statistically significant at a particular confidence level." Moreover, since it is computed using both RMSE and MBE it "takes into account the dispersion of the results which is neglected when the RMSE and MBE are considered separately."

$$t = \left(\frac{(n-1)MBD^2}{(RMSD^2 - MBD^2)}\right)^{1/2}$$

(2.27)

Stone suggested that the smaller the value of t, the better is the model's performance. "To determine whether a model's estimates are statistically significant, one simply has to determine a critical t value obtainable from standard statistical tables, i.e.,  $t_{\alpha/2}$  at the alpha level of significance and (n - 1) degrees of freedom. For the model's estimates to be judged statistically significant at the  $(1 - \alpha)$  confidence level, the calculated t value must be less than the critical t value (Stone, 1993)." Values outside the interval of  $-t_c$  and  $+ t_c$ , the so-called critical region, are those for which the hypothesis that the parameter selection has improved the model is rejected (Oliveira, 2002).

Chandrasekaran and Kumar (1994) used the dimensional and non-dimensional form of RMSD for their model analysis and referred to them as standard deviation (SD) and relative standard deviation (RSD), respectively. RSD differed from the Page-defined • RMSE, in the respect that the denominator is the calculated and not measured value.

$$RSD = \left[ (1/N) \sum \left[ (k_{d,meas} - k_{d,cal}) / k_{d,cal} \right]^2 \right]^{1/2}$$
(2.28)

Other simpler statistical measures, like composite residual sum of squares (CRSS) and mean absolute error (MAB) were used by Chendo and Maduekwe (1994) for model validation and are respectively defined as:

$$CRSS = \sum \left[ (I_d / I)_{pred} - (I_d / I)_{meas} ) \right]^2$$
(2.29)

$$MAB = \sum \{Abs [(I_d / I)_{pred} - (I_d / I)_{meas}]\} / N$$
(2.30)

Olmo et al (1996) used RMSD and MBD to evaluate the various models' performance in their comparative study. They also analysed the linear regression between estimated and measured values based on coefficient of determination  $R^2$ , slope, a and intercept, b. They noted that first value indicates the experimental variance indicated by the model, while

the other two provide information about the tendency to over- or underestimate in a particular range.

Jacovides et al (1996) used MBE, RMSE and t-statistic, as defined by Stone (1993) for quantitative assessment of their regressions for Cyprus. Skartveit and Olseth (1998) used RMSD and MBD to validate the performance of the improved version of their model against independent data from four European stations. Gul et al (1998) used mean absolute deviation (MAD) similar to the MAB (Chendo and Maduekwe, 1994) for statistical evaluation of CRM. They developed an innovative scoring system to quantify the model performance by adding absolute values of MBE, MAD and RMSE, all together. González and Calbó (1999) used RMSE, slope, A, intercept, B,  $R^2$  and another parameter called degree of agreement (d) after Willmott (1982) for evaluating regressions' performance. It is a relative and bounded measure (between 0 and 1) of the agreement between calculated ( $C_i$ ) and observed values ( $O_i$ ), and is very useful for cross-comparisons among model.

$$d = 1 - \left(\frac{\sum_{i=1}^{N} (C_i - O_i)^2}{\sum_{i=1}^{N} (|C_i - \overline{O}| + |O_i - \overline{O}|)^2}\right)$$
(2.31)

De Miguel et al (2001) assessed the accuracy of different models by using along with  $R^2$ , a slightly different version of RMSE and MBE, as a percentage of the average value as defined below:

$$rmse = \frac{100}{\overline{D}} \left[ \sum_{i=1}^{N} (D_{im} - D_{ir})^2 / N \right]^{0.5}$$
(2.32)

$$mbe = \frac{100}{\overline{D}} \left[ \sum_{i=1}^{N} (D_{im} - D_{ir}) / N \right]$$
(2.33)

where,  $D_{im}$  and  $D_{ir}$  are the i<sup>th</sup> estimated and measured values,  $\overline{D}$  is the mean of measured values.

Ianetz and Kudish (2001) evaluated the performance of their non-linear regression model regression daily diffuse radiation as a function of daily beam radiation for Negev region of Israel by means of RMSE and MBE. Both Oliveira et al (2002) and Bashahu (2003) used MBE, RMSE and t-statistic, as defined by Stone (1993), for the evaluation of models in their respective studies. Almorox and Hontoria (2004) tested several models in literature in terms of the coefficient of determination R<sup>2</sup>, standard error of estimate (SEE) and mean absolute error (MAE). SEE is same as RMSE and MAE is same as MAB or MAD defined above.

#### 2.4 Summary

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A review of modeling from measurement of data to evaluation of the final proposed models was presented herein. An account of solar radiation measurements with its brief history to the currently accepted and widely used methods was given. Measurements of other meteorological parameters, presently of interest to this research project were also discussed. Uncertainty in measurements and other - associated errors were also addressed. Various data quality control programs available in literature were reviewed. Solar radiation models were identified based on two broad categories, depending upon the input type. They were further divided into subtypes based on regression relationship of the parameters involved under each category. A brief review of atmospheric transmittance models (including spectraltype) and satellite models was also provided. Eventually, various statistical indicators in use in the modeling literature were discussed and their definitions presented.

To sum up, all the three steps of modelling explored above are deeply inter-related in the sense that the accuracy of *measurements* is crucial for the development of *models* which when *tested* and *validated* should reveal reasonable accuracy of estimation within the given uncertainty of measured data.



Courtesy: http://www.volker-quaschning.de/fotos/messung/index.html

(b)

(c)





Courtesy: http://swera.unep.net/swera/index.php?id=34

Fig. 2.1 Pyrheliometers (a) A typical field pyrheliometer, (b) Absolute cavity pyrheliometer, world reference for calibration of other solar radiation sensors, (c) Angtröm compensation Pyrheliometer developed in nineteenth century



Fig. 2.2 A CM11 (Kipp and Zonen) pyranometer



Fig. 2.3 A pyranometer with a shadow band/ shade ring





Fig. 2.4 Campbell stoke's sunshine recorder (a) Side-view (left), (b) front view of the glass bowl with the sunshine card attached beneath (right)



Fig. 2.5 A celiometer used by US National Weather Service (NWS) for automated stations (extracted from article by Perez et al, 2000)



Fig. 2.6 A clearness index (K<sub>t</sub>) - diffuse ratio (K) plot illustrating the sources of error in radiation measurement. (Courtesy: Solar Radiation and Daylight Models, Muneer, 2004)



Fig. 2.7 Broad classification of solar radiation models available in literature

Instrument Classification	Standard	First-class	Second-class	Third-class
PYRHELIOMETER - TYPES	Absolute cavity	Michelson bimetallic pyrheliometer	Gorczynski	
	Angström electrical compensation	Linke-Feussner ironclad	Old Eppley	
	Abbot silver-disk pyrheliometer	New Eppley (temperature compensated)		
		Yanishevsky thermoelectric		
		Eppley Precision Spectral	Moll-Gorczynski (Kipp) pyranometer	Robitzsch bimetallic
PYRANOMETER - TYPES		Kipp and Zonen CM-11*	Eppley (also known as 180 ° pyrheliometer)	
			Volacine thermopile	
			Dirmhirn Sanberer (star)	
			Yanishevsky thermoelectric	
			Spherical Bellani	

# Table 2.1 Classification of pyrheliometers and pyranometers based on WMO criterion

\* This instrument was used to measure the global and diffuse radiation (with standard Kipp and Zonen shade ring) at 6 of the 9 meteorological stations, from whom the data sets were obtained for the present project. *Note:* The two Japanese sites used Eko design pyranometers and Kipp and Zonen CM6 was used in Bracknell.

K = f (K <sub>t</sub> )	Monthly-average	Liu-Jordan (1960), Page (1961), Klein (1977), Barbaro et al (1981	
		Erbs et al (1982), AlNaser (1988), Newland (1989),	
		Jacovides et al (1996), Oliveira et al (2002), Aras et al (2006)	
	Daily	Collares-Pereira and Rabl (1979), Erbs et al (1982)	
		Muneer and Hawas (1983), Rao et al (1984),	
		Saluja and Muneer (1985), Lalas et al (1987),	
		Jacdovies et al (1996), Oliveira et al (2002), Paliatsos et al (2003)	
		De Miguel et al (2001)-CLIMED1 (1997)	
	Hourly	Orgill and Hollands (1977), Erbs et al (1982),	
		Muneer et al (1984), Muneer and Saluja (1986),	
		Reindl et al (1990), Chandrasekaran and Kumar (1994)	
		De Miguel et al (2001)-CLIMED2 (1997)	
$K_d = f(K_t)$		lqbal (1980)	
$K_d = f(K_b)$		lanetz et al (2001)	
K = f (SF) and/or K <sub>d</sub> = f (SF)		Iqbal (1979), Barbaro et al (1981), Abdalla and Feregh (1988) AlNaser (1988), Castro-Diez et al (1989), Jain (1990), Ahmad et a (1991),	
		Tiris et al (1996), Bashahu (2003), El-Sebaii and Trabea (2003)	
K = f (CC)		Bashahu (1984) (quoted in Bashahu, 2003)	
		Coppolino (1981), Skartveit and Osleth (1987), respectively	
		Macagnan et al (1994) (as quoted in De Miguel et al, 2001)	
$K = f(K_{t}, SF)$		Gopinathan (1988), Al-Hamdani et al (1989), Al-Riahi et al (1992)	
K <sub>d</sub> = f (SF, w)		Garg and Garg, Hussain (1984) (as quoted in Bashahu, 2003)	
$K = f(K_{t},SF,$			
solalt)		Gopinathan and Soler (1996)	
$K = f(K_t, w, m)$		Gul and Muneer (1998)	
$K_d = f(K_t, solalt, \sigma)$		Perez (1992)	
K <sub>d</sub> = f (K <sub>t</sub> , solalt, σ, regional surface albedo)		Skartveit and Osleth (1998)	
$K = f(K_t, \text{ solalt}, T_a, \Phi)$		Reindl et al (1990), Chendo and Maduekwe (1994)	

.

Table 2.2 An overview of diffuse radiation models in literature

Notations:

 $\sigma$  – Inter-hourly variability index

 $\Phi$  – relative humidity

 $T_a$  – ambient temperature w – precipitable water (water vapour)

# CHAPTER 3

# THE PRESENT DATABASE

The present research project involves the proposition of improved models for estimating diffuse irradiance, where it is not measured either by norm or due to operational problems. In the following chapters, modelling, evaluation and validation will be demonstrated on both hourly and daily radiation data. Since the models are to be developed based on ground-based measured parameters, 9 datasets from across the world were selected with a varying range of topographically and geographically.

This chapter gives the details of the database and respective sites under study. It also describes the data processing undertaken for both hourly and daily data. Most of the software and tools developed under this part of the work were a modification of the original programs, developed elsewhere, and therefore not appended herewith in view of the thesis volume. However, the use of original programs has been furnished with adequate references where appropriate.

# 3.1 Geographical and Database Information for the Sites under Study

The chosen nine locations are spread over four countries and two continents. Of those, six are from Asia: four (Chennai, Mumbai, New Delhi and Pune) from Indian subcontinent and two Japanese (Fukuoka and Sapporo) sites in the Far East. The remaining three sites are from western part of the world i.e. Europe. These include two Spanish (Gerona and Madrid) from Southern Europe and a UK site (Bracknell) from Northern Europe. All the locations are shown on the world map in Fig. 3.1(a). Table 3.1 gives the geographical and data information of the nine sites.

Data for all the four Indian sites were provided by Indian Meteorological Department. The solar radiation data was hourly based, with daily number of bright sunshine hours. Also, cloud cover was provided at 8.30, 11.30, 14.30 and 17.30 hours of local clock time for Chennai, Mumbai and Pune, while for New Delhi no cloud data were available to the present research team. Data for Japanese sites were 10-minute values (Courtesy: Kyushu University, Japan). Sunshine duration was measured every 10 minutes. Again, no cloud cover data were obtainable for these two locations. Madrid solar radiation data were hourly (Courtesy: Instituto Nacional De Meteorologia). Daily sunshine fraction and cloud cover data for both Madrid and Gerona were provided at 7, 13 and 18 hours. Gerona data, provided by University of Gerona, was originally 5-minute based, which was later integrated into hourly values. Bracknell (UK) data was obtained from UK Metrological Office. All the data including radiation values, sunshine fraction and cloud cover for Bracknell were provided at hourly level.

The selection of above sites not only covers different longitudes and latitudes from the northern hemisphere but also features varying climates and topographies, a mix of tropical, subtropical, temperate and cold. A world climate map is appended herewith in Fig. 3.1(b). The Indian sites represent tropical climate, with the exception of New Delhi having a semi-arid climate. The two Japanese sites and Bracknell (UK) fall under the broad category of temperate climate (details can be found in Fig. 3.1(b)), while the Spanish sites represent Mediterranean climate.

The global radiation data is measured by Kipp and Zonen CM11 pyranometer for . the Indian and European sites and CM6 for Bracknell (UK). Japanese data is measured by Eko designed pyranometers. All sites use standard size Kipp and Zonen shade rings to measure diffuse radiation. Campbell-Stokes sunshine recorder is used to record sunshine duration. Cloud cover measurements are based on conventional method of human observation by virtually dividing the sky dome into eight parts or octas.

#### 3.2 Hourly Data

#### 3.2.1 Processing

Data sets were processed into required formats with information on year, month, day, time and measured parameters, namely, G, D, SF and CC. For locations which reported sunshine duration rather than sunshine fraction, the latter was obtained using a VBA routine, which calculates the day length and then yields SF as the ratio of bright sunshine hours to the day length. The day length is calculated using the latitude, declination and height above sea level. The data sets were visually cleaned by

removing the missing values and those in early morning and late evening hours. To complete the data sets in the desirable form, clearness index ( $k_t$ ) and diffuse ratio (k) were calculated within the quality control FORTRAN routine (Section 3.2.2) and outputted with the filtered data.

Gerona data was originally 5-minute based as obtained from the University site. However, since the data spans over a period of 7 years, there was a significantly large number of data points. Since, the most frequently used medium for data processing, i.e. EXCEL poses limitation to the maximum number of data entries, 5-minute radiation values were integrated to hourly format. A simple FORTRAN program was used to sum up the values in each hour.

# 3.2.2 Quality control

A closer investigation of the data sets provided by meteorological stations often reveals lack of quality data sometimes even for extended periods of time. This can be attributed to erroneous measurements due to a combination of factors like equipment error and uncertainty and operation related problems and errors. A more detailed account of such errors has been discussed in Chapter 2. Database under consideration is no exception and requires filtering prior to its use for modeling purpose.

A quality control procedure based on a series of physical tests and a semi-automated statistical test was used for each dataset to affect the possible elimination of erroneous data resulting from uncertainties in measurements. The code was developed under common supervision of Prof. T. Muneer and some joint research work was performed (by Younes and Munawwar) to filter the presently used databases. However, the program is a propriety of (Younes et al, 2005) and therefore, not being reproduced here. It was specifically developed to perform such quality checks on the data and identify and eliminate the spurious data values, if any. The code takes as input: site elevation, latitude, longitude and local time meridian. Also, logging related information is required, both solar time and local civil time is acceptable. As a preliminary step, the code performs solar position calculations for each data entry. This includes the calculation of declination angle (DEC), solar hour angle ( $\omega$ ), apparent solar time (AST), solar altitude (SOLALT) and finally the calculation of

solar azimuth (SOLAZM). The first level test proceeds by eliminating entries that show a SOLALT less than 7°. For entries that have passed the first test, the day number and the horizontal extraterrestrial irradiation (E) are calculated. The latter is calculated using the following formula:

$$E = I_{sc} \times (1 + 0.033 \times \cos(.0172024 \times DN)) \times \sin(SOLALT)$$
(3.1)
where, I<sub>sc</sub> is the solar constant (1367 W/m<sup>2</sup>) and DN is the Julian day number.

Finally, hourly clearness index (k<sub>t</sub>) and hourly diffuse fraction (k) are calculated as,  $k_t = G/E$  and k = D/G (3.2)

where, G and D are the measured hourly global and diffuse horizontal radiation values, respectively.

The next step to follow is the second test that logically retains the data for which clearness index and the diffuse ratio were positive and had values between zero and one (inclusive).

 $0 < k_t <= 1 \qquad \text{and} \qquad 0 < k <= 1 \tag{3.3}$ 

At the third stage, global and diffuse irradiation is compared with their corresponding Page-model upper and lower boundaries. The Page model is based on the work undertaken for the production of the European Solar radiation Atlas (ESRA, 2000) and the CIBSE guide (Page, 1997) on weather and solar data. According to his work, the overcast and clear-sky diffuse irradiance set respectively the upper and lower limits for diffuse radiation. For global radiation the upper limit was set by global clear-sky model i.e. the global horizontal irradiation should always be less than or equal to the clear day global horizontal irradiation.

A fourth test involves the construction of k-k<sub>t</sub> quality control envelope. This is a statistical procedure that requires estimation of k<sub>t</sub> banded mean, weighted mean ( $\overline{k}$ ) and standard deviations of 'k' values ( $\sigma_k$ ). Typically the k<sub>t</sub> range of data may be divided in, say, 10 bands of equal width. For each band the above-mentioned statistics is obtained. From this information an envelope may be drawn that connects those

points that respectively represent the top  $(\bar{k} + f \sigma_k)$  and bottom  $(\bar{k} - f \sigma_k)$  curves. The data lying within this envelope represent quality data – free of any measurement related errors (Muneer and Fairooz, 2002). Figure 3.2 shows one such sample plot for Fukuoka. The procedure described below completes the quality control method adopted for all the nine databases.

Once the envelope constituted by the upper and lower boundaries is identified, it is possible to fit a polynomial for a mathematical description of the envelope of acceptance. A second-degree polynomial was found to be adequate. Thus, the upper and lower boundaries are respectively represented as,

A 
$$(k_t) = Max (1, a_1k_t^2 + b_1k_t + c_1)$$
 (3.4)  
B  $(k_t) = Min (0, a_2k_t^2 + b_2k_t + c_2)$  (3.5)

Note that any given polynomial may generate data that can go beyond the physical limits of k, which lie between 0 and 1. The formulation given in Eqs 3.3 and 3.4 satisfy the above constraints. Furthermore, due care had to be taken to incorporate the 'shoulder' effect caused by the intersection of the upper and lower polynomials with the respective k=1 (upper) and k=0 (lower) limits for the plot. In Fig. 3.2 (b), C ( $k_t$ ) and  $D(k_t)$  represent the lines of intersection for upper and lower bounds, respectively. By visual inspection of the plot it is possible to ascertain the intersection points. For all the locations under study, those points have been below  $k_t = 0.4$  (upper bound), and between  $k_t = 0.75$ , and  $k_t = 1$  (lower bound). Moreover, in the present context of boundary polynomials, in certain cases there may be a need for the control of the lower-bound polynomial with respect to its upper limit. It can be noted that within Fig. 3.2 (b) an 'unconstrained flow' of the B  $(k_t)$  curve would exclude a small proportion of otherwise good data belonging to heavy overcast regime. A cut-off shown as  $E(k_t)$  line was thus required, once again by visual inspection. Therefore, procedure of quality control could then be completed with the fully defined 'envelope of acceptance'. Bracknell's 'filtered data' and 'outlier' data is shown in Fig. 3.3. The data points outside the 'envelope of acceptance' were relatively less as compared to other sites, mainly due to good quality measured data. However, it would be worthwhile to note that since the development of quality control envelope was based

on visual study of the nature of plot, the cut-offs and even the type of polynomial curve can vary from site to site. For example, a third degree polynomial was adopted to define the quality control envelope for Mumbai (India).

While processing the database it was found that data sets from some of the sites showed a characteristic droop in the top left-hand corner of the k-k<sub>t</sub> data plot, like the one presented for Chennai in Fig.3.4 (a). Ideally, the data in that section of the plot would be expected to attain the limiting value of k=1 as  $k_t\rightarrow 0$ . This flaw evidently indicates that the shade-ring correction factor had not been applied to diffuse irradiance measurements. Such uncorrected diffuse radiation was found not only for Chennai but all other Indian sites viz., Mumbai, New Delhi and Pune and also in the data sets from the two Japanese sites, i.e. Sapporo and Fukuoka. Appropriate measures were adopted to correct the diffuse radiation sets for the shadow band error using Drummond's (1956) isotropic model. Figure 3.4 (b) gives the Chennai k-k<sub>t</sub> plot after applying shade ring correction in diffuse radiation data.

Table 3.2 summarizes the results for each site using the above described quality control procedure. It gives the factor used for standard deviation and the visual cut-off for lower boundary polynomial for each site. The number of data points is also listed for both prior to quality control and useable clean data sets afterwards. Diffuse correction was applied to the datasets where required. The end-number, therefore, includes those data for which diffuse radiation values have been shade ring corrected.

### 3.3 Daily Data

# 3.3.1 Assimilation

This section of the chapter deals with the compilation of daily data sets. For this purpose, original data provided by the metrological stations is referred. It is found that the Indian sites provide both radiation as well as sunshine duration on a daily basis. Note that although only a cumulative sum of hourly values, their provision in the original data saves further work to produce consistent time-series followed by daily integration. However, this is not the case with Japanese sites. Japanese data is in the form of 10-minutely series with possible intermittent gaps and missing values towards the beginning and end of the day-hours. Therefore, care has to be taken to include

only those days for which the 10-minutely data was both consistent and continuous to produce the daily data sets. The days with non-continuous time stamp were identified using a FORTRAN program adopted from Muneer (2004) (Prog. 4.7e\* as described in the book). As a next step, those days were removed completely from the data set. However, there were still some days which were incomplete in the sense that they may not start from the first hours and/or may not end on the last hours of record keeping. Consequently, a second program was used to identify these days, by giving the total number of hours of observation in each day. Those days for which this number is less than the normal (the routine number of measurements in a day) were then omitted from the series. Eventually, final and complete time-series of data was thus obtained, which was further used as input to a third program to yield daily values. Likewise, for Sapporo, Gerona and Bracknell, the same program integrating hourly values to daily, was used with slight changes, to obtain consistent time series and subsequent summation to yield daily datasets. Daily radiation values were provided by the meteorological station of Madrid.

Daily sunshine duration was provided for Indian sites, whilst 10-minutely and hourly values were summed up along with the radiation data, for Japanese and UK sites, respectively. This was followed by the calculation of daily clearness index (K<sub>t</sub>), daily diffuse ratio (K) and daily sunshine fraction (SF) using a modified version of Prog. 2.2\* (extracted from Muneer, 2004). Likewise, K<sub>t</sub> and K were also calculated for Spanish sites with the exception of SF as it was provided by the local meteorological office. Cloud cover (CC) was recorded on a four-hourly basis for Indian, three-hourly for Spanish sites and on an hourly basis for Bracknell (UK). This information is utilized on a daily level by averaging the CC (provided by the meteorological offices in units of octas) over a day against the corresponding daily radiation data to provide an

\**Note:* These software tools can be accessed and downloaded from the following website: <u>www.bh.com/companions/0750659742</u>

It is worthwhile to note here, that since radiation, sunshine duration and cloud cover values were summed up (and averaged in the last case) for a day, any day which had even one single missing value of either of the parameters was omitted from the daily data series to avoid incompleteness.
It was also revealed that the daily diffuse values from Gerona and Japanese sites needed shade ring correction, as was the case for hourly data. Drummond's (1956) method is used for diffuse correction of data from Gerona (Muneer, 2004: Prog. 4.8). For Japanese sites, the correction factors as derived from hourly data were applied to the respective daily values.

Daily data sets were not subjected to the quality control procedure used for hourly values. Hourly radiation is more prone to erroneous measurements, whilst daily values even out the inaccuracies.

#### 3.4 Summary

Data processing is a preliminary step to radiation modeling. Since simulation is to be performed on the data under consideration, it is important not only to compile datasets in user friendly format, but also to remove the incomplete and inaccurate values.

Data sets from 9 sites across the globe, representing a range of climates, were gathered. They were processed and filtered to yield consistent and clean data sets. This job was done to produce hourly as well as daily data for their respective modeling and evaluation. Within the hourly data sets, the quality control procedure adopted to filter the spurious data was explained. Other data processing, like applying diffuse shade ring correction, summing up the hourly values to yield a daily series and calculating the additional data, like clearness index, diffuse ratio, sunshine fraction, etc., was also described herein.



Fig.3.1(a) Geographical location of the sites under study



Fig. 3.1(b) World Climate map (Courtesy: http://www.dhaynes.freeserve.co.uk/university/ecol212/figure1.htm)



Fig. 3.2 Scatter plot of crude data for Fukuoka with the defining curves ( $\bar{k} \pm 2.0\sigma_k$ ) enveloping only the quality data (91.2 % of the total data)



Fig.3.3 Scatter plot for Bracknell (a) quality controlled data, (b) outlier or 'bad quality' data





Fig. 3.4 k-kt plot of quality-controlled Chennai database (a) prior to diffuse radiation correction, (b) post- diffuse radiation correction

(a)

Country	Location	Geographic information			Data information				
		Latitude (°N)	Longitude	Elevation (masl)	Period of measured data	Time stamp	Meteorological data for present analysis		
							minutely/ hourly	intermittent hours	daily
India	Chennai	13	80.18 ° E	16	1990-1994	AST spot	G, D	СС	G, D, SS
	Mumbai	19.12	72.85 <sup>°</sup> E	14	1990-1994	AST spot	G, D	СС	G, D, SS
	New Delhi	28.6	77.20 ° E	236	1989-1998	AST spot	G, D	-	G, D, SS
	Pune	18.53	73.85 º E	559	1990-1994	AST spot	G, D	CC	G, D, SS
Japan	Fukuoka	33.52	130.48 ° E	69	1992-1994	LCT 10 min avg	G, D, B <sub>n</sub> , SF	-	-
	Sapporo	43.05	141.33 ° E	40	1991, 1993	LCT 10 min avg	G, D, B <sub>n</sub> , SF	-	-
Spain	Gerona	41.97	2.88 ° E	100	1995-2001	GMT centred 5 min avg	G,D	SS, CC	SF
	Madrid	40.45	3.73 ° W	680	1999-2001	AST centred	G, D, B	SS, CC	SF
UK	Bracknell	51.26	0.46 ° W	74	1990-1995	AST centred	G, D, SS, CC	-	-

Table 3.1 Sites' geographic and database information

Note: All radiation values were converted to W/m<sup>2</sup> for hourly and W-hr/m<sup>2</sup> for daily. Sunshine duration (SS) is given in hours or minutes as the case may be.

Country	Location	Total data points	f x (σ <sub>k</sub> )	Lower bound polynomial cut-off	% Rejection through QC procedure	No of data points that cleared all tests and for which SF was recorded
India	Chennai	16551	2.2	0.85	8.2	13047
	Mumbai	17461	2.0	0.90	5.4	12569
	Delhi	28713	2.0	NA	7.9	24671
	Pune	16241	2.0	0.80	13.0	11716
Japan	Fukuoka	20680	2.2	0.90	5.4	19650
	Sapporo	14701	2.0	0.85	7.7	13563
Spain	Gerona	27869*	2.0	0.80	1.8	27328
	Madrid	11808	2.0	0.90	4.4	11162
UK	Bracknell	22580	2.3	0.90	2.1	22111

### Table 3.2 'Quality Control' results for all datasets

\* Note that total data points for Gerona's original (5-minutely) dataset were 309248. QC was performed after hourly integration.

### CHAPTER 4

# PRELIMINARY QUALITATIVE ANALYSIS FOR DIFFUSE IRRADIANCE MODELLING

For any modelling procedure, the first step is to recognize the parameters that could be instrumental in the proposed estimation. This chapter demonstrates the influence of three such synoptic elements, namely, sunshine fraction, cloud cover and air mass on diffuse irradiance modelling.

It has been established in the past and acknowledged herein that the most crucial parameter for the estimation of diffuse irradiance is its global counterpart. Therefore, bearing this in mind, the famous Liu and Jordan (1960) relationship between the daily diffuse fraction of the global radiation (k) and daily clearness index  $(k_t)$ , which is the ratio of global to extra terrestrial radiation, is adopted as the basis of the present methodology. Since then, several other k-kt regressions based on hourly, daily and monthly-averaged data have been proposed (Orgill and Holland, 1977; Collares-Pereira and Rabl, 1979; Erbs et al., 1982; Spencer, 1982). However, as discussed in Chapter 2 (Review of the Relevant Literature) this relationship is not universal and there is a need for individual models based on local climatic and geographical conditions. Apart from global radiation, it was found that other weather elements could also significantly effect and thus improve the diffuse irradiance estimation. Various regressions have been developed taking into account one or some of the following: air mass (m), albedo, ambient temperature, atmospheric aerosols, atmospheric turbidity, cloud cover (CC), relative humidity, solar elevation and sunshine fraction (SF) (Bugler, 1977; Iqbal, 1980; Muneer and Saluja, 1986; Skartveit and Osleth, 1987; Reindl, 1990; Vázquez, 1991). A detailed account of such models can be found in Chapter 2.

Under the current research, daily SF (ratio of number of bright sunshine hours to day length) or hourly or sub-hourly SF, as the case may be, CC and m are considered as

potential parameters to be included in the modelling. While the meteorological stations provide the first two, the third is a solar geometric parameter that can be calculated e.g. by using Kasten's (1993) model (Eq. 4.1) which provides an accuracy of 99.6% for zenith angles up to 89 °.

$$m = [\sin SOLALT + 0.50572 (SOLALT + 6.07995)^{-1.6364}]^{-1}$$
(4.1)

Another modified expression for air mass has been provided by Gueymard (1993), expressed as below.

$$m = [\sin SOLALT + 0.00176759(SOLALT(94.37515 - SOLALT)^{-1.21563})]^{-1}$$
(4.2)

Air mass was calculated by both methods. On investigating the correlation between the two, it was found that the coefficient of determination was of the order of 0.999 for all sites. A sample plot for Gerona is shown in Fig. 4.1. Also, for a typical day the maximum variation in the air mass calculated by the two methods was approximately 4% while the average variation only being 0.6%. Therefore, it is recommended to use any of the two models for air mass calculation. Kasten's formula was used for the present study.

The effects of these parameters were qualitatively investigated by studying their individual influence, if any, on the conventional hourly k- $k_t$  relationship. Data sets from nine locations were used, details of which are covered under Chapter 3.

## 4.1 Significant Factors in Characterization of Diffuse Irradiance: Need for Improvement over the Conventional k-kt Model

Of all the datasets, Bracknell data is most consistent with respect to SF and CC being measured during the same hours as radiation values. Therefore, this site was used to demonstrate the influence of the three parameters under discussion.

The very basic model, which shows a polynomial relationship between k and  $k_t$ , does not provide an accurate estimation of diffuse fraction of global radiation. A typical k $k_t$  plot shown in Fig. 4.2 displays a considerable scatter of data points for this chosen site (Bracknell, UK). Any suitable regression fit (linear, quadratic or cubic) does not and cannot account for the whole data. For example, a  $k_t$  value of 0.5 has observed values of k = 0.35 and 0.87, respectively, in clear and overcast regimes (marked by highlighted points in the figure). Whereas, cubic regression fit for the same data overestimates the clear sky observation by 74% and under estimates the corresponding overcast value by 30 %. Likewise, quadratic regression fit yields errors of a similar order of magnitude. Linear fit, as can be inspected visually, is worse in performance than the other two, again emphasizing the fact, that diffuse radiation is very poorly predicted from k-kt model alone. There definitely remain other potential parameters that exert a significant influence on the diffuse fraction and consequently on diffuse radiation.

While m can be calculated from the knowledge of solar altitude, measurement of SF and CC in contrast to the diffuse radiation is widely undertaken along with other meteorological data such as humidity and temperature. In UK itself, some 600 sites measure CC, out of which 230 sites measure sunshine duration while diffuse radiation is measured at relatively fewer sites. When the sky is completely covered by clouds (8 oktas of cloud cover), the sunshine fraction is zero, and the radiation received on the earth's surface is completely diffuse in nature. Likewise, for completely clear skies i.e. with nil cloud cover and sunshine fraction equal to unity, the global radiation chiefly comprises of beam component. Sunshine duration has conventionally been used to characterize the climate of a given location and in deducing the total flux of solar radiation on a horizontal surface at locations for which no pyranometric measurements are available (Coulson, 1975). This is a common practice even now in various parts of the world, owing to the simplicity, convenience, and relatively low cost of sunshine recorders. Since diffuse (as the name suggests) is the scattered radiation, cloudiness is a very important determinant of diffuse radiation value. With recent technological advancement, cloudiness is now being measured by laser techniques, at least for some locations within UK. However, for the subjectivity of this parameter and more importantly for ease and economics of measurement, most of the world sites still rely on traditional visual methods of cloud observation. Hence, it is logical to say that both SF and CC can potentially play a significant role in the determination of the diffuse fraction of global radiation. Regarding the third parameter presently under investigation i.e. m, it is known that the scattering effects of greater air mass render considerable portion of global radiation as diffuse component at lower solar altitudes (De Miguel et al., 2001). This implies that for a

given value of  $k_t$  an increase in m can lead to a corresponding increase in k. Air mass was preferred to solar altitude in the present research, because the former is a more appropriate parameter for the characterization of atmosphere, e.g. turbidity and aerosol loading.

To physically demonstrate the relevance of the chosen synoptic parameters, following approach was adopted.

The range of SF (0 to 1) and CC (0 to 8) were divided into 11 and 9 equal bands, respectively. Air mass (ranging from 1.136 to 7.725) was likewise divided into 7 bands of equal interval, with the inner and outer range inclusive of the actual limits of the data. Frequency plots for SF, CC and m are shown in Fig. 4.3. The next step was to plot the data for various bands of each of the parameters on separate k-k<sub>t</sub> plots. The bands were selected on the basis of frequency of each parameter; highest frequency band, second highest and lowest frequency bands abbreviated as HFB, SHFB and LFB, respectively. Fig. 4.4 shows the data plots for those bands of SF. It is quite evident from the figure that the scatter is relatively small and the data points are thickly populated forming discrete bands for different bands of SF. The plots, Fig. 4.4 (a) and (b), show the highest frequency band (HFB) of SF=0 and the lowest frequency band LFB of SF=0.4, respectively. Figure 4.4 (c) displays the data points for SHFB, which is SF=1. The HFB represents 42% of the total data points whereas the LBF comprises of 3% of the same. HFB is expected to have widest scatter, however, the fact that the degree of scatter in each band is comparable suggests that SF is a strong parameter in characterization of diffuse fraction. The plots in Fig. 4.5 indicate clear distinction for two widely spaced bands (i.e. CC=0 and CC=8); however, in Fig. 4.5 (a), the LFB comprises of only 2% of the data yet the scatter in this case is considerable. Moreover, the HFB (CC=7) of Fig.4.5 (b) is spread over the entire span of the complete data set. Fig. 4.5 (c) on the other hand, which represents the SHFB of CC, forms a distinct curve in the upper left hand portion of the  $k-k_t$  envelope symbolising the fact, that for overcast skies k approaches unity with low values of k<sub>t</sub>. From this analysis, it can be concluded that CC does show certain promise in influencing the diffuse fraction but is less effective when compared to SF. Fig. 4.6 presents the data plots for three air mass bands. It can be seen clearly that there are no discrete bands; in fact the data of one band overlaps the other significantly. Not only

this, the scatter of HFB (Fig. 4.6-a) is as much as what it would be for the complete data set. The immediate next band, SHFB, (Fig. 4.6-b) is very much the same. As for LFB (Fig. 4.6-c), the scatter is much wider than any of the LFB's of SF and CC. In addition, LFB, holding only 0.9% of the total data, covers the whole k-k<sub>t</sub> envelope span. From Fig. 4.6 it is evident that all air mass bands yield multiple k-k<sub>t</sub> values and do not belong to a discrete portion of the k-k<sub>t</sub> envelope, unlike SF and CC. Thus, in the context of presently considered parameters, it can be concluded that m is apparently the weakest parameter in the characterization of diffuse radiation.

## 4.2. Inter-comparison of Sunshine Fraction, Cloud Cover and Air Mass Influence on Diffuse Irradiance

It has been established in the past, that  $k_t$  is closely correlated to k and hence is a determinant for estimation of diffuse radiation, provided global radiation is known. Exhaustive models have been developed using k-k<sub>t</sub> relationships. In the present analysis, k is taken as a quadratic function of k<sub>t</sub>. This polynomial relationship was chosen to provide a simple yet a widely applicable platform in order to explore the other factors which might lead to more accurate estimates of diffuse radiation as compared to using k-k<sub>t</sub> models alone. In other words, the effect of the three synoptic parameters is studied qualitatively on the fundamental k-k<sub>t</sub> relationship in the following section.

#### 4.2.1 The effect of sunshine fraction (SF)

The available data for each site is binned into appropriate bands of SF, which ranges from 0 to 1. For each band of SF, a quadratic regression curve is fitted to the data in that band. Regressions were carried out for various combination bands and the most suitable ones are presented here (Figs. 4.7-4.10). The first band for all the sites is wider than the other bands. For example, first band for Indian sites is 0 to 0.4 and for others it is 0 to 0.3. This convention is adopted throughout as the above-stated lower SF bands represent overcast skies and the data in this range has a greater tendency to overlap. Consequently, it is appropriate to group the data lying within, in order to maintain the distinctness of regression bands. However, with increasing values of SF the bandwidth reduces to 0.1 or 0.2, as the case may be. Within each banded data, there is an upper as well as lower limit set by maximum and minimum values of k and  $k_t$  prevalent in that band. These limiting values, the number and percent of data points per band are provided in Table 4.1 for each site. From the plots (Figs. 4.7-4.10), it is quite evident that even though the bands are very closely grouped, their respective regression lines are distinct and separate. One can also observe that all the SF bands follow a unique order throughout all sites. As could be expected, the higher the SF value, the lower the value of k for a given  $k_t$ . In other words, higher value SF bands are expected to fall in the lower region of k-kt envelope (clear skies) and lower value bands in the upper region (overcast skies). The only exception to this general trend is upper left corner and bottom right corner of the plots representing overcast and clear skies, respectively. It is only in these regions that the regression lines cross and overlap each other. Herein, it is important to note that one of the apparent reasons for this phenomenon is the method of approach used, which takes into account all the  $k-k_t$ points within each band defining the two limits. That is to say, even a single erroneous point, which is not a representative of the actual data in that band, can contribute in forcing the regression curve to that limit. Another reason for the bending of the curves and thus overlapping is the quadratic nature of the fits, which is further accentuated towards the two extremes. Therefore, it is recommended to consider the regressions for k<sub>t</sub> ranging between 0.2-0.8 in order to exclude completely overcast and clear sky regimes for the present graphical analysis. This is true for both CC and m analysis which would be presented in the following sections.

The fact that the overall generalised trend is in accordance with the trend that is theoretically predicted for all sites irrespective of their geographical/ topographical variations, suggests that SF has a universal bearing on k-k<sub>t</sub> relationships and can be used as an effective tool for diffuse radiation estimation. It was also reported by Gopinathan and Soler (1996) in their study based on monthly mean daily values that, when both clearness index and relative sunshine duration are used together in multiple regressions, the estimated diffuse radiation is more accurate than when the two predictors are used separately. Another common characteristic feature is that, the regression curve for lower SF values are generally convex, that for intermediate values are close to linear and the upper SF values display concave regression trends. With the exception of Chennai and Pune, the SF band of 0.9 to 1 extends only partially over the span of the k-k<sub>t</sub> envelope. This is in confirmation with what is expected with higher SF values that diffuse radiation should be lower and k<sub>t</sub> should be higher.

#### 4.2.2 The effect of cloud cover (CC)

A similar analysis, as that for SF, was carried out for those six databases for which CC was available. For this part of the work, the data was split in three CC bands for all sites. Table 4.2 provides the information on all bands of CC for each site. Since CC was measured only at certain fixed hours for each day, unlike the hourly SF, the number of data points is considerably less. Again, it can be interpreted that the regressions for these categorized data are distinct and follow a unique order for all the sites (Figs. 4.11-4.13). Lowest CC band defines the lowermost curve (generally convex) while highest values of CC represent the uppermost curve (generally concave) and in the middle lies the intermediate CC band (a near linear curve). Like SF, CC banded regression curves also deviate from the general trend towards the two extremes of overcast and clear sky conditions. Since the CC bands appear discretely and in (theoretically-predicted) order for the k-kt data, it can be concluded that CC holds significance as one of the influential parameters for diffuse radiation modelling.

#### 4.2.3 The effect of air mass (m)

In this part of the investigation, k-k<sub>t</sub> regressions were developed for different bands of air mass. Of the quality-controlled databases along with complete synoptic information that were presently available, it was found that m varies from a minimum of 1 to a maximum of 8. The data sets were binned accordingly in three air mass bands. Table 4.3 provides information on the air mass banded data for all sites. It was found that there was no specific trend for the k-kt regressions under banded m data (Figs. 4.14 - 4.17). While for Indian sites the regression curves were rather distinct but completely random, they overlapped each other for other sites. This can be well explained from the fact that same air mass values can lead to disparate sky conditions. In other words, both a clear sky with a minimum value and an overcast sky with a high value of diffuse ratio can have the same air mass. Thus, it can be concluded that air mass is a comparatively weak parameter on its own for diffuse radiation estimation. This observation is also supported by the work of Vázquez et al (1991), where they explored the impact of air mass on  $K_d$  (daily diffuse to daily total extraterrestrial) versus K<sub>t</sub> (daily clearness index) relationship. They concluded from their study that although both absorption and scattering vary with the air mass, the K<sub>d</sub>-Kt relationship can be explained from scattering alone, however, variations in absorption caused by air mass do not impact the basic shape of the relationship but,

rather, account for seasonal variability, and for variations as a function of solar altitude.

# 4.3 Evaluation of Air Mass Influence on Diffuse Fraction using Cloud Cover and Sunshine Fraction Filters for Clear Skies

The effect of air mass is more apparent for clear than for overcast skies. For this reason, the effect of air mass for clear skies was studied in a detailed manner for Bracknell and Madrid in the following section. Bracknell was the only site with complete information on all measured data. Madrid was chosen because it is the head quarter for Spanish meteorological office. The proximity of Madrid to Bracknell in terms of latitude ensures that the effect of air mass will be of a similar order.

To identify and isolate the clear sky data for present analysis, two consequential filters were applied.

#### 4.3.1 Basic clear sky filter using cloud cover

The first filter employed was CC <=1. As a next step, k versus m was plotted for this filtered data for both Bracknell and Madrid (Figs. 4.18, 4.19). Large scatter for Bracknell data was due to the fact that it had a larger database than Madrid (almost double the data points, refer to Table 3.2). Moreover, for Madrid cloud cover information was available only for selective hours in a day, while for Bracknell CC was provided for every hour. At first glance, the picture provided by Fig. 4.18(a) appears to be contradictory with k approaching unity in a clear sky condition like this (CC<=1). For clarification purpose, the data was further divided in two plots; one with CC=0 (Fig 4.18-b) and the other for CC=1 (Fig 4.18-c). The scatter and trend in Fig. 4.18(b) is very much similar to Fig. 4.19 that shows the clear sky (CC $\leq 1$ ) data for Madrid. One peculiar observation in the plot of Fig. 4.19 is the stepwise pattern, specifically for air mass ranging from 1 to 4 where the bulk of data lies. This can be attributed to the fact that CC for Madrid data was available for definite hours during a day (7, 13 and 18). Also, since radiation data was available at the mid of each clock hour, i.e. at 6:30, 7:30 and so on, the CC value recorded at one particular hour was taken for the preceding as well as succeeding half-hour to match with the radiation data available for those hours. That is to say, a CC value recorded at 7 hour was assumed to be the same for 6:30 and 7:30 hour radiation data. Further investigation of Fig. 4.19 revealed that the data corresponding to radiation values at 12.5 and 13.5 hours, or in other words CC at 13 hours (close to zenith), was prevalent only for m ranging from 1 to 2.6 and formed the major portion of the first two demarcating steps. Of that data, 24% belonged to radiation data at 7.5 hours. Interestingly, this data was from the summer months (April-August) only. This peculiarity can be explained on the basis of the fact that sun traces a higher solar elevation in summer months and also the latitudinal location of Madrid. The data, with values of m greater than 2.6, belongs to radiation hours of 6.5, 7.5, 17.5 and 18.5. Also, only 2.3 % of the total data has a diffuse ratio of greater than 0.5; which is one of the establishing conditions of clear sky. Thus, in spite of the varying nature of the two sites and their respective data sets, for the present work, it can be concluded that the impact of air mass (m) for absolutely cloudless conditions is same on the diffuse ratio (k). A cloud condition of one octa for Bracknell (Fig.4.18-c) on the other hand leads to a wide variation of k for the same m. This can be explained as follows: it is practically possible that a cloud covering one octant of the sky actually obstructs the sun's path. In such a situation, most of the global irradiance falling on the sensor is bound to be diffuse and hence there is data with high k values. However, it was found that only 4.8% of the total data had diffuse ratio greater than equal to 0.7.

#### 4.3.2 Basic clear sky filter using sunshine fraction

Another clear sky filter employed here is SF>=0.9. Considering, the Bracknell plot first (Fig. 4.20) there is a distinct trapezium-like shape with its base roughly at m =1 and apex pointing towards higher air masses, meaning as the air mass values increase the tendency for k to vary decreases until it falls within a narrow limit of partially diffuse skies (0.2 to 0.6, approx.). Now, SF >=0.9 implies that the sun was not shining for 0.1 hour or less. This suggests that the sun was being obstructed by cloud during that one-tenth hour. Since Bracknell is prone to high winds, for m ranging between 1 and 4, there is a greater chance of dynamic cloud movement. Hence, a cloud obstructing direct irradiance at one instance might be cleared off the sun's path at the next instance. As a result diffuse fraction would be alternatively high and low, respectively. However, with higher m sun is far away from the zenith and thus, the probability of cloud affecting the solar irradiance is considerably reduced. Also, in such a scenario there would be much less inter-reflection owing to the presence of clouds, which is an apparent phenomenon behind low k values, since it renders direct

irradiance as diffuse. Therefore, k would more likely tend to vary in the lower to middle range for high air masses. Figure 4.21 demonstrates the mechanics of this phenomenon. Nevertheless, such high sunshine fraction (SF>=0.9) ideally should occur for lower air masses when sun is closer to the zenith. On investigation, it was found that only 2.7% of the data had m>=5 which conforms the expectation.

Figure 4.22 shows a similar k versus m plot for daily SF>=0.9 applied to all Madrid data, irrespective of the cloud cover availability for those hours. It is worthwhile to note here that, while Bracknell has hourly SF, Madrid data contains integrated daily SF values. Therefore, there is bound to be some difference in the nature of the above two plots. Nevertheless, the trend of SF filtered data for Madrid is very much similar to that of its corresponding CC filter (Fig. 4.19). Also, comparison of the two plots reveals that a significant number of data points overlap, due to the fact that the two conditions of CC<=0 and SF>=0.9 suggest clear sky. The Madrid data however does not represent an ideal picture due to the inconsistency in measurement of CC, SF and irradiation. Bracknell data is more reliable in this respect.

There is a common feature for both Bracknell and Madrid, which was found when their respective SF and CC filtered data plots were compared. It was observed that for air mass values ranging roughly from 5 to 8, CC has a significant scatter as against the corresponding SF plot. The SF data specifically removes the data points that have high (0.6–0.8) and low values (0.2-0.3) of k, which are prevalent in the corresponding plots of CC filter. This discrepancy can be attributed to the prospective errors associated with the cloud cover observation. Apart from this, there is yet another limitation in terms of CC, which is inherent in even a highly precise and accurate data set. This is: While SF is a continuous record of what transpires during an hour, CC is but a spot reading usually taken 10 minutes prior to the measurement of radiation value for that hour. Consequently, SF filter is more appropriate than the CC filter for the current data sets in particular and for all other data in general. Another conclusion that could be derived from this study is that air mass alone does not provide a strong parameterization of diffuse radiation even under clear skies.

#### 4.4 Summary

Most of the meteorological stations around the world measure weather elements like, sunshine duration, cloud cover, humidity, temperature, precipitation, etc., along with global irradiation. Diffuse radiation measurement, however, is unavailable for many of those sites. This accentuates the need to estimate it whereupon it can be used for the simulation of solar applications.

In the light of above case, this chapter explored the role of synoptic information, e.g., sunshine fraction, cloud cover and air mass on the basic k-kt relationship for nine sites across the globe in order to assess their relative relevance to the estimation of diffuse irradiance. To start with, it was shown that the conventional k-kt model for diffuse irradiation produces a wide scatter and therefore, in itself is unsatisfactory. The influence of sunshine fraction, cloud cover and air mass on k-kt regressions was studied qualitatively through graphical means. It was found that while sunshine fraction showed a strong bearing, followed closely by cloud cover, air mass on the other hand was found to be a weak parameter for general estimation of diffuse radiation. However, it was concluded that it might also lead to better estimation of diffuse irradiation if used in conjunction with any or both of the two parameters, i.e. sunshine fraction and cloud cover. Air mass effect was analyzed for clear sky data based on two sites and it was found that for clear skies it has more significance than under all-sky conditions. Clear sky data is of interest for numerous solar energy projects. It was found that the SF>=0.9 filter provides the best means of selecting clear sky data under the present scope.

In conclusion, this section of the thesis opens an avenue where utilization of such complimentary data along with global irradiation can effectively increase the accuracy of estimation procedures conventionally used for diffuse irradiation.

Note that the present chapter deals only with individual role of each parameter. Further investigation of the influence of the above parameters on a combinatorial basis will be undertaken in the following chapters, both on hourly and daily scales.



Fig. 4.1 Calculated air mass: Kasten's versus Gueymard's model



Fig. 4.2 k-k<sub>t</sub> regression analysis for Bracknell quality controlled database: Dashed curve represents linear fit ( $R^2$ =0.855), thick solid line is for quadratic polynomial fit ( $R^2$ =0.893) and thin solid line for cubic polynomial fit ( $R^2$ =0.903)



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Fig. 4.4 k versus  $k_t$  plots (Bracknell data): (a) HFB of SF, (b) LFB of SF and (c) SHFB of SF

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Fig. 4.5 k versus k, plots (Bracknell data): (a) LFB of CC, (b) HFB of CC and (c) SHFB of CC











Fig. 4.7 k versus k<sub>t</sub> regression curves for different SF bands (Indian data) (a)Chennai, (b) Mumbai, (c) New Delhi and (d) Pune





Fig. 4.8 k versus  $k_t$  regression curves for different SF bands (Japanese data) (a) Fukuoka and (b) Sapporo





Fig. 4.9 k versus kt regression curves for different SF bands (Spanish data) (a) Gerona and (b) Madrid



Fig. 4.10 k versus k<sub>t</sub> regression curves for different SF bands for Bracknell (UK)

(a)



(b)











Fig. 4.13 k versus k<sub>t</sub> regression curves for different CC bands for Bracknell (UK)



Fig. 4.14 k versus k<sub>1</sub> regression curves for different m bands (Indian data) (a) Chennai, (b) Mumbai, (c) New Delhi and (d) Pune

(a)





Fig. 4.15 k versus k<sub>t</sub> regression curves for different m bands (Japanese data) (a) Fukuoka and (b) Sapporo





Fig. 4.16 k versus kt regression curves for different m bands (Spanish data) (a) Gerona and (b) Madrid



Fig. 4.17 k versus k<sub>t</sub> regression curves for different m bands for Bracknell (UK)









Fig. 4.18 k versus m plot (Bracknell data) (a) for CC<= 1, (b) for CC=0, (c) for CC<1



Fig. 4.19 k versus m plot (Madrid data) for CC<=1



Fig. 4.20 k versus m plot (Bracknell data) for SF>= 0.9


A: Possible cloud movement due to westerly winds from sky-octant 7 to sky-octant 2. Note that this is an arbitrary example to demonstrate the ease with which cloud can move from one sky-octant to another for lower air masses.

B: This movement shows the transfer of cloud between the same sky-octants as above for higher air masses. Movement B will take a considerable time as opposed to the other rapid movement A.

Fig. 4.21 Demonstration of cloud movement across the sky dome for given air masses and prevailing wind conditions



Fig. 4.22 k versus m plot (Madrid data) for SF>= 0.9

SF band	k <sub>t</sub> ,min	k <sub>t</sub> ,max	k,min	k,max	No of pnts % of tota	
					per band	points
Chennai						<u> </u>
0.0 - 0.4	0.01	0.94	0.31	1.00	1337	10.25
0.4 - 0.5	0.03	0.96	0.21	1.00	821	6.29
0.5 - 0.6	0.03	0.99	0.19	1.00	1039	7.96
0.6 - 0.7	0.03	1.00	0.12	1.00	1802	13.81
0.7 - 0.8	0.03	1.00	0.11	1.00	3064	23.48
0.8 - 0.9	0.04	1.00	0.09	1.00	4373	33.52
0.9 - 1.0	0.05	1.00	0.09	0.90	611	4.68
Mumbai						
0.0 - 0.4	0.01	0.95	0.16	1.00	3275	26.08
0.4 - 0.5	0.06	0.82	0.17	1.00	642	5.11
0.5 - 0.6	0.09	0.82	0.13	1.00	498	3.97
0.6 - 0.7	0.07	0.84	0.15	1.00	923	7.35
0.7 - 0.8	0.08	0.79	0.10	1.00	1623	12.92
0.8 - 0.9	0.04	0.92	0.10	1.00	3963	31.56
0.9 - 1.0	0.19	0.92	0.10	0.87	1635	13.02
New Delhi						
0.0 - 0.4	0.01	0.80	0.27	1.00	4643	18.82
0.4 - 0.5	0.02	0.83	0.18	1.00	1449	5.87
0.5 - 0.6	0.03	0.81	0.14	1.00	2162	8.76
0.6 - 0.7	0.06	0.82	0.13	1.00	3729	15.11
0.7 - 0.8	0.05	0.85	0.11	1.00	7264	29.44
0.8 - 0.9	0.17	0.85	0.11	0.92	5222	21.17
0.9 - 1.0	0.46	0.82	0.12	0.53	202	0.82
Pune						
0.0 - 0.4	0.02	0.96	0.17	1.00	1215	10.38
0.4 - 0.5	0.03	0.88	0.23	0.99	501	4.28
0.5 - 0.6	0.03	0.94	0.19	1.00	765	6.54
0.6 - 0.7	0.03	0.96	0.18	1.00	951	8.12
0.7 - 0.8	0.03	0.98	0.11	1.00	1905	16.27
0.8 - 0.9	0.03	1.00	0.08	1.00	5635	48.14
0.9 - 1.0	0.05	0.98	0.06	0.98	734	6.27
Fukuoka						
0.0 - 0.3	0.01	0.56	0.62	1.00	9498	48.68
0.3 - 0.7	0.18	0.67	0.33	1.00	1543	7.91
0.7 - 0.9	0.25	0.76	0.20	0.94	866	4.44
0.9 - 1.0	0.36	0.90	0.09	1.00	7603	38.97
Sapporo						
0.0 - 0.3	0.02	0.69	0.29	1.00	6601	48.76
0.3 - 0.7	0.03	0.86	0.32	1.00	1134	8.38
0.7 - 0.9	0.32	0.86	0.21	0.89	616	4.55
0.9 - 1.0	0.36	0.93	0.11	1.00	5187	38.31

Table 4.1 Statistics for sunshine band regressions

Table 4.1 continued							
Gerona							
0.0 - 0.3	0.02	0.80	0.09	1.00	5576	20.40	
0.3 - 0.7	0.02	0.82	0.07	1.00	9943	36.38	
0.7 - 0.8	0.05	0.85	0.07	0.97	5275	19.30	
0.8 - 0.9	0.04	0.83	0.05	0.96	6050	22.14	
0.9 - 1.0	0.20	0.82	0.06	0.87	484	1.77	
Madrid							
0 - 0.3	0.02	0.79	0.12	1.00	1923	17.23	
0.3 - 0.7	0.02	0.81	0.06	1.00	3118	27.93	
0.7 - 0.8	0.14	0.82	0.06	1.00	1229	11.01	
0.8 - 0.9	0.12	0.82	0.06	1.00	3385	30.33	
0.9 - 1.0	0.31	0.82	0.05	0.65	1507	13.50	
Bracknell							
0.0 - 0.3	0.02	0.70	0.32	1.00	11257	50.91	
0.3 - 0.7	0.15	0.73	0.24	1.00	2776	12.55	
0.7 - 0.9	0.27	0.77	0.22	0.99	1676	7.58	
0.9 - 1.0	0.32	0.83	0.09	1.00	6402	28.95	

CC band	kt,min	kt,max	k,min	k,max	No of pnts % of total	
					per band	points
Chennai						
0 - 2	0.16	0.97	0.10	0.87	911	21.50
3 - 5	0.13	0.99	0.09	1.00	2158	50.92
6 - 8	0.02	0.94	0.18	1.00	1169	27.58
Mumbai						
0 - 2	0.16	0.84	0.11	1.00	1841	45.90
3 - 5	0.07	0.92	0.10	1.00	853	21.27
6 - 8	0.02	0.82	0.18	1.00	1317	32.83
Pune						
0 - 2	0.09	0.98	0.06	1.00	1809	45.13
3 - 5	0.12	0.97	0.11	0.99	915	22.83
6 - 8	0.03	0.94	0.16	1.00	1284	32.04
Gerona						
0 - 2	0.09	0.82	0.06	0.98	1889	38.84
3 - 5	0.06	0.81	0.07	0.96	1582	32.53
6 - 8	0.02	0.79	0.13	1.00	1392	28.62
Madrid						
0 - 2	0.12	0.82	0.05	1.00	1912	47.32
3 - 5	0.09	0.81	0.07	1.00	837	20.71
6 - 8	0.03	0.79	0.14	1.00	1292	31.97
Bracknell						
0 - 2	0.07	0.79	0.09	1.00	3607	66.97
3 - 5	0.07	0.83	0.11	1.00	3439	23.45
6 - 8	0.02	0.79	0.11	1.00	15065	9.58

## Table 4.2 Statistics for cloud cover band regressions

CC band	m,min	m,max	kt,min	kt,max	k,min	k,max	No of pnts % of total	
							per band	points
Chennai								
1 - 3	1.01	2.25	0.02	0.95	0.09	1.00	4229	98.42
3 - 5	4.39	4.96	0.12	0.88	0.49	1.00	36	0.84
5 - 8	5.05	7.45	0.15	0.99	0.21	0.96	32	0.74
Mumbai								
1 - 3	1.01	2.56	0.02	0.92	0.10	1.00	3463	85.78
3 - 5	3.82	5.00	0.03	0.84	0.37	1.00	309	7.65
5 - 8	5.00	7.72	0.05	0.73	0.31	1.00	265	6.56
New Delhi								
1 - 3	1.01	3.00	0.01	0.85	0.11	1.00	20175	81.78
3 - 5	3.00	5.00	0.03	0.83	0.15	1.00	3236	13.12
5 - 8	5.00	7 <sub>.</sub> 71	0.05	0.79	0.18	1.00	1260	5.11
Pune								
1 - 3	1.01	2.53	0.03	0.98	0.06	1.00	3971	99.08
3 - 5	3.87	4.86	0.04	0.58	0.34	0.98	24	0.60
5 - 8	5.05	6.62	0.08	0.90	0.39	1.00	13	0.32
Fukuoka								
1 - 3	1.02	3.00	0.01	0.90	0.09	1.00	15867	81.12
3 - 5	3.00	5.00	0.03	0.79	0.20	1.00	2469	12.62
5 - 8	5.00	7.73	0.04	0.68	0.31	1.00	1224	6.26
Sapporo								
1 - 3	1.06	3.00	0.02	0.93	0.11	1.00	10248	75.56
3 - 5	3.00	5.00	0.03	0.89	0.22	1.00	2224	16.40
5 - 8	5.00	7.73	0.04	0.79	0.32	1.00	1091	8.04
Gerona								
1 - 3	1.01	2.99	0.02	0.82	0.06	1.00	3401	69.94
3 - 5	3.00	5.00	0.03	0.71	0.14	0.98	449	9.23
5 - 8	5.00	7.69	0.05	0.71	0.18	0.96	1013	20.83
Madrid								
1 - 3	1.05	3.00	0.03	0.82	0.05	1.00	2870	71.02
3 - 5	3.00	4.9 <u>9</u>	0.03	0.73	0.14	1.00	699	17.30
5 - 8	5.00	7.73	0.05	0.79	0.17	1.00	472	11.68
Bracknell								
1 - 3	1.14	3.00	0.02	0.83	0.09	1.00	14808	66.97
3 - 5	3.00	5.00	0.03	0.78	0.16	1.00	5184	23.45
5 - 8	5.00	7.73	0.04	0.79	0.21	1.00	2119	9.58

## Table 4.3 Statistics for air mass band regressions

## CHAPTER 5

## HOURLY DIFFUSE IRRADIANCE MODELLING

Solar energy applications require readily available, site-oriented and long-term solar data. However, the frequent unavailability of measured diffuse irradiation, in contrast to its need, led to the evolution of various regression models to predict it from the more commonly available data (as elaborated in Chapter 2). Estimating the diffuse component from global radiation is one such technique. Inclusion of sunshine fraction (SF), cloud cover (CC) and relative air mass (m), along with global for diffuse irradiance modelling, forms the research methodology being developed under this section of the thesis.

In Chapter 4, the influence of sunshine fraction (SF), cloud cover (CC) and air mass (m) on the clearness-index – diffuse ratio relationship was explored qualitatively. This laid the foundation of the present chapter, which focuses on the quantitative aspect i.e. the improvement that can be achieved by using these auxiliary parameters along with *hourly* clearness index ( $k_t$ ) as a function of *hourly* diffuse ratio (k). Such polynomial relationships lead to the development of a series of empirical models. Diffuse irradiance can then be calculated as a product of measured global radiation and the estimated value of diffuse ratio.

This research is demonstrated for datasets from the same 9 sites that were used in Chapter 4 and described in detail in Chapter 3. The latter also gives an elaborate account on the procedure used for quality control of data under study. The present chapter deals with the hourly or sub-hourly values of horizontal radiation, while daily data and its modelling will be undertaken subsequently in Chapter 6. Hourly radiation is useful for detailed simulation of solar energy systems which require computation of hour by hour radiation rather than monthly average or daily values. Moreover, hourly values of radiation assist in deducing the performance of a solar energy system more precisely.

For the sites where only daily sunshine duration was given rather than an hourly fraction, the former was used within the hourly regression models. Air mass (m) for each hour of the data was calculated using Kasten's formula (Eq. 4.1) in Chapter 4. Eventually, the regression analyses were carried out for only those hours of each database for which both sunshine fraction and cloud cover were provided by the respective meteorological stations. This information is summarised in Table 5.1.

#### 5.1 Development of Models

Since the models involve interaction of four parameters, all possible combinations were applied to generate different sets of models. Eventually, the best model for each of the nine sites under study was selected, bearing in mind the optimum number of input variables and the gain in accuracy.

#### 5.1.1 Clearness index for diffuse irradiance: monovariate model

It is a well-known fact that clearness index ( $k_t$ ) strongly influences the diffuse ratio (k). Hence, it is an intrinsic parameter for the estimation of diffuse radiation. Under this section the very basic model, i.e., k as a function of  $k_t$  alone was developed. Regression equations with k as a polynomial function of  $k_t$  were explored up to the third order. It is generally found that the coefficient of determination increases with an increase in complexity of equation. However, taking Bracknell as an example, the increase from quadratic (0.89) to cubic regression model (0.90) was not as significant as the improvement from a linear (0.86) to quadratic fit. Also, if a cubic or quartic (4<sup>th</sup> order) relationship was chosen it would have produced a large number of coefficients due to the multiple interactions between the involved parameters thus contributing to the complexity of model equations. Therefore, the second-degree polynomial k-k<sub>t</sub> relationship is selected as the optimum and used throughout the modelling structure for the sake of simplicity as well as uniformity for all sites.

$$k = a_{10} + a_{11}k_t + a_{12}k_t^2 \tag{5.1}$$

# 5.1.2 Clearness index and sunshine fraction/ cloud cover/ air mass: bivariate models

Retaining  $k_t$  as the main regressor, the other three parameters, namely, SF,

CC and m were used to develop bivariate models by using following model equation.

$$k = (a_{i0} + a_{i1}X + a_{i2}X^{2}) + (b_{i0} + b_{i1}X + b_{i2}X^{2})k_{t} + (c_{i0} + c_{i1}X + c_{i2}X^{2})k_{t}^{2}$$
(5.2)

where, i = 2, 3 or 4 and X is SF, CC or m, respectively.

## 5.1.3 Clearness index, sunshine fraction, cloud cover and air mass: multivariate models

Under this section, regression equations involving a combination of two variables and later on a tripartite variable combination, besides  $k_t$ , were developed. All the possible combinations were applied, not neglecting of course, the linear and quadratic models for each parameter.

$$k = (a_{50} + a_{51}X + a_{52}X^2 + a_{53}Y + a_{54}Y^2) + (b_{50} + b_{51}X + b_{52}X^2 + b_{53}Y + b_{54}Y^2)k_t + (c_{50} + c_{51}X + c_{52}X^2 + c_{53}Y + c_{54}Y^2)k_t^2$$
(5.3)

where, i=5,6 or 7, X and Y are SF and CC, or SF and m, or CC and m, respectively.

The regression equation proposed to evaluate the effect of the independent variables  $k_t$ , SF, CC and m taken all together is represented in the form given by Eq. (5.4),

$$k = (a_{80} + a_{81}SF + a_{82}SF^{2} + a_{83}CC + a_{84}CC^{2} + a_{85}m + a_{86}m^{2}) + (b_{80} + b_{81}SF + b_{82}SF^{2} + b_{83}CC + b_{84}CC^{2} + b_{85}m + b_{86}m^{2})k_{t} + (c_{80} + c_{81}SF + c_{82}SF^{2} + c_{83}CC + c_{84}CC^{2} + c_{85}m + c_{86}m^{2})k_{t}^{2}$$
(5.4)

Regression analysis for the models given by Eq.s (5.1 - 5.4) was carried out for each location. Note that although regression models presented here are in quadratic form, a linear fit was also tried and the better of the two was selected for each parameter of each site. That is to say, if a linear model in SF was found to deliver comparable or better accuracy than a corresponding quadratic one, the former model was chosen. To avoid repetition the equations with same parameters but linear fit are not presented here. More so, quadratic form gives an explicit idea of the scope of a given expression.

## 5.2 Evaluation of Models

## 5.2.1 Statistical indicators

In order to evaluate the performance of each set of models for individual locations, the following statistical indicators were employed:

- Coefficient of determination (R<sup>2</sup>)
- Mean bias deviation (MBD)
- Root mean square deviation (RMSD)
- Skewness
- Kurtosis

Coefficient of determination  $(R^2)$  is the ratio of explained variation to the total variation. It lies between zero and one. A high value of  $R^2$ , thus indicating a lower unexplained variation, is desirable.

$$R^{2} = \sum (Y_{c} - Y_{m})^{2} / \sum (Y_{o} - Y_{m})^{2}$$
(5.5)

 $R^2$  is often used to judge the adequacy of a regression model but it should not be the sole criterion for choosing a particular model.

*Mean bias deviation* (MBD) provides a measure of the overall long-term trend of a given model. Positive values of MBD indicate under estimation while negative values imply over estimation by the proposed model. An MBD nearest to zero is desired. MBD is presently computed as:

$$MBD = \sum (Y_0 - Y_c) / n \tag{5.6}$$

*Root mean square of deviation* (RMSD) provides a means of comparison of the actual deviation between the predicted and the measured values. RMSD is always positive. A lower absolute value of RMSD indicates a better model.

$$RMSD = \left[\sum (Y_O - Y_C)^2 / n \right]^{1/2}$$
(5.7)

*Skewness* is defined as a measure of the lack of symmetry in a distribution. A distribution is symmetric or normal if it looks the same to the left and right of the centre point, yielding a zero value for perfect symmetry. A positively skewed distribution tails off to the high end of the scale while negative skew tails off the low end of the scale. Skewness is expressed as,

Skewness = (mean-mode)/standard deviation (5.8)

*Kurtosis* is defined as a measure of the degree of peakedness in the distribution, relative to its width. The kurtosis statistic will be zero (mesokurtic) for a normal distribution, positive for peaked distributions (leptokurtic) and negative for flat distributions (platykurtic). Numerical representation of kurtosis based on quartiles and percentiles is given by,

 $Kurtosis = Q / (P_{90} - P_{10})$ (5.9) where, Q=(Q<sub>3</sub>-Q<sub>1</sub>)/2 is the semi-inter quartile range

Though, practically speaking, the actual values of the skewness and kurtosis statistics rarely turn out to be exactly zero.

For the present analysis, R<sup>2</sup> was obtained directly from the regression analysis of diffuse ratio. All the other parameters were evaluated for calculated diffuse radiation. Errors in estimation are of prime importance to both the developers and users of the models. Since the objective here is to estimate diffuse radiation, it is a wise practice to evaluate the error statistics involved in the calculation of diffuse radiation rather than diffuse ratio. MBD and RMSD enable insight in the performance evaluation of diffuse radiation of diffuse radiation prediction, whereas, skewness and kurtosis characterize the symmetry and shape of the distribution, respectively. Since, in the present study it is the error distribution under consideration, low absolute skewness and high kurtosis is desirable.

However, each statistical indicator has certain associated inherent drawbacks which are worth addressing. Some of which are as follows:

(1) Over-estimation of one observation within a data set cancels the under-estimation

of another, making it difficult for MBD to represent the true nature of model accuracy.

(2) RMSD fails to give a complete assessment of a model as only a few large errors can increase its value substantially.

(3)  $R^2$  does not always measure the appropriateness of the model, since it can be artificially inflated by adding another parameter or higher order polynomial terms in the regression equation. Furthermore, even though  $R^2$  is relatively high, this does not necessarily imply that that regression model will provide accurate predictions of future observation (Montgomery and Runger, 1999).

(4) Skewness does not account for the magnitude of errors; it only gives information on the normality of their distribution.

(5) Kurtosis can be very sensitive to outliers particularly, if the data set involves measured values (Huber, 1985). In other words, only a few errors in the tails of the distribution, resulting as a deviation from erroneous or irrelevant observations can affect its value.

In view of such drawbacks discrepancy is inevitable while evaluating a model performance, unless a common means of evaluation is devised. The following section deals with the description and development of such indices which were used within the present evaluation analysis and also for *daily* diffuse irradiance modelling in the next chapter.

#### 5.2.2 Comparative indices: Development of accuracy score

From among the sets of models (8 models for Delhi and 9 models each for the Japanese sites and 18 models for each of the remaining sites) for each of the nine sites, it is an increasingly difficult task to separate out a particular model as 'the best'. While some models might show promise on a few of the statistical tests under discussion, others may indicate a better performance in terms of other measures of evaluation. Also, it is practically impossible to determine the degree to which a given statistical parameter influences the model performance. Hence, a methodology should be devised such that, provided all the indicators were considered to bear more or less similar effect, it can aid in the selection of an overall 'best' model. Furthermore, for analysing the best model, it is essential that all the parameters follow a unidirectional

trend. That is to say, if a higher  $R^2$  suggests better model performance then an increase in all the other four parameters should also be indicative of the same. However, this is not the case here. Whereas, a high  $R^2$  and kurtosis indicate better performance, a high MBD, RMSD and skewness suggest the opposite. Moreover, both skewness and MBD can either have negative or positive values, so an absolute value that is closest to zero is desired. Therefore, there is a need to develop a tool to facilitate a discrete comparison and help in the assessment of all the presently developed models. In the present work one such technique of evaluation, a comparative statistical index, is proposed. This index introduced as *Accuracy Score*\*, sums up all the credits accounted by each test of assessment.

Before testing the model accuracy, the range of variability in the statistical tests needs to be addressed. MBD and RMSD have the same units as diffuse radiation  $(W/m^2)$ , while  $R^2$ , kurtosis and skewness are dimensionless quantities. It is worthwhile to note here that it was preferred to evaluate MBD and RMSD in units of energy to give a clearer idea of model accuracy in quantitative terms. So, in order to sum them up these statistics (varying substantially both in terms of values as well as units) should be normalized. In other words, they are to be converted to dimensionless fractions ranging between zero and one to provide a commonality for the addition process. The calculation of such 'algebraic equivalents' from the five original indicators was a step-by-step procedure, as explained below and also represented in the form of flow-chart in Fig. 5.1.

### Algorithm for Accuracy Score calculation

- The very first step was to make MBD and skewness absolute so that all the parameters were then positive.
- As a second step, every item of each parameter was divided by the maximum value of that parameter (within a given table) to convert it into a ratio. This gave the algebraic equivalents for corresponding R<sup>2</sup> and kurtosis values.
- However, since MBD, RMSD and skewness follow an opposite trend to that of  $R^2$  and kurtosis, the third step thus involved the subtraction of resulting

<sup>\*</sup>*Note:* This system of scoring was later adopted by co-author Serge Younes who added slope as another statistical indicator for his part of work on cloud radiation modelling under the joint publication Muneer et al (2005).

ratios of MBD, RMSD and skewness from one, to yield their corresponding algebraic equivalents. This was done in order to achieve a unanimous trend for all the parameters.

- The fourth step involved the addition of all the five algebraic equivalents of statistical parameters for each model, thus obtaining the respective accuracy scores (AS) as reproduced in Tables 5.2-5.5.

The calculation procedure of AS can more explicitly be understood by its numerical form, which is expressed as:

 $AS = [R_i^2 / R_{i,max}^2] + [1 - abs(MBD_i) / abs(MBD_i)_{max}] + [1 - RMSD_i / RMSD_{i,max}] + [1 - abs(Skew_i) / abs(Skew_i)_{max}] + [Kurtosis_i / Kurtosis_{i,max}]$ (5.10)

*Note:* Here each term within the square brackets, as mentioned earlier, has been so designed that their respective values lie between 0 and 1. Therefore, since the presently developed scoring system is based on 5 statistical indicators, AS values would range between 0 and 5; the latter representing a perfect model. It is highly important to note here that AS is a comparative index and only compares between a given set of models.

Theoretically, the higher the accuracy score, the better the model's performance. Nevertheless, at the same time the increase in complexity of the model cannot be overlooked. Therefore, an optimum model has to be chosen: a model whose prediction accuracy considerably overweighs the involved intricacy. Not only this, one of the assumptions made in the development of this system of scoring that-all the presently employed statistical indicators contribute equally to the performance credits of a given model, indicates that AS, if supported with another index/ indices of performance evaluation, might yield a more reliable picture.

Hence, for this reason, two other statistical indices, namely, *Sum Deviation* (SD) and *t-statistic* are used along with AS. SD is the sum of deviation as represented by MBD and RMSD (Eq. 5.11). The t-statistic as taken from the work of Stone (1993) and represented in Eq. (5.12), also uses MBD and RMSD.

$$SD = [abs(MBD_i) / abs(MBD_i)_{max}] + [RMSD_i / RMSD_{i,max}]$$
(5.11)

$$t = [(n-1)MBD^{2} / (RMSD^{2} - MBD^{2})]^{1/2}$$
(5.12)

where, the symbols have their usual meanings.

SD and t-statistic give an additional perspective based only on the two most widely used and acknowledged tools in solar radiation modelling i.e. MBD and RMSD. The t-statistic was employed to provide a comparison with the presently used methods (AS and SD) to that already established in the literature (t-statistic). Advantages of t-statistic have been elaborated in Section 2.3 of Chapter 2. For the current analysis, as expected, variation in SD corresponded to the t-statistic, with a few exceptions and the fact that latter is more sensitive to change in MBD. As obvious from the definition, while higher AS suggests better performance, both SD and t-statistic should decrease with increasing model accuracy. Thus, on the basis of assessment of above statistical indices, an optimum model was recommended for each site (highlighted figures in Tables 5.2-5.5).

#### 5.2.3 Error distribution

Additionally, for each data point under investigation the calculated value of diffuse radiation was obtained from the 'k' models developed in Section 5.1. This calculated value was then subtracted from observed diffuse radiation. The errors thus generated, having the same units as diffuse radiation i.e.  $W/m^2$ , were plotted against their frequency of occurrence for each model. Such error histograms were obtained for all models of each site, however, in view of economy of thesis length, the histograms are reproduced for landmark or short listed models only; Fig. 5.2-5.5. It is evident from the charts that with an increase in number of parameters the error distribution shrinks (i.e., the peakedness of the error histogram increases) with the addition of independent variables, thus suggesting an improvement in the accuracy of estimation.

This trend was observed indisputably for all the sites. The simplistic k-k<sub>t</sub> model or 'Model 1' has the widest error distribution thus reflecting poor model performance. For example, there is a significant increase in performance (more than 40%) from Model 1 to Model 8, in context of error frequency in the range of -10 to +10 W/m<sup>2</sup> for Mumbai (Fig. 5.2-b) and -5 to +5 W/m<sup>2</sup> for Gerona (Fig. 5.4-a), respectively.

Careful observation revealed, that models with most peaked distribution or in other words, most accurate estimates within each site were same as the ones highlighted in Tables 5.2-5.5. Thus, histogram plots confirm the choice of optimum models based on statistical indices.

## 5.3 Model Proposition

On the basis of above statistical analysis, encompassing the standard indicators and indices, indigenous index like Accuracy Score and error histograms, the optimum models are proposed henceforth.

Since the four Indian sites are widely located within the sub-continent, the most appropriate models were found to be different for different locations. From Table 5.2 it is evident that both for Chennai and New Delhi Indian model 12 gave the best AS while another model (model 16) was found to be consistent for Mumbai and Pune. It is worthwhile to note here, that model numbers and types varied for different regions; however, care has been taken to number the models consistently for all sites falling within one region. Owing to unavailability of CC data, the models for New Delhi are numbered intermittently in order to match with the corresponding models for other Indian sites (Table 5.2-c). For Japan it was found that optimum model for Fukuoka (model 7) and Sapporo (model 8) share a commonality with respect to the parameters involved as shown in Table 5.3. Note that although the t-statistic of Sapporo's model 8 is higher than the preceding model 7, all the other statistics show considerable improvement, besides the error distribution in the closest zero band range being significantly higher, for Model 8. Thus, a particular model for any site was proposed only after investigating all the tests involved. For Spain, while model 9 suffices for Madrid, Gerona data fits best with a more complex model 17 (Table 5.4). Bracknell's model 12 (Table 5.5) was found to be the optimum for the site. However, analysing the models on a comparative scale, it was found that a single model could more than adequately estimate the diffuse radiation for the locations within a given region, which do not differ widely in their local climate. For instance, not only does model 12 appropriately reflect Chennai data set, it may also effectively be used for estimating diffuse radiation for the other Indian sites. Likewise, model 8 reasonably represents the solar climate of Japanese sites, considering the fact that Fukuoka and Sapporo lie at the two extreme ends of the country. In the vein of the above argument it may well

be deduced that model 17 can be employed to estimate diffuse radiation for Spanish sites, as is evident from the accuracy scores of Gerona and Madrid. However, though beyond the scope of this research project, further evaluation work is a way forward to a fuller validation. As for UK, since only one site (Bracknell) was under study a generalized conclusion could not be drawn for that country.

Accuracy scores were also plotted against the model number for each site (Fig. 5.6). These plots reveal that almost all recommended models present a hike of twice the accuracy score from their worst counterparts for most of the sites. This, in itself, signifies the consequent improvement in diffuse prediction with the inclusion of synoptic parameters and air mass along with k<sub>t</sub>. The minimum increase in accuracy score from the poorest model to the most adequate one is 35% (for Sapporo, Fig. 5.6b). On the other hand, AS of optimum model of sites like Pune increased three fold compared to the minimum, Fig. 5.6(a). Note that the lack of monotonic behaviour of the accuracy curves suggests that an increase in degree of the polynomial function or addition of another independent parameter does not necessarily improve the model performance. There is always a unique set of arguments that gives the best regression fit or highest AS for the site concerned. So, one model which is optimum for one site may not yield results of similar order for another site. This may also be due to a disparity of accuracy of measurement for the given data set at different sites. Another reason could be the inconsistency of frequency of measurement of SF and CC data as compared to radiation values. That is to say, the total daily SF for majority of sites was regressed against hourly values of radiation and the incorporation of CC, measured at three to six hourly intervals, did not always coincide with the instance when radiation data was recorded. The results would have been much more improved if SF and CC were recorded concurrently with global and diffuse radiation.

The regression coefficients of optimum models for each site are presented in Table 5.6. Note that some models involved only a linear function for some of the given independent parameters and hence the respective second order coefficients were left blank. Equations (5.1-5.4) can be referred in this respect. An overall model was indicated for the country in question within the table.

#### 5.3.1 Modelled versus measured

Diffuse ratio was calculated and plotted against the actual k-kt envelope for all the 9 sites. Figure 5.7 represents one such plot for Bracknell. In the figure, the lightcoloured scatter points form the 'real envelope' which is the actual data points, the dark-coloured envelope is the 'computed envelope' which represents the estimated values using the optimum model and the black curve is the locus of quadratic k-kt regression. It is evident from the figure that the proposed model worked adequately for the entire k-k<sub>t</sub> range with the computed envelope overlapping the real envelope. Plots of other sites also revealed similar overlapping trends, which is a strong indication of the accuracy of the models. Moreover, over/under estimation of diffuse ratio (k) is considerably reduced, because k- estimates from the proposed model amply cover the broad scatter owing to the actual data points. This implies that k can be calculated with reasonable accuracy for different skyconditions within the same kt range, unlike the single return-value k-kt relationship. It can be attributed to the fact that improved models include other parameters as well (apart from k<sub>t</sub>) which play a critical role in the estimation of diffuse ratio. However, the model poses limitations in the high  $k_t$ -low k range. For instance, if the same model is employed in that range, k can attain a zero value at a kt of 0.9 (Fig .5.7). Practically speaking, such clear-sky conditions are very rare. This is also supported by the fact that none of the data points from the 9 databases under study fell in that range i.e. k=0 for  $k_t \ge 0.9$ . Nonetheless, there has to be a more physically based modelling condition that does not give negative k values when k<sub>t</sub> exceeds a certain limit. The method adopted to modify this limitation is the use of a constant value of k, for a k<sub>t</sub> exceeding the maximum limit. By observation, two points from the actual k-k<sub>t</sub> envelope at the bottom right end that contain the minimum k and maximum kt were selected. Interpolation of the corresponding k values of the two points determined the average k value. For those rare cases of points that may exceed k<sub>t</sub>,max, the latter, constant value of k was prescribed. Thus, the kt constraint was identified and a constant k value was calculated for 4 selected sites, as shown in Table 5.7, representing optimum regression models for the respective regions/countries.

Calculated diffuse horizontal radiation against its observed value was also plotted for each site; Fig. 5.8-5.11. The improvement from the conventional k-kt model is evident

with the mere addition of SF. However, the improvement from the intermediate to the optimum model is not that prominent for those sites which only include one more additional parameter. Nevertheless, there is a significant reduction in scatter i.e. more accurate estimation from the intermediate bivariate to the multivariate models that include all the four parameters.

It is important to note that the above described procedure for comparative analysis of developed models and proposal for optimum models henceforth, is only based on the available data. The models can be modified and adjusted according to the site-available data. The major assumptions in the above described approach were: (1) Unlike the radiation data, the quality of other intrinsic parameters (SF and CC) measurements was not queried. (2) Approximation of daily SF and sub-daily CC data to fit the frame of present regression analysis for hourly radiation. (3) Assumption in the accuracy score system, used for the evaluation of best models, that all of the statistics contribute equally towards the model accuracy.

#### 5.4 Summary

In order to effect the estimation of radiation on tilted surfaces, knowledge of both diffuse and direct components of global radiation falling on a horizontal surface is required. However, quite often, projects involving utilization of solar energy are not supported by the required solar data at the place of interest, mainly due to the capital and maintenance costs that measuring instruments incur. Consequently, they need to be estimated from alternative information available at the site or a near by location.

This chapter focussed on improving the accuracy of the conventional k-k<sub>t</sub> models for predicting *hourly* horizontal diffuse irradiation using the solar radiation database from 9 sites across the globe. This was achieved by incorporating synoptic elements such as sunshine fraction and cloud cover, and air mass in addition to the k<sub>t</sub> variable leading to the development of a series of models for each site. Performance of the models was assessed by the means of statistical indicators like, R<sup>2</sup>, MBD, RMSD, skewness and kurtosis. A new comparative index called 'accuracy score' was devised to evaluate the model performance. Accuracy score was used along with 'sum deviation'; which is the sum of MBD and RMSD, and the standard index like t-statistic to assess the effect on accuracy with subsequent addition of each parameter and increase in

complexity of equation. Estimated values of hourly diffuse radiation were compared with measured values by plotting error histograms and scatter plots of the data.

Generally, models, which included all the parameters, gave highest accuracy scores. However, for some sites an optimum level solution was to propose one of the bivariate model forms that yielded reasonable accuracy, entailing minimal intricacy at the same time. On a quantitative scale, it was found that the proposed models improved the accuracy of diffuse radiation estimation by more than 50% (based on the Accuracy score system) in most cases with the exception of Sapporo (where the improvement is of slightly lower order) over the k-k<sub>t</sub> counterparts. These models were found to be site-dependent; however, the model types were fairly consistent for neighbouring stations or locations with similar climates. An overall optimum model was also recommended for each of the given countries.

It was noted that incorporation of SF to the k- $k_t$  relationship among all three parameters had the most significant effect on the model's performance for all sites. This was also evident from the fact, that all the proposed individual site models essentially have SF as one of the additional parameters.

The work demonstrated in this chapter shows that the three parameters, namely, SF, CC and m have a significant bearing on the model accuracy and can be effectively used along with hourly global radiation to improve the hourly diffuse radiation modelling.



\* Represents the five statistical indicators (R<sup>2</sup>, MBD, RMSD, Skewness, Kurtosis); *ae* stands for algebraic equivalents as mentioned in Section 5.2.2.

Fig.5.1 Schematic flow chart describing the calculation procedure for Accuracy Score for any given site



Fig. 5.2 (a) Error histograms of calculated diffuse radiation of selectively chosen models: Chennai



Fig. 5.2(b) Error histograms of calculated diffuse radiation of selectively chosen models: Mumbai

780

`7<sub>60</sub>

70

Model 16 (Kt, lin SF, quad CC, lin m)

ଡ

700

60

70 ୶

`~<sub>60</sub>

`°С

Model 14 (Kt. quad CC, lin m)

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Fig. 5.2(c) Error histograms of calculated diffuse radiation of selectively chosen models: New Delhi





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Fig. 5.3(a) Error histograms of calculated diffuse radiation of selectively chosen models: Fukuoka



Fig. 5.3(b) Error histograms of calculated diffuse radiation of selectively chosen models: Sapporo





Fig. 5.4(a) Error histograms of calculated diffuse radiation of selectively chosen models: Gerona







Fig. 5.5 Error histograms of calculated diffuse radiation of selectively chosen models: Bracknell



Fig. 5.6 Evaluation of given models by means of presently developed accuracy scoring system (a) India, (b) Japan, (c) Spain and (d) UK



Fig.5.7 Calculated versus measured k-k<sub>t</sub> plot for Bracknell (Light- and dark-coloured data points represent actual and calculated values, respectively. Solid black curve is the locus of quadratic k-k<sub>t</sub> regression.)

(a)



Fig.5.8 Diffuse calculated versus diffuse measured radiation from the basic  $k-k_t$  model through an intermediate ( $k-k_t$ , SF) to the eventual models selected as optimum for Indian sites (a) Chennai, (b) Mumbai

(c)



Fig.5.8 Diffuse calculated versus diffuse measured radiation from the basic k-k<sub>t</sub> model through an intermediate (k-k<sub>t</sub>, SF) to the eventual models selected as optimum for Indian sites (c) New Delhi, (d) Pune

.

(a)



Fig.5.9 Diffuse calculated versus diffuse measured radiation from the basic  $k-k_t$  model through an intermediate ( $k-k_t$ , SF) to the eventual models selected as optimum for Japanese sites (a) Fukuoka, (b) Sapporo

(a)



Fig.5.10 Diffuse calculated versus diffuse measured radiation from the basic k- $k_t$  model through an intermediate (k- $k_t$ , SF) to the eventual models selected as optimum for Spanish sites (a) Gerona, (b) Madrid


Fig.5.11 Diffuse calculated versus diffuse measured radiation from the basic k-k<sub>t</sub> model through an intermediate (k-k<sub>t</sub>, SF) to the eventual models selected as optimum for Bracknell, UK

Country	Location	Time s	tamp of the measured c	lata	data points	
		Irradiance, G and D	Sunshine Duration	Cloud Cover	After quality control**	For regression analysis***
INDIA	Chennai	Hourly	Daily	intermittent four- hourly format	13047	4297
	Mumbai	Hourly	Daily	intermittent four- hourly format	12569	4037
	New Delhi	Hourly	Daily	NA	24671	24671
	Pune	Hourly	Daily	intermittent four- hourly format	11716	4008
JAPAN	Fukuoka	10-minutely	10-minutely	NA	19650	19560
	Sapporo	10-minutely	10-minutely	NA	13563	13563
SPAIN	Gerona	5-minutely integrated to hourly	Daily	WMO std. three- hourly format	27328	4863
	Madrid	Hourly	Daily	WMO std. three- hourly format	11162	4041
_UK	Bracknell	Hourly	Hourly	Hourly	22111	22111

## Table 5.1 Data base information of the meteorological sites under study

\*\*This number excludes the data points for which sun shine duration was missing. With the exception of Fukuoka, Sapporo and Bracknell, for all other sites daily sunshine fraction rather than hourly was taken for each hour of that day.

\*\*\* This number represents those data points for which cloud cover information was available. Although radiation data was hourly, cloud cover was recorded only at certain hours of the day, so only those hours of consistent data were retained.

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Table 5.2 Statistical indicators, comparative indices and accuracy scores for India (a) Chennai,

(b) Mumbai, (c) New Delhi and (d) Pune

(a)

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Model				<b>DIIOD</b>					t-
		R2	MBD	RIVISD	Skew	Kurtosis	AS	SD	statistic
1	k=f(q kt)	0.42	-2.81	98.84	0.19	0.30	2.0	1.3	1.9
2	k=f(q kt, lin SF)	0.67	-8.58	77.87	-0.31	1.24	2.2	1.8	7.3
3	k=f(q kt, qSF)	0.67	-8.41	77.69	-0.38	1.27	2.1	1.8	7.1
4	k=f(q kt, lin CC)	0.43	-2.82	98.44	0.20	0.29	2.0	1.3	1.9
5	k=f(q kt, q CC)	0.67	-3.22	76.32	-0.32	1.14	2.8	1.1	2.8
6	k=f(q kt, lin m)	0.45	-0.52	95.62	0.31	0.38	2.2	1.0	0.4
7	k=f(q kt, q m)	0.52	-1.04	90.12	0.34	0.60	2.3	1.0	0.8
8	k=f(q k <sub>t</sub> , lin SF, lin CC)	0.66	-3.48	76.58	-0.28	1.42	3.0	1.2	3.0
9	k=f(q kt, lin SF, q CC)	0.72	-3.42	69.92	-0.45	1.64	2.9	1.1	3.2
10	k=f(q k <sub>t</sub> , q SF, q CC)	0.72	-3.50	69.95	-0.50	1.70	2.8	1.1	3.3
11	k=f(q kt, lin SF, lin m)	0.68	-0.90	73.63	-0.15	1.37	3.5	0.9	0.8
12	k≕f(q kt, lin SF,q m)	0.70	-0.59	69.13	-0.05	1.56	4.0	0.8	0.6
13	k=f(q kt, q SF,q m)	0.71	-0.55	68.65	-0.12	1.53	3.8	0.8	0.5
14	k=f(q kt, q CC, lin m)	0.69	-0.89	73.89	-0.17	1.04	3.3	0.9	0.8
15	k=f(q kt, q CC, q m)	0.71	-0.58	70.86	-0.07	0.98	3.6	0.8	0.5
16	k=f(q kt, lin SF, q CC, lin m)	0.74	-0.97	67.17	-0.31	1.54	3.5	0.8	0.9
17	k=f(q kt, lin SF, q CC, q m)	0.75	-0.48	63.54	-0.21	1.55	3.8	0.7	0.5
18	k=f( q kt, q SF, q CC, q m)	0.76	-0.45	63.31	-0.26	1.58	3.7	0.7	0.5

(b)

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Model No	Model Type	R <sup>2</sup>	MBD	RMSD	Skew	Kurtosis	AS	SD	t- statistic
						· · · · · · · · · · · · · · · · · · ·			
1	k=f(q kt)	0.82	1.45	58.18	0.91	2.22	2.0	1.6	1.6
2	k=f(q kt, lin SF)	0.87	-1.67	49.41	0.92	3.47	2.4	1.5	2.2
3	k=f(q kt, qSF)	0.87	-1.92	48.80	1.04	3.83	2.3	1.6	2.5
4	k=f(q kt, lin CC)	0.82	1.10	56.77	0.91	2.22	2.2	1.4	1.2
5	k=f(q kt, q CC)	0.88	-1.94	47.54	1.01	4.18	2.4	1.6	2.6
6	k=f(q kt, lin m)	0.82	1.37	58.15	0.95	2.49	2.1	1.5	1.5
7	k=f(q kt, q m)	0.83	0.37	57.35	0.88	2.53	2.6	1.1	0.4
8	k=f(q k <sub>t</sub> , lin SF, lin CC)	0.87	-1.76	48.59	0.95	3.55	2.3	1.5	2.3
9	k=f(q kt, lin SF, q CC)	0.88	-2.48	45.71	1.04	4.65	2.2	1.8	3.5
10	k=f(q k <sub>t</sub> , q SF, q CC)	0.89	-2.55	45.65	1.09	4.85	2.2	1.8	3.6
11	k=f(q kt, lin SF, lin m)	0.88	0.26	48.70	1.10	4.08	2.9	0.9	0.3
12	k=f(q kt, lin SF,q m)	0.88	0.12	48.60	1.09	4.06	3.0	0.9	0.2
13	k=f(q kt, q SF,q m)	0.88	0.11	47.79	1.25	4.62	3.0	0.9	0.1
14	k=f(q kt, q CC, lin m)	0.88	0.38	46.88	1.19	4.66	2.9	1.0	0.5
15	k=f(q kt, q CC, q m)	0.88	0.16	46.72	1.18	4.67	3.0	0.9	0.2
16	k=f(q kt, lin SF, q CC, lin m)	0.89	0.06	44.73	1.28	5.54	3.2	0.8	0.1
17	k=f(q kt, lin SF, q CC, q m)	0.89	0.10	44.64	1.28	5.56	3.2	0.8	0.1
18	k=f( q kt, q SF, q CC, q m)	0.89	0.10	44.44	1.35	5.94	3.2	0.8	0.1

Nodel No	Model Type	R <sup>2</sup>	MBD	RMSD	Skew	Kurtosis	AS	SD	t- statistic
1	k=f(q kt)	0.81	1.75	47.69	0.52	0.75	1.4	2.0	5.8
2	k=f(q kt, lin SF)	0.87	-1.12	38.86	0.29	1.27	2.7	1.5	4.5
3	k=f(q kt, qSF)	0.87	-1.33	38.41	0.22	1.28	2.8	1.6	5.4
6	k=f(q kt, lin m)	0.82	1.26	47.61	0.50	0.83	1.8	1.7	4.1
7	k=f(q kt, q m)	0.82	0.27	47.09	0.34	0.72	2.6	1.1	0.9
11	k=f(q kt, lin SF, lin m)	0.87	0.50	38.74	0.50	1.65	2.9	1.1	2.0
12	k=f(q kt, lin SF,q m)	0.87	0.12	38.56	0.42	1.55	3.2	0.9	0.5

(d)

Model No	Model Type	R2	MBD	RMSD	Skew	Kurtosis	AS	SD	t- statistic
1	k=f(q kt)	0.49	0.86	90.83	0.67	0.35	1.0	1.7	0.6
2	k=f(q kt, lin SF)	0.77	-0.98	60.92	0.24	3.24	2.5	1.5	1.0
3	k=f(q kt, qSF)	0.80	-1.19	58.45	0.11	2.62	2.5	1.6	1.3
4	k=f(q kt, lin CC)	0.75	-0.26	64.76	0.61	8.12	3.1	0.9	0.3
5	k=f(q kt, q CC)	0.79	-0.26	58.35	-0.15	1.84	3.1	0.9	0.3
6	k=f(q kt, lin m)	0.53	0.65	87.65	0.72	0.47	1.2	1.5	0.5
7	k=f(q kt, q m)	0.60	-0.66	85.06	0.68	0.68	1.4	1.5	0.5
8	k=f(q k <sub>t</sub> , lin SF, lin CC)	0.82	-0.95	54.77	0.06	4.59	3.1	1.4	1.1
9	k=f(q kt, lin SF, q CC)	0.83	-0.78	52.04	-0.20	2.72	2.8	1.2	0.9
10	k=f(q k <sub>t</sub> , q SF, q CC)	0.84	-0.92	51.13	-0.19	2.35	2.7	1.3	1.1
11	k=f(q kt, lin SF, lin m)	0.78	-0.29	60.27	0.30	3.41	3.0	0.9	0.3
12	k=f(q kt, lin SF,q m)	0.78	-0.44	60.17	0.29	3.34	2.9	1.0	0.5
13	k=f(q kt, q SF,q m)	0.80	-0.35	57.68	0.22	2.64	3.0	0.9	0.4
14	k=f(q kt, q CC, lin m)	0.79	0.06	57.28	-0.13	2.15	3.4	0.7	0.1
15	k=f(q kt, q CC, q m)	0.80	-0.29	56.94	-0.12	2.11	3.2	0.9	0.3
16	k=f(q kt, lin SF, q CC, lin m)	0.83	-0.20	51.34	-0.13	2.82	3.4	0.7	0.2
17	k=f(q kt, lin SF, q CC, q m)	0.83	-0.29	51.31	-0.13	2.78	3.3	0.8	0.4
18	k=f( q kt, q SF, q CC, q m)	0.84	-0.25	50.36	-0.09	2.40	3.4	0.8	0.3

Table 5.3 Statistical indicator	s, comparative indices	and accuracy scores	s for Japan (a)	) Fukuoka, (b	) Sapporo
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(a)

Model									t-
No	Model Type	R*	MBD	RMSD	Skew	Kurtosis	AS	SD	statistic
1	k=f(a kt)	0.88	2 84	53 11	1.55	8.32	20	20	75
2	k=f(q kt, lin SF)	0.92	1.06	44.64	0.83	4.64	2.8	1.2	3.3
3	k=f(q kt, q SF)	0.92	0.97	44.14	0.78	4.71	2.9	1.2	3.1
4	k=f(q kt, lin m)	0.89	0.45	52.20	1.25	8.00	3.0	1.1	1.2
5	k=f(q kt, q m)	0.89	0.02	52.28	1.18	8.21	3.2	1.0	0.1
6	k=f(q kt, lin SF, lin m)	0.92	0.21	44.53	0.71	4.72	3.2	0.9	0.6
7	k=f(q kt, lin SF,q m)	0.92	0.03	44.51	0.66	4.73	3.3	0.8	0.1
8	k=f(q kt, q SF, lin m)	0.92	0.23	44.01	0.68	4.77	3.2	.0.9	0.7
9	k=f(q kt, q SF, q m)	0.92	0.03	43.97	0.61	4.80	3.3	0.8	0.1

(b)

Model No	Model Type	R <sup>2</sup>	MBD	RMSD	Skew	Kurtosis	AS	SD	t- statistic
		_							
1	k=f(q kt)	0.85	-0.07	55.61	1.18	6.30	2.9	1.0	0.1
2	k=f(q kt, lin SF)	0.91	-2.59	44.42	0.42	4.45	2.4	1.8	6.8
3	k=f(q kt, q SF)	0.92	-2.51	43.27	0.36	4.99	· 2.6	1.7	6.8
4	k=f(q kt, lin m)	0.85	0.02	55.54	1.40	7.56	2.9	1.0	0.0
5	k=f(q kt, q m)	0.85	0.07	55.47	1.48	8.20	2.9	1.0	0.1
6	k=f(q kt, lin SF, lin m)	0.92	-0.06	42.34	1.30	6.77	3.2	0.8	0.2
7	k=f(q kt, lin SF,q m)	0.92	0.05	42.29	1.37	7.05	3.2	0.8	0.1
8	k=f(q kt, q SF, lin m)	0.92	-0.07	41.15	1.24	7.43	3.3	0.8	0.2
9	k≕f(q kt, q SF, q m)	0.92	0.04	41.12	1.29	7.64	3.3	0.8	0.1

Table 5.4 Statistical indicators, comparative indices and accuracy scores for Spain (a) Gerona, (b) Madrid

(a)

Model									t-
No	Model Type	R <sup>2</sup>	MBD	RMSD	Skew	Kurtosis	AS	SD	statistic
1	k=f(q kt)	0.88	5.50	36.41	1.37	3.28	1.6	2.0	10.7
2	k=f(q kt, lin SF)	0.91	3.45	31.54	1.32	4.09	2.4	1.5	7.7
3	k=f(q kt, qSF)	0.91	3.26	31.27	1.32	4.15	2.4	1.5	7.3
4	k=f(q kt, lin CC)	0.92	2.04	28.55	1.15	4.66	3.0	1.2	5.0
5	k=f(q kt, q CC)	0.93	1.99	28.51	1.15	4.77	3.0	1.1	4.9
6	k=f(q kt, lin m)	0.90	0.80	31.00	0.95	2.81	2.9	1.0	1.8
7	k=f(q kt, q m)	0.90	0.17	30.58	0.76	· 2.65	3.1	0.9	0.4
8	k=f(q k <sub>t</sub> , lin SF, lin CC)	0.93	1.89	27.74	1.08	4.74	3.1	1.1	4.8
9	k=f(q kt, q SF, q CC)	0.93	1.83	27.57	1.05	4.70	3.1	1.1	4.6
10	K=f(qKt,linSF,lin m)	0.92	0.75	27.61	0.87	3.66	3.2	0.9	1.9
11	k=f(q kt, lin SF,q m)	0.92	0.12	26.98	0.62	3.56	3.5	0.8	0.3
12	k=f(q kt, q SF,q m)	0.92	0.12	26.78	0.63	3.33	3.5	0.8	0.3
13	k=f(q kt, lin CC, lin m)	0.93	0.45	26.49	0.79	4.11	3.5	0.8	1.2
14	k=f(q kt, lin CC, q m)	0.93	0.05	26.15	0.59	3.91	3.7	0.7	0.1
15	k=f(q kt, q CC, q m)	0.93	0.04	26.18	0.59	4.08	3.7	0.7	0.1
16	k=f(q kt, lin SF, lin CC, lin m)	0.93	0.50	25.59	0.70	4.33	3.6	0.8	1.4
17	k=f(q kt, lin SF, lin CC, q m)	0.93	0.05	25.17	0.47	4.25	3.8	0.7	0.1
18	<u>k=f( q kt, q SF, q CC, q m)</u>	0.94	0.04	25.06	0.45	4.16	3.8	0.7	0.1

# (b)

Model	Model Type	R <sup>2</sup>	MBD	RMSD	Skow	Kurtosis	45	sn	t- statistic
	Model Type			TANGO	<u>OKew</u>	Ruitosis			Statistic
1	k=f(q kt)	0.87	6.76	40.20	1.26	2.30	1.4	10.8	2.0
2	k=f(q kt, lin SF)	0.92	2.10	32.42	1.23	4.80	2.9	4.1	1.1
3	k=f(q kt, qSF)	0.92	92 1.69 31.60		1.06	4.51	3.0	3.4	1.0,
4	k=f(q kt, lin CC)	0.94	0.47	28.34	0.36	4.06	3.8	1.0	0.8
5	k=f(q kt, q CC)	0.94	0.48	28.19	0.40	4.37	3.8	1.1	0.8
6	k=f(q kt, lin m)	0.89	1.99	36.47	0.67	1.87	2.6	3.5	1.2
7	k=f(q kt, q m)	0.89	0.09	35.36	0.23	2.01	3.3	0.2	0.9
8	k=f(q k <sub>t</sub> , lin SF, lin CC)	0.94	0.24	27.53	0.38	4.22	3.9	0.6	0.7
9	k=f(q kt, q SF, q CC)	0.94	0.17	27.20	0.35	4.51	4.0	0.4	0.7
10	K=f(qKt,linSF,lin m)	0.92	1.13	31.69	1.00	4.47	3.2	2.3	1.0
11	k=f(q kt, lin SF,q m)	0.92	0.12	30.67	0.61	3.91	3.5	0.2	0.8
12	k=f(q kt, q SF,q m)	0.93	0.13	30.28	0.54	3.90	3.6	0.3	0.8
13	k=f(q kt, lin CC, lin m)	0.94	0.64	28.54	0.39	4.15	3.7	1.4	0.8
14	k=f(q kt, lin CC, q m)	0.94	0.08	28.05	0.17	4.15	4.0	0.2	0.7
15	k=f(q kt, q CC, q m)	0.94	0.08	27.83	0.20	4.46	4.1	0.2	0.7
16	k=f(q kt, lin SF, lin CC, lin m)	0.94	0.60	27.77	0.48	4.30	3.7	1.4	0.8
17	k=f(q kt, lin SF, lin CC, q m)	0.94	0.09	27.27	0.26	4.24	4.0	0.2	0.7
18	k=f( q kt, q SF, q CC, q m)	0.94	0.09	26.95	0.27	4.58	4.1	0.2	0.7

Model No	Model Type	R2	MBD	RMSD	Skew	Kurtosis	AS	SD	t- statistic
				·····					
1	k=f(q kt)	0.89	2.86	33.85	1.06	5.43	1.8	2.0	12.6
2	k=f(q kt, lin SF)	0.94	2.15	28.61	1.06	6.13	2.4	1.6	11.2
3	k=f(q kt, qSF)	0.94	2.03	28.40	0.96	6.15	2.5	1.6	10.7
4	k=f(q kt, lin CC)	0.92	0.86	29.49	0.70	5.26	3.0	1.2	4.4
5	k=f(q kt, q CC)	0.92	0.95	29.02	0.74	5.28	2.9	1.2	4.9
6	k=f(q kt, lin m)	0.90	0.55	32.25	0.51	4.80	3.1	1.1	2.5
7	k=f(q kt, q m)	0.90	-0.02	31.93	0.23	4.54	3.5	1.0	0.1
8	k=f(q kt, lin SF, lin CC)	0.95	1.24	26.25	0.77	5.91	3.0	1.2	7.0
9	k=f(q kt, q SF, q CC)	0.95	1.25	26.13	0.74	6.07	3.0	1.2	7.1
10	k=f(q kt, lin SF, lin m)	0.94	0.28	27.71	0.62	6.37	3.5	0.9	1.5
11	k=f(q kt, lin SF,q m)	0.94	0.02	27.55	0.42	6.23	3.8	0.8	0.1
12	k=f(q kt, q SF,q m)	0.94	0.01	27.40	0.37	6.25	3.8	0.8	0.0
13	k=f(q kt, lin CC, q m)	0.92	-0.01	29.02	0.27	4.74	3.6	0.9	0.1
14	k=f(q kt, q CC, lin m)	0.92	0.37	29.21	0.52	4.97	3.3	1.0	1.9
15	k=f(q kt, q CC, q m)	0.93	-0.02	28.44	0.28	4.79	3.6	0.8	0.1
16	k=f(q kt, lin SF, q CC, lin m)	0.95	0.25	25.88	0.49	5.90	3.6	0.9	1.4
17	k=f(q kt, lin SF, q CC, q m)	0.95	0.01	25.73	0.29	5.76	3.9	0.8	0.1
18	k=f(akt.aSF.aCC.am)	0.95	0.00	25.56	0.28	5.95	3.9	0.8	· 0.0

Table 5.5 Statistical indicators, comparative indices and accuracy scores for Bracknell (UK)

	INDIA						JAP	AN			SPAIN				UK		
Ch	ennai*	M	umbai		Pune	Nev	v Delhi	Fı	ukuoka	Sa	pporo*	G	erona*	Ν	1adrid	Bra	acknell
a <sub>60</sub>	0.9508	A <sub>80</sub>	0.9665	a <sub>80</sub>	0.8747	a <sub>60</sub>	0.845	$a_{60}$	0.9701	a <sub>60</sub>	0.9311	a <sub>80</sub>	1.0585	a <sub>50</sub>	0.9956	a <sub>60</sub>	0.8991
a <sub>61</sub>	0.1172	A <sub>81</sub>	0.2862	$a_{81}$	0.0040	$a_{61}$	0.357	a <sub>61</sub>	0.3739	$a_{61}$	-0.3966	a <sub>81</sub>	0.0079	a <sub>51</sub>	0.0922	a <sub>61</sub>	-0.6826
a <sub>62</sub>	-	a <sub>82</sub>	-	a <sub>82</sub>	-	a <sub>62</sub>	-	a <sub>62</sub>	-	a <sub>62</sub>	0.7583	a <sub>82</sub>	-	a <sub>52</sub>	-0.0096	a <sub>62</sub>	0.6482
a <sub>63</sub>	-0.0609	a <sub>83</sub>	-0.0118	a <sub>83</sub>	0.0426	a <sub>63</sub>	-0.010	a <sub>63</sub>	0.0088	a <sub>63</sub>	0.0091	a <sub>83</sub>	-0.0329	a <sub>53</sub>	0.0157	a <sub>63</sub>	0.0277
a <sub>64</sub>	0.0087	a <sub>84</sub>	-0.0001	a <sub>84</sub>	-0.0047	a <sub>64</sub>	-0.002	a <sub>64</sub>	-0.0010	a <sub>64</sub>	-	a <sub>84</sub>	-	a <sub>54</sub>	-0.0031	a <sub>64</sub>	-0.0017
b <sub>60</sub>	2.2681	a <sub>85</sub>	0.0016	a <sub>85</sub>	-0.0256	b <sub>60</sub>	1.025	b <sub>60</sub>	0.4060	b <sub>60</sub>	0.7206	a <sub>85</sub>	0.0517	b <sub>50</sub>	-0.8392	b <sub>60</sub>	0.8799
b <sub>61</sub>	-2.2769	a <sub>86</sub>	-	a <sub>86</sub>	-	b <sub>61</sub>	-2.736	b <sub>61</sub>	-2.0874	b <sub>61</sub>	-2.2515	a <sub>86</sub>	-0.0084	$b_{51}$	-0.9612	b <sub>61</sub>	-0.6656
b <sub>62</sub>	-	b <sub>80</sub>	-0.0856	b <sub>80</sub>	-0.1501	b <sub>62</sub>	-	b <sub>62</sub>	-	b <sub>62</sub>	-0.3544	b <sub>80</sub>	-1.2333	b <sub>52</sub>	-0.1230	b <sub>62</sub>	-0.3144
b <sub>63</sub>	-1.3345	b <sub>81</sub>	-1.8640	$b_{81}$	-1.4875	b <sub>63</sub>	-0.033	b <sub>63</sub>	-0.0277	b <sub>63</sub>	-0.1259	b <sub>81</sub>	-0.4660	b <sub>53</sub>	0.0260	b <sub>63</sub>	-0.1580
b <sub>64</sub>	0.2065	b <sub>82</sub>	-	b <sub>82</sub>	-	b <sub>64</sub>	0.013	b <sub>64</sub>	-0.0007	b <sub>64</sub>	-	b <sub>82</sub>	-	b <sub>54</sub>	0.0210	b <sub>64</sub>	0.0031
c <sub>60</sub>	-4.0137	b <sub>83</sub>	0.1277	b <sub>83</sub>	-0.1360	c <sub>60</sub>	-2.121	c <sub>60</sub>	-1.3740	c <sub>60</sub>	-1.8335	b <sub>83</sub>	0.2375	c <sub>50</sub>	-0.5441	c <sub>60</sub>	-1.7511
C <sub>61</sub>	1.8349	b <sub>84</sub>	0.0013	b <sub>84</sub>	0.0346	c <sub>61</sub>	2.560	c <sub>61</sub>	1.7343	c <sub>61</sub>	5.1822	b <sub>84</sub>	-	c <sub>51</sub>	1.6523	c <sub>61</sub>	2.7865
c <sub>62</sub>	-	b <sub>85</sub>	-0.0831	b <sub>85</sub>	-0.0261	c <sub>62</sub>	-	c <sub>62</sub>	-	c <sub>62</sub>	-2.8571	b <sub>85</sub>	-0.1092	c <sub>52</sub>	-0.3052	c <sub>62</sub>	-1.9243
c <sub>63</sub>	2.5424	b <sub>86</sub>	-	b <sub>86</sub>	-	c <sub>63</sub>	0.069	c <sub>63</sub>	-0.0879	c <sub>63</sub>	0.2712	b <sub>86</sub>	0.0278	c <sub>53</sub>	-0.0452	c <sub>63</sub>	0.0438
C <sub>64</sub>	-0.3669	c <sub>80</sub>	-1.3538	c <sub>80</sub>	-0.5558	c <sub>64</sub>	-0.006	c <sub>64</sub>	0.0168	c <sub>64</sub>	-	C <sub>80</sub>	0.3954	C <sub>54</sub>	-0.0213	c <sub>64</sub>	0.0124
		c <sub>81</sub>	1.8634	c <sub>81</sub>	1.3729							c <sub>81</sub>	0.4238				
		c <sub>82</sub>	-	c <sub>82</sub>	-							c <sub>82</sub>	-				
		c <sub>83</sub>	-0.1266	c <sub>83</sub>	0.1020							c <sub>83</sub>	-0.2421	·			
		c <sub>84</sub>	-0.0014	c <sub>84</sub>	-0.0309							C <sub>84</sub>	-				
		c <sub>85</sub>	0.2164	C <sub>85</sub>	0.1566							c <sub>85</sub>	-0.1544				
		C <sub>86</sub>	-	C86	-		_					C <sub>86</sub>	-0.0026				

Table 5.6 The regression coefficients for the recommended models in reference to Eq.s (5.1-5.4)

\* Optimum regression model for diffuse radiation for the given country.

Region	k <sub>t</sub> ,max	k*	k,min	k,constant
Chennai, India	0.99	0.38	0.09	0.24
Sapporo, Japan	0.93	0.33	0.11	0.22
Gerona, Spain	0.82	0.08	0.06	0.07
Bracknell, UK	0.83	0.28	0.09	0.19.

Table 5.7 Recommended constant k-values for  $k_t$  exceeding  $k_t,\!max$ 

 $k^{\ast}$  is the corresponding k-value for  $k_{t},max$  k,constant is the average of  $k^{\ast}$  and k,min

# CHAPTER 6

# DAILY DIFFUSE IRRADIANCE MODELLING

The frequency at which solar radiation data is required depends on the type of application. While monthly-averaged or even annual-energy budget would suffice in agricultural meteorology; detailed simulation studies require computation of inclined surface irradiation at hourly or sub-hourly level. On the other hand, daily data is required for day to day performance monitoring in applications such as solar gains from vertical glazing, daylighting, and agricultural processes. Apart from radiation values being measured on a daily basis, hourly or sub-hourly radiation data is often condensed into simpler daily forms for use in various abbreviated solar energy applications.

In Chapter 5, models for hourly diffuse irradiation were developed. However, the same models cannot be used to estimate the daily radiation values, as the models obtained from data recorded on an hourly basis differ from those obtained from hourly-based data. In other words, regression models are strictly temporal and cannot be interchanged. Since radiation measurements are an expensive affair, there is an obvious need not only to develop solar radiation models for use in different time stamps, but also to make continual efforts towards achieving the accuracy in prediction. Therefore, in this chapter models to estimate daily diffuse irradiation are proposed and tested, using 8 sites' daily data, all of which were used for hourly analysis.

As described in Chapter 2 of Review of the Relevant Literature, clearness index diffuse ratio relationships have been used as the foundation of diffuse radiation models both on hourly and daily levels by researchers in the past. This chapter follows the theme of preceding chapter by using the already established significant parameters like sunshine fraction and cloud cover to estimate diffuse radiation on a daily basis. In other words, daily sunshine fraction (SF) and averaged-daily cloud cover or

cloudiness factor (CF) are used along with daily clearness index ( $K_t$ ) as model inputs for daily diffuse ratio (K). Air mass could not be used for daily diffuse irradiance modelling owing to the fact that by definition it changes with change in solar elevation, i.e. its value varies with time throughout the solar day. Generalising this geometric parameter over a day to use it as one of the tools for the present modelling would be a considerable and unjust approximation.

The work demonstrated here is a step forward, as it not only proposes multivariate daily models involving sunshine duration, cloud cover and global radiation, but also highlights the challenges involved in the validation of such models. It was noted that there is a significant improvement with the addition of parameters like SF and/or CF within the dataset. However, it is a challenging task to generalize the model as involvement of more measured parameters means greater measurement inaccuracies which in turn increases the performance uncertainty, particularly when applied to an independent dataset.

Data sets of 8 locations from Asia and Europe were used for the present analysis, as described in Section 3.3 of Chapter 3. With the exception of Chennai, all of the sites used here are same as that for hourly diffuse irradiance modelling. Chennai's daily data showed anomalous results in models' performance in contrast to its hourly models. Definite causes could not be identified, although one possible reason could be mal-reporting of daily data. As a result, it was dropped altogether from the set of 9 data sets originally taken for diffuse irradiation modelling.

A brief review of the daily data sets assimilation would be helpful here. Daily radiation values were obtained by summing up the hourly radiation (10minutely in case of Fukuoka and Gerona) provided by all sites, except for the Indian locations where they were provided by the Met Office. Daily sunshine duration was provided for Indian sites, whilst 10-minutely and hourly values were summed up for Japanese and UK sites, respectively. Daily sunshine fraction was (SF) then calculated by evaluating the total sunshine hours as a percent of day length for all but Spanish sites, where it was provided by the local meteorological office. Cloud cover (CC) was recorded on a four-hourly basis for Indian, three-hourly for Spanish sites and on an hourly basis for Bracknell (UK). This information was utilized on a daily level by

averaging the CC (provided by the meteorological offices in units of octas) over a day against the corresponding daily radiation data to provide an approximate diagnostic tool, referred henceforth as *Cloudiness factor* (CF). It is worthwhile to note here, that since radiation, sunshine duration and cloud cover values were summed up (and averaged in the last case) for a day, any day which had even one single missing value of either of the parameters was omitted from the daily data series to avoid incompleteness.

The present approach involves the characterisation of daily diffuse radiation using  $K_t$ , SF and CF, derived originally from global radiation, sunshine duration and cloud cover, respectively. The improvement from the single  $K_t$  dependent diffuse radiation model to the proposed structure of models was then investigated through an extensive statistical evaluation procedure backed up by subsequent validation analysis.

# 6.1 Measured Parameters' Trends based on their Monthly-Averaged Daily Values

Under this sub-section annual pattern of irradiance, sunshine and cloud cover variability was studied. For this purpose, daily monthly-averages of each parameter were obtained and then further averaged over the given number of years to plot an annual pattern of the four parameters i.e.  $K_t$ , K, SF and CF. Unlike other parameters; CF was not in dimensionless ratio form. Therefore, each monthly-averaged value of CF was fractionalized by dividing by the maximum CF value in the respective year to yield a value which could be used on a common scale with all other parameters. The monthly patterns were plotted to reflect the correlation of K with other parameters. Mumbai, Sapporo, Gerona and Bracknell plots, one from each region, are presented here in Fig. 6.1. From careful observation, it was found that the monthly-averaged values of K were closely correlated with K<sub>t</sub> for all sites. It was also seen that K correlates well with monthly-averaged daily SF and CF, indicating their potential to be used as auxiliary parameters along with K<sub>t</sub> to characterize K.

Figure 6.1 also gives an idea of sky-types for each site and possible attribution to the local weather. Mumbai's K and K<sub>t</sub> curves acquire crests and troughs interchangeably (Fig.6.1-a). K<sub>t</sub> is higher than K in all months except from June to September, during which the region is affected by monsoons, thus increasing the scattered radiation

which in turn leads to a sharp rise in K and an equally sharp drop in K<sub>t</sub>. For Sapporo (Fig.6.1-b), K curve is higher than the K<sub>t</sub> throughout all months. The main reason for such high diffuse irradiation is believed to be the site's relatively high precipitable water content. Highest K values and lowest K<sub>t</sub> values were observed for winter months. This accentuated rise can be partly attributed to the increased albedo owing to the snowing season in Sapporo which lasts from November to February. The K curve is in the lower range while K<sub>t</sub> is in the high range for Gerona apart from the three winter months, indicating its predominantly clear-sky nature during summer (Fig.6.1-c). Bracknell meteorological trend is very similar to that of Sapporo with K curve always higher than the K<sub>t</sub>, representing its characteristic overcast weather (Fig. 6.1-d). The deviation between K and corresponding K<sub>t</sub> values is exceptionally large in winter months as expected. It was observed in all plots that SF follows K<sub>t</sub> trend and CF that of K and thus they reciprocate each other in a manner similar to K-K<sub>t</sub>. Therefore, SF and CF can thus justifiably be referred to as auxiliary parameters in respect of diffuse radiation modelling.

There is often a misconception that since SF has a good correlation with  $K_t$ , including sunshine fraction in the K-  $K_t$  regressions is like adding a third order term of  $K_t$ . However, investigation in this regards revealed that this was not the case, i.e. SF's influence on diffuse ratio does not depend on clearness index. In this respect, Fig. 6.2 demonstrates the scatter plot of K with respect to SF for Bracknell. A narrow band of  $K_t$  was selected (0.26 <=K\_t <0.3) and based on that, variation of K was studied with respect to corresponding variation in SF. It was found that for a nearly constant  $K_t$ , there was a steep change in diffuse ratio with change in SF i.e. SF has a significant bearing on diffuse ratio with  $R^2$  of the order of 0.7. This indicates that SF has a good correlation with K, independent of  $K_t$ . Although, Bracknell has been presented here as a sample plot, such qualitative investigation could also be extended to other sites' data and is expected to show similar direct bearing of SF on diffuse irradiance. Hence, it can be reasonably concluded that SF is not a proxy variable for  $K_t$  in the equation of K rather has its own significance.

During the averaging process for each year, notable variation between the corresponding month's parameter values was revealed. Therefore, a model based on only one or two years' data is not reliable particularly if the variation in yearly

radiation patterns is significant, or alternatively, if the data quality is questionable. It is suggested to include at least a minimum of three years data, where possible, to account for weather variability for both developing the models and their subsequent validation.

# 6.2 Modelling and Evaluation

Based on K<sub>t</sub>, SF and CF, 14 progressive models were presently developed for each site. These models are empirical, polynomial functions of the parameters under consideration, same as produced in Chapter 5, except for the following: (a) third order degree of K<sub>t</sub> was additionally explored herewith, (b) there was no air mass involved in the modelling and (c) model types and their numbering was consistent between all sites irrespective of the regions they belonged to.

The models developed here not only vary in parameter combinations, but they also differ with respect to degrees of expression within each parameter qualification. For example, both quadratic and cubic models were tried for  $K_t$ , while SF and CF were tested for linear and quadratic combinations. It was distinctly observed that since the K-K<sub>t</sub> variations are typically curvilinear for all sites, a quadratic or cubic fit emerged to be more appropriate than a linear one, both in terms of R<sup>2</sup> and slope. Cubic or higher orders of the auxiliary parameters, SF and CF, were not taken into consideration as it would only involve additional complexity. Equation 6.1 represents the comprehensive model frame work, within which there were 13 other simpler models; two of them falling under monovariate, eight under the category of bivariate and another four in the multivariate category.

$$K = (a_0 + a_{11}SF + a_{12}SF^2 + a_{21}CF + a_{22}CF^2) + (b_0 + b_{11}SF + b_{12}SF^2 + b_{21}CF + b_{22}CF^2) * K_t + (c_0 + c_{11}SF + c_{12}SF^2 + c_{21}CF + c_{22}CF^2) * K_t^2 + (d_0 + d_{11}SF + d_{12}SF^2 + d_{21}CF + d_{22}CF^2) * K_t^3$$
(6.1)

In order to evaluate the given set of models (as listed under the 'Model type' of Table 1), the same statistical indicators as in Chapter 5 were used, namely, MBD, RMSD,  $R^2$ , Kurtosis and Skewness. Like in the previous chapter, it may be worthwhile to note here that while  $R^2$  was obtained as a result of diffuse ratio (K) model fit, the other statistical measures were derived directly from the errors in diffuse irradiance

estimation. The accuracy of a model is better checked by calculating the error statistics involved in estimating the diffuse radiation rather than the diffuse ratio.

Each statistical indicator has certain associated inherent drawbacks, an account of which was given under Section 5.2.1. However, it would be worth reiterating some of the discrepancies that may arise as a result of incomprehensiveness of any individual indicator. A low MBD value and a large RMSD value can occur at the same time for a model that has an even but large distribution of errors. In another scenario, consistently small under- or over-estimation can yield a relatively small RMSD yet, a relatively large MBD (Stone, 1993). If the error distribution is symmetrical, i.e. skewness is low; a low MBD is not a reliable criterion for better model estimates. Likewise, if kurtosis of error histogram is high, a high RMSD does not necessarily indicate poor model performance. R<sup>2</sup> is bound to increase with addition of each new parameter; however, this does not necessarily imply that the new model is better than the previous one.

Therefore, here again, three statistical indices namely, Accuracy score (AS), Sum Deviation (SD) and t-statistic, were computed and used as evaluators to give a more reliable assessment. 'AS', a sum of the performance credits contributed by the above-discussed five statistical indicators, was developed in the previous chapter for hourly diffuse radiation as expressed in Eq. (5.10). SD and t-statistic are presently evaluated using the mathematical expressions as represented by Eq. 5.11 and 5.12, respectively.

Table 6.1 provides a list of all models and their corresponding AS(s), SD(s) and tstatistic(s) for respective locations. As obvious from the definition, while higher AS suggests better performance, both SD and t-statistic should decrease with increasing model accuracy.

Figure 6.3 gives the pictorial trend of accuracy scores for all the sites. While, Fig 6.3 (a) shows those sites which had information on all the parameters under study, Fig 6.3 (b) represents those sites which did not provide cloud cover measurements. It was seen that with the exception of Gerona all the K-K<sub>t</sub> models scored lowest credits in the model series. It was also observed, that there was not only a significant increase in the AS but also a considerable decrease in SD and t-statistic values (Table 6.1) from the K-K<sub>t</sub> models to the next model from SF series. Again, Gerona was the only

exception to this trend; in fact a closer look at the statistics of Gerona models confirms this anomalous behaviour with all the models that involve SF as one of the parameters. One major reason for the non-coordination of radiation and sunshine data could be the fact that, while sunshine duration was obtained from the Instituto Nacional de Meteorología (15 km from Gerona), the radiation data was measured on the roof-top of one of the University of Gerona's building.

From the statistics, two types of models i.e. best scoring models and optimum models showing improvement over the conventional K-  $K_t$  model are summarised in Table 6.2 for corresponding sites. Although the best scoring models were site-specific, optimum models are relatively general. Model 7 (K-Kt, CF) gives the optimal performance for Mumbai, Gerona, Madrid and Bracknell. For other four sites i.e. New Delhi, Pune, Fukuoka and Sapporo K-Kt, SF models were optimum with variation in degrees of parameters involved. It is important to note here that the favourability of New Delhi and two Japanese sites for CF models could not be evaluated as information on cloud was not available for these sites.

Thus, this section reflects the models' accuracy and improvements in relation to the individual locations and specific time periods concerned. However, to evaluate the long-term performance of these models and to achieve generalized coefficients so that a model developed for one site can be used for another, validation of the proposed models is required.

# 6.3 Validation of the Models

A proposed model is inconsequential unless it is validated. A model which is an optimum choice based on the statistical analysis, may not yield promising results for another data using the same statistical tools. Hence, it is better practice to test the models against a completely independent data set rather than proposing models based solely on their performance against the same data. Evaluation of models in Section 6.2 was only a preliminary step to the 'true' validation on which the proposition of region-wise models will be based.

However, testing the models against independent data, revealed certain issues which are addressed in the following section.

#### 6.3.1 Challenges in developing a standard or validated model

Although models involving additional parameters like SF and/or CF improve the accuracy of estimation for the same site, a limitation of such models is the generalization of its coefficients to yield a universally acceptable model. On the other hand, K-K<sub>t</sub> relationship is relatively universal in the sense that a standard empirical equation can be used to estimate daily diffuse irradiation in any part of the world, irrespective of time. For that purpose K as a function of K<sub>t</sub> second-degree polynomial was plotted for all sites under study in Fig. 6.4. The proximity of K-K<sub>t</sub> curves irrespective of the multi-climatic and varied topography of the sites confirmed the relative non site-dependency of a model derived from K-K<sub>t</sub> relationship alone. However, this relationship compromises on accuracy which can possibly be achieved with bi- and multivariate models. Part of the reason for the specificity of such models is the uncertainties and systematic errors associated with the commonly employed ground-based measurements in most parts of the world. Undoubtedly, this leads to significant variations in measured parameter values even for similar sky-conditions, thus affecting the predicted values adversely. As is the widely acknowledged fact that even the most accurate model can only be as good as the measurements it is derived from. Such errors are inconsistent and unaccountable, often entailed by the meteorological standards which differ from site to site. Sunshine duration measurements and cloud cover observations are more susceptible to erroneous measurement/reporting than radiation data. Therefore, addition of such parameters increases the prediction uncertainty and hence comparison against an independent data set (whether it is the same site with different time period or a different site altogether) often reveals serious non-conformity. In this light, a K-Kt model involves minimum measured parameters, hence, minimum measurement uncertainty and therefore yields better results when applied to an independent dataset. Nevertheless, this does not invalidate the improved accuracy of estimation that can be brought about by incorporating other auxiliary parameters. Therefore, in this chapter an attempt is made to achieve a balance in the accuracy and site-independence by proposing regionwise bi- or multivariate models through the following validation strategy.

Validation can be achieved by either comparing the modelled values with the data developed from a standard model or testing it against the measured data. The presented work follows the latter approach by using a previously reserved section of the data sets for validation. Two methods were adopted under this section. The first one was to use models developed for one site to evaluate diffuse irradiation for other sites from the same country. Second method of validation involves culling a given data set into two halves. The first half was used to develop the models and the other part was used for testing or validating the developed models. The former method was used for all sites but Bracknell, since this was the only site from UK presently under consideration. Hence, models for Bracknell were validated by culling the data. Simultaneous use of the above two methods, would not only meet the practical limitation with one of the sites but also give an explicit validation analysis on the whole.

#### 6.3.2 Validation by testing models for other sites

Under this section, improved models, over the conventional yet more universal K- $K_t$  model, were proposed and tested against other sites to yield generalised models for a whole country or region. It was found that an improved and comprehensive model based on say,  $K_t$  and SF when used for an independent site within a given region performs more accurately than a locally developed  $K_t$  model.

Mumbai models (derived from the full data set) were tested against New Delhi and Pune, Sapporo models were validated using Fukuoka data and Madrid models were used to predict diffuse irradiation for Gerona. The models were evaluated again using the same statistical tools as in Section 6.2, along with the % MBD and %RMSD and Dm vs Dc plots to clearly identify the optimum model from other models for respective sites. Percent MBDs and RMSDs, as defined by Stone (1993) were used in addition to their dimensional counterparts, as they facilitate the model testing under various meteo-climatic conditions (Page, 1979). Not all models were re-evaluated. Only the critical models for each site and/or models involving basic function of the parameters are shown here.

# 6.3.2.1 India

From Table 6.3 (a) and Fig. 6.5 (d), it was found that model 6 i.e. K= f (cubic  $K_t$ , quadratic SF) yields most accurate estimation for Delhi. The same model 6, based on Mumbai data, reveals optimal performance for Pune on comparison between the 5 evaluators of AS, SD, t-statistic, %MBD and %RMSD (Table 6.3 (b)). This fact is

also supported by the measured versus calculated diffuse radiation plots for the different Pune models (Fig. 6.6). It was also observed from Table 6.1 and Fig. 6.7 that the model 6 gives reasonable accuracy for Mumbai. Hence, Mumbai's model 6 can impartially be adopted as the optimum over-all model for the three sites and in turn for the Indian region, for improved estimation of diffuse irradiation over K-K<sub>t</sub> models.

## 6.3.2.2 Japan

Among the models under validation for Fukuoka, model 5 i.e. K= f (quadratic K<sub>t</sub>, quadratic SF) based on Sapporo data was the optimum, as is evident from Table 6.4 (a) and Fig. 6.8 (c). However, this model does not supersede the statistics of model 3 (K= f (quadratic K<sub>t</sub>, linear SF) for Sapporo (Table 6.1). Nevertheless, a closer examination of the breakdown of statistical indicators (Table 6.4-b) and significant improvement shown by the Dm versus Dc plot of model 5 (Fig. 6.9-b) for Sapporo, suggests that the minimal variations between the performance results of the two models be overlooked. Therefore, model 5 was chosen to be the optimum model for the Japanese region. This exercise also reveals that none of the statistical tools is completely reliable for the datasets under study. Hence, it is worthwhile to assess the individual contributors apart from the three aggregates of AS, SD and t-statistic.

#### 6.3.2.3 Spain

Madrid regression models were used to estimate diffuse irradiation for Gerona. Despite of the limitation of Gerona's sunshine data measured elsewhere in contrast with the other meteorological data, Table 6.5 shows improvement in terms of  $\mathbb{R}^2$ , MBD (%), RMSD and kurtosis for model 3 (K= f (quadratic K<sub>t</sub>, linear SF) compared to model 1 (K= f (quadratic K<sub>t</sub>). Figure 6.10, which compares the Dc against Dm for respective models, reveals that though model 1 yields calculated values closer to 1 to 1 line, model 3 (Fig. 6.10-b) gives a uniform scatter as it eliminates the obvious subjugation present in Fig. 6.10 (a) towards the high diffuse radiation end. Figure 6.11 represents similar plots for Madrid. It was seen under Section 6.2 that the optimum model for Spanish sites was model 7 (K= f (quadratic K<sub>t</sub>, linear CF), as opposed to the present indication of model 3. Nevertheless, following conclusions can safely be drawn; (a) Model 7 is an optimum short-term, site-specific model for both Gerona and Madrid. In other words, although coefficients are not interchangeable, the two models yield best performance if used within the respective data set to fill the gaps in radiation data, (b) the proposed additional parameter (SF) provides improved results if measured at the same place as global irradiation, (c) model 3 of Madrid can be used as long-term model for the Spanish sites.

## 6.3.3 Validation for culled data of same site

Apart from obtaining a validated model, the following exercise also gives an insight in second type of validation. Regression models based on cull data yield conforming results for the control data, provided that the data quality is reasonably good. Bracknell data measurements meet WMO standards thus making it an ideal candidate among all other sites for this type of validation.

# 6.3.3.1 UK

Bracknell validation was done by culling the data of same site into two halves. The minimum number of years' data required to account for the weather variability has not been explicitly established in the literature so far. Since, 6 years of data is available for Bracknell, 3 years were used for developing models and the other 3 years for validation. This procedure resulted in three sets of statistics, one for the full data (as shown in Table 6.1), another for culled data and the third for the validation of the control data (Table 6.6(a) and Table 6.6(b), respectively). It was found that model 7 gave the best score of statistical evaluators for full data and culled data. Individual comparison of the contributing statistical indicators between model 3 (K= f (quadratic  $K_t$ , linear SF) and model 7 (K = f (quadratic  $K_t$ , linear CF) revealed that with the exception of dimensional MBD, all other values were in favour of model 3. This dimensional MBD naturally contributes to lower values of both SD and t-statistic. One reason for exceptionally low MBD could be that one over-estimated value cancels another under-estimated value. In addition, scatter plots of Dm against Dc were plotted for the two models along with the model 1 under both-validation data (or independent data) and full data (or same data), represented by Fig. 6.12 and Fig. 6.13. The plots reveal improved estimation by model 3. Hence, model 3 was recommended to be used for Bracknell and thus, for UK when estimating daily values of diffuse irradiation. Subsequent testing of models (obtained from culled data) against the control data for Bracknell (Table 6.6-b) and the Dm versus Dc plots (Fig. 6.12), confirm that model 3 is a more reliable choice.

## 6.3.4 Results and discussion

Table 6.7 gives the regression coefficients of the validated daily diffuse irradiation models under each region. It can be noted that all the proposed models involve only SF as additional parameter. The different regions differ only in degree of correlation of the two parameters. It will be worthwhile to mention that careful inspection of all the Dm versus Dc plots reveals that both K-Kt and K-Kt, CF models tend to underestimate the diffuse radiation and give nearly constant estimated values for high values of measured diffuse irradiation. In K-Kt case this trend could be attributed to the physical limitation of clearness index in defining the multi-sky conditions or failure to account for the scattering in overcast sky regime. For K-K<sub>t</sub>, CF models a possible reason could be perspective errors in cloud cover observations. In other words, low performance of such models for high measured diffuse radiation could be related to usually associated underestimation of the amount of cloud cover in overcast conditions. However, SF incorporation improves the estimation particularly at the high end of measured diffuse radiation with no subjugation trend unlike the other two parameters. Thus, it can be concluded that in order to estimate diffuse irradiance in a given place, regional Kt, SF models can reliably be used. It was found that the bivariate models of Kt, CF and multivariate models such as Kt, SF and CF developed for one site, stand redundant if *daily* diffuse radiation is to be estimated in another location. Nevertheless, the latter models can yield reasonable improvement in accuracy for the same site if used to fill the gap in data series, i.e. to estimate diffuse irradiance where it was not measured due to station shut down or other such operational issues.

#### 6.4 Summary

Although, global radiation is by large recognized as a key input in diffuse radiation models, the study presented here shows how other meteorological parameters such as sunshine duration and cloud cover could also be instrumental in estimating the *daily* diffuse radiation. Data from each of the 8 locations was used as a case study of model proposition and subsequent evaluation. Daily sunshine fraction (SF) and daily cloudiness factor (CF) were used along with daily clearness index ( $K_t$ ) by intercombination to develop a series of diffuse ratio (K) empirical models for each site. Diffuse radiation was then calculated from the estimated daily diffuse ratio. Various statistical tools were employed to establish the criterion of best performing model.

Each model's performance was initially assessed based on the data it is derived from and then validated against an independent dataset. This validation was achieved by two methods; one by testing the models developed for one site against another site in the same region (for seven sites) and, second by testing the models derived from one section of data against the other from the same site covering a different period of time (for one site). The accuracy of prediction was evaluated using three statistical indices (AS, SD, t-statistic). Final assessment also included the plotting of calculated versus measured diffuse irradiation and indicators such as percent MBD and percent RMSD for potential models.

It was found that a model based on K<sub>t</sub> and SF (or CF) performs better than a model based on Kt alone within the same data set. In other words, incorporation of SF and CF in K-K<sub>t</sub> models yields greater accuracy of estimation, particularly if they are used to fill the gaps within the measured data series. However, these models were found to be site-specific and in some cases time-specific too, owing to the poorly maintained meteorological standards and systematic inevitable errors associated with such parameters. The fact that, majority of world-wide stations continue to rely on traditional methods of meteorological measurements and many others hold historical pre-satellite databases, makes it incumbent to produce a reasonably accurate model with general applicability. After an exhaustive evaluation, it was established that SF is the most influential parameter next to K<sub>t</sub>, in order to produce diffuse radiation models with general applicability and increased accuracy. Therefore, an optimum solution was to select a higher performing model (K<sub>t</sub>, SF in this case) from one site which yields reasonably improved results for other sites within that region. This model could then be reliably proposed as a regional model. If daily diffuse irradiation is to be estimated at a site belonging to a region where no such daily model has been developed, it is both wise and reasonable to use a well-established K-K<sub>t</sub> model developed elsewhere. However, if a K-Kt, SF model is available in literature for that region, it would not only suffice to use that model to estimate diffuse radiation but will give better estimates than the locally developed K-K<sub>t</sub> model.

Through this work, it was concluded that the validation is equally important to the original proposition for any model application. This chapter, like Chapter 5, also demonstrated the subjective nature of various statistical tests used within solar radiation modelling. Therefore, one of the conclusions drawn here is that a good

research analysis should encompass all the major evaluation methods to establish a criterion of selection for the best model.



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Fig.6.1 Annual K, Kt, SF and CF pattern based on monthly-averaged daily values.(a) Mumbai, (b) Sapporo, (c) Gerona, (d) Bracknell



Fig. 6.2 Variation of K with respect to SF for selected band of data with  $K_{\rm t}$  ranging between 0.26 and 0.3



(b)



Fig. 6.3 (a) Accuracy score plots for sites with both SF and CF, (b) Accuracy score plots for sites with SF but no CF



Fig. 6.4 Quadratic K-K t curve fits for each of the eight datasets



Fig. 6.5 Dm versus Dc plots for New Delhi, clockwise L-R (a) Model 1:  $K = f(q K_t)$ , (b) Model 3:  $K = f(q K_t \lim SF)$ , (c) Model 5:  $K = f(q K_t q SF)$ , (d) Model 6:  $K = f(c K_t q SF)$ 

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Fig.6.6 Dm versus Dc plots for Pune (a) Model 1:  $K = f(q K_t)$ , (b) Model 3:  $K = f(q K_t \ln SF)$ , (c) Model 6:  $K = f(c K_t q SF)$ , (d) Model 7:  $K = f(q K_t \ln CF)$ , (e) Model 14:  $K = f(c K_t q SF, q CF)$ 



Fig.6.7 Dm vs Dc plots for Mumbai. (a) Model 1:  $K = f(q K_t)$ , (b) Model 6:  $K = f(c K_t, q SF)$ 



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Fig. 6.8 Dm versus Dc plots for Fukuoka, clockwise L-R (a) Model 1:  $K = f(K_t)$ , (b) Model 3:  $K = f(q K_t lin SF)$ , (c) Model 5:  $K = f(q K_t q SF)$ , (d) Model 6:  $K = f(c K_t q SF)$ 



Fig. 6.9 Dm versus Dc plots for Sapporo (a) Model 1:  $K = f(K_t)$ , (b) Model 5:  $K = f(q K_t q SF)$ 



Fig. 6.10 Dm versus Dc plots for Gerona (a) Model 1:  $K = f(q K_t)$ , (b) Model 3:  $K = f(q K_t \ln SF)$ , (c) Model 7:  $K = f(q K_t \ln CF)$ , (d) Model 11:  $K = f(q K_t \ln SF, \ln CF)$ , (e) Model 14:  $K = f(c K_t q SF, q CF)$ 



(a)

(b)

(c)



Fig. 6.11 Dm versus Dc plots for Madrid (same data set) (a) Model 1:  $K = f(q K_t)$ , (b) Model 3:  $K = f(q K_t \text{ lin SF})$ , (c) Model 7:  $K = f(q K_t \text{ lin CF})$ 



Fig. 6.12 Dm versus Dc plots for Bracknell (independent data set), clockwise L-R (a) Model 1:  $K = f(q K_t)$ , (b) Model 3:  $K = f(q K_t, \lim SF)$ , (c) Model 7:  $K = f(q K_t, \lim CF)$ , (d) Model 11:  $K = f(q K_t, \lim SF, \lim CF)$ 



Fig. 6.13 Dm versus Dc plots for Bracknell (same data set) (a) Model 1:  $K = f(q K_t)$ , (b) Model 3:  $K = f(q K_t \text{ lin SF})$ , (c) Model 7:  $K = f(q K_t \text{ lin CF})$
Model No	Model Type	AS	t- statistic	SD	20	t- statistic	SD	ΔS	t- etatistic	sn.
	Middel 1990	/10	Mumbai			New Delhi	00			
1	K=f(a Kt)	1 65	1.06	2.00	1 56	2.56	2.00	1 55	2.34	2.00
2	K=f(c Kt)	1.80	0.92	1 77	1.50	2.50	1 93	1.55	2.04	1.76
3	K=f(a Kt. lin SF)	2 59	0.31	1 16	2.88	1 21	1.00	3 12	1 27	1.70
4	K=f(c Kt. linSF)	2.62	0.34	1 17	2 91	1 16	1 15	2.87	1.27	1.21
5	K=f(a Kt a SF)	2.81	0.07	1.01	2.01	1.10	1.13	2.07	1.00	1.12
6	K=f(c Kt. g SF)	2.86	0.16	0.99	2.00	1 11	<sup>°</sup> 1 13	2.00	1.25	1 11
7	K=f(a Kt. lin CF)	2.90	0.20	1.00				2 71	1.39	1 22
8	K=f(c Kt, lin CF)	2.91	0.21	1.00				2 79	1 49	1 22
9	K=f(a Kt. a CF)	2.89	0.26	1.03				2.69	1 42	1 22
10	K=f(c Kt, q CF) K=f(a Kt, lin SF, lin	2.92	0.25	1.02				2.85	1.50	1.21
11	CF)	3.02	0.05	0.87				3.16	1.07	1.04
12	K=f(q Kt, q SF, q CF) K=f(c Kt, lin SF, lin	3.10	0.06	0.86				3.13	1.04	1.01
13	CF)	3.04	0.08	0.88				3.11	1.08	1.04
14	K=f(c Kt, q SF, q CF)	3.17	0.04	0.83				3.25	1.08	1.01
			Fukuoka			Sapporo				
1	K=f(q Kt)	1.87	0.55	2.00	1.82	1.86	1.99			j
2	K=f(c Kt)	1.91	0.53	1.95	1.87	1.93	1.98			
3	K=f(q Kt, lin SF)	2.60	0.23	1.28	3.04	1.57	1.37			
4	K=f(c Kt, linSF)	2.64	0.23	1.27	2.78	1.76	1.44			
5	K=f(q Kt, q SF)	3.05	0.06	0.97	2.44	1.64	1.33			
6	K=f(c Kt, q SF)	3.09	0.05	0.93	2.40	1.66	1.34			
			Gerona			Madrid			Bracknell	
1	K=f(q Kt)	2.72	1.18	1.61	1.84	3.03	2.00	1.72	3.24	2.00
2	K=f(c Kt)	2.69	1.14	1.60	1.72	2.63	1.87	1.73	2.83	1.87
3	K=f(q Kt, lin SF)	2.20	2.05	1.93	2.65	2.58	1.67	3.53	2.89	1.40
4	K=f(c Kt, linSF)	2.22	2.04	1.93	2.75	2.51	1.64	3.59	2.87	1.40
5	K≕f(q Kt, q SF)	2.04	2.01	1.90	2.96	2.16	1.51	3.56	2.99	1.42
6	K=f(c Kt, q SF)	2.16	1.97	1.87	3.03	2.15	1.50	3.51	3.03	1.43
7	K=f(q Kt, lin CF)	3.24	0.32	1.11	3.48	1.49	1.29	3.35	1.76	1.23
8	K=f(c Kt, lin CF)	3.24	0.31	1.11	3.54	1.55	1.30	3.19	1.91	1.25
9	K=f(q Kt, q CF)	3.10	0.33	1.11	3.50	1.50	1.29	3.22	2.04	1.29
10	K=f(c Kt, q CF) K=f(q Kt, lin SF, lin	3.22	0.38	1.14	3.55	1.50	1.28	3.18	2.02	1.28
11	CF)	2.70	1.36	1.56	3.23	1.90	1.35	3.52	2.81	1.36
12	K=f(q Kt, q SF, q CF) K=f(c Kt, lin SF, lin	2.60	1.34	1.55	3.37	1.71	1.28	3.55	2.89	1.37
13	CF)	2.69	1.35	1.55	3.30	1.86	1.33	3.57	2.82	1.36
14	K=f(c Kt, q SF, q CF)	2.53	1.40	1.57	3.37	1.72	1.28	3.49	2.95	1.38

Table 6.1 Stat	istical evaluatior	1 of K <sub>t</sub> , SF	, CF	models	for	each	site

Table 6.2 Model proposition based on the same data as they are derived from (a) Model types (b) regression coefficients for optimum models

(a)

Sites	Model No	Best Model	Model No	Optimum Model
Mumbai	11	K=f(q Kt, lin SF, lin CF)	6	K=f(c Kt, q SF)
New Delhi	5	K=f(q Kt, q SF)	5	K=f(q Kt, q SF)
Pune	11	K=f(q Kt, lin SF, lin CF)	6	K=f(c Kt, q SF)
Fukuoka	6	K=f(c Kt, linSF)	5	K=f(q Kt, q SF)
Sapporo	3	K=f(q Kt, lin SF)	3	K=f(q Kt, lin SF)
Gerona	7	K=f(q Kt, lin CF)	7	K=f(q Kt, lin CF)
Madrid	7	K=f(q Kt, lin CF)	7	K=f(q Kt, lin CF)
Bracknell	7	K=f(q Kt, lin CF)	7	K=f(q Kt, lin CF)

(b)

	IND	IA			JAPAN			SPAIN		U	к –
	Mumbai	New Delhi	Pune		Fukuoka	Sapporo		Gerona	Madrid		Bracknell
a <sub>0</sub>	0.932648	0.716451	1.088294	ao	0.888072	1.020016	a <sub>0</sub>	0.789779	1.138496	a <sub>0</sub>	1.210367
a <sub>11</sub>	-2.475764	-2.545049	1.899403	a <sub>11</sub>	-2.702855	-0.110957	a <sub>11</sub>	-	-	a <sub>11</sub>	-
a <sub>12</sub>	-15.099539	2.987993	-1.780142	a <sub>12</sub>	0.027305	-	a <sub>12</sub>	-	· -	a <sub>12</sub>	-
a <sub>21</sub>	-	-	-	a <sub>21</sub>	-	-	a <sub>21</sub>	0.031028	-0.016411	a <sub>21</sub>	-0.024402
a <sub>22</sub>	-	-	-	a <sub>22</sub>	-	-	a <sub>22</sub>	-	-	a <sub>22</sub>	-
bo	0.094633	1.725483	-2.102734	b <sub>0</sub>	1.499943	-0.341552	b <sub>0</sub>	-0.576475	-2.039030	bo	-1.875642
b <sub>11</sub>	16.541663	5.109565	-15.987594	b <sub>11</sub>	8.055224	-2.219247	b <sub>11</sub>	-	-	b <sub>11</sub>	-
b <sub>12</sub>	68.009197	-9.144027	16.555273	b <sub>12</sub>	-2.616854	-	b <sub>12</sub>	-	-	b <sub>12</sub>	-
b <sub>21</sub>	-	-	-	b <sub>21</sub>	-	-	b <sub>21</sub>	0.054951	0.220691	b <sub>21</sub>	0.240919
b <sub>22</sub>	-	-	-	b <sub>22</sub>	-	-	b <sub>22</sub>	-	-	b <sub>22</sub>	-
C <sub>0</sub>	0.962085	-3.094253	8.641748	$c_0$	-4.114280	0.454857	C <sub>0</sub>	-0.422801	0.886289	C <sub>0</sub>	0.691790
C <sub>11</sub>	-38.563109	-1.564915	28.701036	C <sub>11</sub>	-3.909532	1.697363	C <sub>11</sub>	-	-	C <sub>11</sub>	-
C <sub>12</sub>	-100.338110	5.948152	-39.615768	C <sub>12</sub>	2.083854	-	C <sub>12</sub>	-	-	C <sub>12</sub>	-
C <sub>21</sub>	-	-	-	C <sub>21</sub>	-	-	C <sub>21</sub>	-0.123128	-0.243135	C <sub>21</sub>	-0.290985
C <sub>22</sub>	-	-	-	C <sub>22</sub>	-	-	C <sub>22</sub>	-	-	C <sub>22</sub>	-
do	-4.185458	-	-10.957400	do	-	-	do	-	-	do	-
d <sub>11</sub>	30.612355	-	-11.551793	d <sub>11</sub>	-	-	d <sub>11</sub>	-	-	d <sub>11</sub>	-
d <sub>12</sub>	46.960675	-	25.747840	d <sub>12</sub>	-	-	d <sub>12</sub>	-	-	d <sub>12</sub>	-
d <sub>21</sub>	-	-	-	d <sub>21</sub>	-	-	d <sub>21</sub>	-	-	d <sub>21</sub>	-
d <sub>22</sub>	-	-	-	d <sub>22</sub>	-		d <sub>22</sub>		-	d <sub>22</sub>	-

.

Model No	Model Type	R <sup>2</sup>	MBD (W/m²)	RMSD (W/m²)	Skew	Kurtosis	AS	SD	t- statistic	MBD (%)	RMSD (%)
1	K=f(q Kt)	0.64	274	567	0.85	1.4	1.2	2.0	22.9	0.11	0.41
3	K=f(q Kt, lin SF)	0.74	187	439	0.80	2.3	2.1	1.5	19.6	0.06	0.33
5	K=f(q Kt, q SF)	0.75	151	422	0.82	2.8	2.4	1.3	15.9	0.04	0.32
6	K=f(c Kt, q SF)	0.76	95	414	0.69	4.1	3.1	1.1	9.8	0.00	0.32

Table 6.3 Statistical results of Mumbai models validated against (a) New Delhi, (b) Pune

.

(a)

(b)

Model No	Model Type	R²	MBD (W/m²)	RMSD (W/m²)	Skew	Kurtosis	AS	SD	t- statistic	MBD (%)	RMSD (%)
1	K=f(q Kt)	0.70	-96	486	0.51	2.6	2.3	1.4	7.6	-0.11	0.34
3	K=f(q Kt, lin SF)	0.80	-114	409	0.71	3.7	2.5	1.3	11.0	-0.13	0.29
6	K=f(c Kt, q SF)	0.81	-129	410	0.82	5.5	2.6	1.4	12.6	-0.14	0.29
7	K=f(q Kt, lin CF)	0.79	-234	401	0.19	2.6	2.4	1.8	27.4	-0.17	0.28
14	K=f(c Kt, q SF, q CF)	0.84	-211	367	0.34	4.5	2.9	1.7	26.8	-0.17	0.27

Model No	Model Type	R²	MBD (W/m²)	RMSD (W/m²)	Skew	Kurtosis	AS	SD	t- statistic	MBD (%)	RMSD (%)
1	K=f(q Kt)	0.77	-155	396	-0.14	5.0	2.2	2.0	7.8	-0.119	0.244
3	K=f(q Kt, lin SF)	0.80	87	367	1.24	10.8	2.2	1.5	4.5	0.025	0.177
5	K=f(q Kt, q SF)	0.82	48	347	0.90	14.4	3.1	1.2	2.6	-0.001	0.181
6	K=f(c Kt, q SF)	0.82	46	351	0.77	14.7	3.2	1.2	2.4	-0.003	0.185

Table 6.4	(a) Statistical results of Sapporo models validated against Fukuoka, (b) Statistical results of Sapporo models from Table
	with breakdown of statistical contributors

(b)

(a)

Model No	Model Type	R²	MBD (W/m²)	RMSD (W/m²)	Skew	Kurtosis	AS	SD	t- statistic
1	K=f(q Kt)	0.80	-49	404	-0.41	1.6	1.8	2.0	1.86
2	K=f(c Kt)	0.81	-50	395	-0.38	1.5	1.9	2.0	1.93
3	K=f(q Kt, lin SF)	0.90	-31	302	-0.40	3.0	3.0	1.4	1.57
4	K=f(c Kt, linSF)	0.90	-35	301	-0.54	3.1	2.8	1.4	1.76
5	K=f(q Kt, q SF)	0.91	-31 <sup>°</sup>	287	-0.70	2.3	2.4	1.3	1.64
6	K=f(c Kt, q SF)	0.91	-31	286	-0.69	2.2	2.4	1.3	1.66

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Model No	Model Type	R <sup>2</sup>	MBD (W/m²)	RMSD (W/m <sup>2</sup> )	Skew	Kurtosis	AS	SD	t- statistic	MBD (%)	RMSD (%)
				-							
1	K=f(q Kt)	0.81	26	337	0.23	3.1	3.2	1.2	3.9	-0.03	0.26
3	K=f(q Kt, lin SF)	0.83	72	319	0.39	3.7	2.7	1.6	11.4	0.00	0.22
7	K=f(q Kt, lin CF)	0.82	109	334	0.43	2.7	2.0	1.9	17.0	0.04	0.22
11	K=f(q Kt, lin SF, lin CF)	0.83	115	318	0.54	3.0	1.9	1.9	19.1	0.04	0.20
14	K=f(c Kt, q SF, q CF)	0.84	102	317	0.53	2.9	2.0	1.8	16.7	0.03	0.20

Table 6.5 Statistical results of Madrid models validated against Gero	lts of Madrid models validated against Gero	drid models validated again:	Statistical results of Madrie	Table 6.5
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Model No	Model Type	R <sup>2</sup>	MBD (W/m²)	RMSD (W/m²)	Skew	Kurtosis	AS	SD	t- statistic	MBD (%)	RMSD (%)
1	K=f(q Kt)	0.91	15	254	0.17	4.2	2.0	2.0	2.7	-0.02	0.15
3	K=f(q Kt, lin SF)	0.95	10	217	-0.25	7.1	2.6	1.6	2.2	-0.01	0.12
7	K=f(q Kt, lin CF)	0.92	6	242	-0.21	4.8	2.6	1.3	1.1	-0.02	0.15
11	K=f(q Kt, lin SF, lin CF)	0.95	10	215	-0.29	7.0	2.4	1.5	2.2	-0.01	0.12

Table 6.6 (a) Statistical results of Bracknell's culled data models, (b) Statistical results of Bracknell's culled data models validated against Bracknell's independent data

(a)

(b)

Model No	Model Type	R <sup>2</sup>	MBD (W/m²)	RMSD (W/m²)	Skew	Kurtosis	AS	SD	t- statistic	MBD (%)	RMSD (%)
1	K=f(q Kt)	0.94	34	250	0.69	2.4	1.5	2.0	4.6	-0.01	0.15
3	K=f(q Kt, lin SF)	0.96	-15	209	-0.19	4.9	3.5	1.3	2.3	-0.03	0.13
7	K=f(q Kt, lin CF)	0.95	7	227	0.46	2.5	2.7	1.1	1.0	-0.02	0.14
11	K=f(q Kt, lin SF, lin CF)	0.96	-17	206	-0.25	4.7	3.3	1.3	2.8	-0.03	0.13

Table 6.7 Reg	gion-wise re	gression mo	odels for	daily	diffuse	irradiation	(a) Model	types,
		(b) Reg	gression of	coeffi	cients			

(a	)

Region	Model No	Optimum Model
India	6	K=f(c Kt, q SF)
Japan	5	K=f(q Kt, q SF)
Spain	3	K=f(q Kt, lin SF)
UK	3	K=f(q Kt, lin SF)

(b)

			*	· · · · · · · · · · · · · · · · · · ·				
India			Japan		Spain	UK		
a	0.932648	ao	1.011750	a	0.955901	a	0.962987	
a <sub>11</sub>	-2.475764	a <sub>11</sub>	-0.812356	a <sub>11</sub>	-0.815132	a <sub>11</sub>	-1.519794	
a <sub>12</sub>	-15.099539	a <sub>12</sub>	2.327577	bo	0.116885	bo	0.410093	
bo	0.094633	bo	-0.315121	b <sub>11</sub>	1.007268	b11	3.231226	
b <sub>11</sub>	16.541663	b11	-2.095615	C <sub>0</sub>	-1.380342	C <sub>0</sub>	-1.370749	
b <sub>12</sub>	68.009197	b <sub>12</sub>	-3.760995	C <sub>11</sub>	-0.214451	C <sub>11</sub>	-2.349734	
C <sub>0</sub>	0.962085	C <sub>0</sub>	0.984846					
C <sub>11</sub>	-38.563109	C <sub>11</sub>	1.378566					
C <sub>12</sub>	-100.338110	C <sub>12</sub>	1.674327					
do	-4.185458							
d <sub>11</sub>	30.612355							
d <sub>12</sub>	46.960675							

#### CHAPTER 7

### APPLICATION: SUSTAINABLE SOLAR ELECTRICITY PROVISION FOR INDIA IN 2025

This chapter is reproduced based on a feasibility study that was undertaken in 2004 to propose sustainable energy provisions for 6 major cities in India for the year 2025. It also serves as a demonstration of the application of solar radiation database for proposing an electricity network based on solar-hydrogen energy vector.

India's population is expected to reach 2289 million by the year 2051 (Nawaz et al, 2003). Huge population and development activities are assumed to increase India's energy demand tremendously over the coming years. The study presents the energy scenario of India in terms of its total energy demand and supply and its context within the world community. The renewable energy prospects of India have been highlighted herein. Furthermore, prospects of solar hydrogen to be used, to meet the energy demand of six major energy consuming Indian conurbations: Chennai, Delhi, Jodhpur, Kolkata, Mumbai, and Trivandrum, have been explored and based on that an electricity network is proposed. Figure 7.1 shows the geography of these locations and general solar energy distribution in India.

#### 7.1 Backgorund Information

#### 7.1.1 Solar hydrogen economy

Solar energy coupled with hydrogen has immense potential to meet the future energy needs provided technological advancements are taken on board. Hydrogen is not only a high energy density carrier but can also effectively fill the intermittency of solar power.

#### 7.1.1.1 Solar PV energy

Although solar photovoltaics have briefly been covered in Chapter 1, a quick review would be helpful. Solar photovoltaic (SPV) technology enables direct conversion of sunlight into electricity through semi-conductor devices called solar cells. Solar cells are interconnected and hermetically sealed to constitute a photovoltaic module. The photovoltaic modules are integrated with other components such as storage batteries to constitute SPV systems and power plants. Photovoltaic systems and power plants are highly reliable and modular in nature.

Photovoltaic cells have been in use in spacecraft since the 1950s. However, with the energy crisis of the early 1970s, a steadily growing terrestrial industry has developed. Initially, it supplied PV cells mainly for remote area applications where conventional electricity is expensive. Nonetheless, the industry is now in an explosive period of growth where the subsidised urban–residential use of photovoltaics is providing the main market. The global industry had grown at a compounded rate of 30% per annum from 1996 to 2001, corresponding to a quadrupling of annual production over this period (Green, 2004). India, though on a smaller scale, is following similar trends. Figure 7.2, for example, shows the world as well as Indian annual growth in PV modules shipments.

In places where there is enough solar potential, replacing coal with the former to generate power, can provide both commercial cost savings as well as carbon dioxide emission reductions. A comparison of the economics and emissions of some of the conventional electricity generation technologies against solar electricity generation has been provided in Table 7.1 (Sims, 2004).

The present market in the application of PV cells is defined by three sectors: the Professional sector, the Off-grid sector and the Grid-connected sector.

#### Professional sector

This sector represents, on one hand, the earliest exploitation route, viz. remote telecommunications repeater stations, but also, on the other hand, futuristic technology, such as the US proposal for a 10 GW orbiting solar power station.

#### Off-grid or stand alone sector

Stand-alone systems produce power independently of the utility grid. In some off-the-grid locations, as near as one-quarter mile from the power lines, stand alone PV systems can be more cost effective than extending power lines. They are especially appropriate for remote, environmentally sensitive areas, such as national parks, cabins and remote homes. In rural areas, small stand-alone solar arrays often power farm lighting, fence chargers and solar water pumps, which provide water for livestock. Direct-coupled systems need no electrical storage because they operate only during daylight hours, but most systems rely on battery storage so that energy produced during the day can be used at night. Some systems, called hybrid systems, combine solar power with additional power sources, such as wind or diesel.

#### Grid-connected sector

Grid-connected PV systems, also called grid interface systems, supply surplus power back through the grid to the utility, and take from the utility grid when the home system's power supply is low. These systems remove the need for battery storage, although arranging for the grid interconnection can be difficult. In some cases, utilities allow net metering, which allows the owner to sell excess power back to the utility.

In the last two decades, the cost of PV electricity has gone down by a factor of 10, and is expected to reduce further thus creating more potential (MNES report, 2001). Global demand of PV equipment has grown consistently by 20-25% per annum over the past 20 years. It is reported that in 2001 and 2002 global PV shipments were 395 MW and 525 MW respectively. During 2002, world production of PV increased by a record 43.8% (Maycock, 2003).

#### 7.1.1.2 Hydrogen as the energy carrier

In present energy chain, collected or extracted primary energy is, in one or several steps, converted into energy carriers, such as diesel oil or gas that are suitable for end uses. In future, it is expected that hydrogen will take over the role of energy carrier. Hydrogen in

the capacity of energy vector will be the optimum solution for intermittency and storage of energy produced by renewables.

Hydrogen can primarily be produced through reformation of natural gas, electrolysis of water, or partial oxidation of heavy fossil fuels such as diesel. In a renewable energy scenario, solar PV energy will be utilised to carryout electrolysis of water to yield hydrogen.

Hydrogen's potential use in fuel and energy application includes powering vehicles, running turbines or fuel cells to produce electricity and generating heat and electricity for buildings. Eventually, the hydrogen produced could replace fossil fuels in broader applications.

In order to move towards a sustainable hydrogen economy (an economy which relies on an energy system supported predominantly by the use of hydrogen), a future strategy must be outlined, followed, and continually revised. Around the world there are significant efforts being undertaken to strive towards hydrogen economy. Iceland for example, has set targets to be the first country in the world to have the hydrogen economy that is through switching all its energy sources onto renewable based hydrogen by around 2030-2040 (Sigfusson and Arnason, 2003). In his 2003 State of the Union address, President Bush announced a \$1.2 billion initiative to reverse America's growing dependence on foreign oil by developing the technology for commercially viable hydrogen-powered fuel cells to power cars, trucks, homes and businesses with no pollution or greenhouse gases (USED, 2003). All major energy companies around the world are starting to position themselves towards the emerging hydrogen economy. BMW is developing hydrogen fuelled ICE (internal combustion engine) passenger vehicles. Together with a fuel retailer, BMW intends to offer liquid hydrogen at refuelling stations in the vicinity of all BMW dealerships around Europe by 2005. Similarly General Motors have committed themselves towards being the first automobile company to have one million fuel cell vehicles on the road. Shell and BP both have major hydrogen divisions within their companies.

#### 7.1.2 The Indian subcontinent

The subcontinent of India lies in south Asia. It is a peninsula and the three sides are surrounded by Arabian Sea in the southwest, Bay of Bengal in the southeast and Indian Ocean in the South as shown in Fig. 7.1. India lies between 8.4 and 37.6 degrees north latitude and 68.7 and 97.3 degrees east longitude. It has a total area of 3,287,590 km<sup>2</sup>, which is slightly more than one third the size of US. India measures 3214 km from north to south and 2933 km from east to west. It has a land frontier of 15,200 km and a coastline of 7517km. India shares its political borders with Pakistan and Afghanistan on the west, Bangladesh and Burma in the east, Nepal, China, Tibet and Bhutan in the north. The nation is divided into four large natural regions. The great mountain zone: the Himalayas, along the northern border; the fertile, densely populated Ganges plains immediately to the south, the desert region in the northwest and the Deccan plateau in the centre and south. Most of the country lies in the tropics, and so stays warm throughout the year. The Himalayas shelter the country from cold north winds. The climate is subject to monsoon influence; hot and dry for eight months of the year, and raining heavily from June to September.

India has a population of 1,041,144,000 (2002 figures) with an annual growth rate of 1.8 % (1985-2000). About half a billion people belong to middle class. In the year 2000, per capita GDP was reported to be \$ 2,358 with an annual growth of 2.0% and an annual inflation of 4.0% (The World Guide, 2003/04). India's GDP is composed of agriculture-25%, industry - 30% and services - 45%. Main industries include textiles, chemicals, food processing, steel, transportation equipment, cement, mining, petroleum and machinery.

#### 7.2 Energy Scenario in India

#### 7.2.1 Status and trends

Despite increased energy use in India, per capita consumption (3629 kWh) remains low as against the world average of 17620 kWh. Indian per capita electricity use averages only one-sixth that of the world, one-half that of the Chinese, and less than one-twentieth that of North Americans (Amit and Shukla, 2002). Annual capacity additions have not been able to keep up with demand, leading to power shortages and supply interruptions. India is home to one third of worlds poor (WBD, 2003). There are 580 million people lacking electricity in India. Although the electricity network is technically within reach of 90% of the population, only 43% are actually connected because many poor people cannot afford the cost of connection. Even with average incomes groups, households are often discouraged from connecting to the grid because of the poor quality of service, including frequent blackouts and brownouts. Over the last five years, Rural Electrification Corporation Limited (REC) has extended significant financial support to facilitate and accelerate the pace of electrification of villages and hamlets. Loan sanctions by REC witnessed growth of 79% amounting to \$2662 million in 2003 against \$ 1485 million sanctioned in the previous year (Tiwari, 2003).

India accounted for 3.5 % of world primary consumption and 12 % that of total primary energy consumed in Asia-Pacific region in 2002 (BP, 2003). The country is the world's sixth largest energy consumer and indeed a net energy importer. India is a vast country with diverse mix of resources. The energy consumption is attributed to a number of fuels with varying use patterns. Table 7.2 describes various fuels that share India's energy market.

Coal dominates the energy mix in India, meeting about 60 % of energy requirements in the country. Nearly 30 % of India's energy needs are met by oil, and more than 60 % of that oil is imported. Natural gas has experienced the fastest rate of increase of any fuel in India's primary energy supply. Presently, the natural gas contribution is met entirely by domestic production. However, the gap between demand and supply is set to widen unless major gas discoveries are made. It is expected that by 2010 almost three-quarters of India's oil and gas needs will be met by imports (FEI, 2002).

Industrial sector is the largest consumer of energy in India, consuming about half of the total energy consumption in 1999/2000. The transport sector is the next biggest consumer at 22% of total commercial energy consumption. Figure 7.3 shows the sectoral

composition of commercial energy consumption in India. It consumes nearly half of the oil products, mainly in the form of diesel oil and gasoline. Agriculture sector mainly consumes electric power and diesel oil, major portions of which go into pump sets used for irrigation purposes. Residential sector is another significant consumer in India. Traditional biomass accounts for more than a third of the energy consumed in the Indian household sector. A detailed account on the use of biomass in India has been presented by Ramachandra et al (2004). It is estimated that out of the total household sector energy needs, 30 % is consumed in lighting, 1 % in cooking and the rest by other household appliances (Amit and Shukla, 2002). Indian electric power sector now consumes over 40 % of primary energy, with an overwhelming contribution by coal (70%), hydroelectricity (25%), followed by natural gas, nuclear power, oil and renewables, which account for the remaining 5 % (EIA).

The all-India installed generating capacity increased from a meagre 1362 MW in 1947 to 101630 MW in early 2001, a gain of nearly 75 times in capacity addition. The demand of electricity in India is enormous and is growing steadily. Electricity use has more than doubled in the last decade, and has grown faster than GDP for the past twenty years (CMIE Energy, 1999). Electricity consumption per person has increased to over 493 kWh in 2001, up from 90 kWh in 1972 (IEA, 2003). The energy demand, GDP and population are predicted to increase significantly within the next two decades as shown in Fig. 7.4.

#### 7.2.2 Energy and environmental challenges

For India to tackle the economic and environmental challenge of its energy demand growth it is important to have a good understanding of how these and other factors shape energy use in various sectors of the economy. Detailed and coherent information is needed in order to judge the potential for energy efficiency improvements or to measure the progress of already implemented policies.

India's rapidly growing economy will drive energy demand growth at a projected annual rate of 4.6 % through to the year 2010 (EIA). It has been reported that India's electric power demand are likely to increase three-fold by the year 2051. Indications are that the

electric power demand is expected to grow at around 10% per annum in next 15 years requiring about 10,000 MW of capacity addition every year over this period (Nawaz et al, 2003). Other studies indicate that by 2020, India's demand for commercial energy is expected to increase by a factor of 2.5 (WEO, 2000). Underpinning this trend will be the ongoing growth in population, urbanization, industrial production and transport demand.

Energy shortages in India have been increasing in the past few years, from 5.9 % in 1998/99 to 7.8% in 2000/01. The peak energy demand during 2001-02 touched 86 TWh, of which only 75TWh could be met. India will continue to experience this energy supply shortfall for at least another 15 years. This gap has been exacerbated since 1985, when the country became a net importer of coal (EIA). The growing gap between the demand and supply of energy, and environmental externalities associated with energy use are the key issues today. Almost half of India's trade deficit is due to petroleum imports, the cost of which also limits capital that could be invested in the economy (EIA). High economic development requires rapid growth in energy sector. This implies substantial increases in electric power generation and transmission capacities, and exploitation of new avenues of energy supply.

Nuclear energy contributes 2 % to India's total power generation. Indications are that the share would be even less in 2010 due to many unsolved problems- high cost, radioactive wastes and decommissioning costs (TERI). In 2002, India's oil consumption raised to 97.7 million tonnes, more than 2.6 times the domestic production (BP, 2003). Estimates indicate that oil imports will meet 75% of total oil consumption requirements and coal imports will meet 22% of total coal consumption requirements in 2006 (TERI). India can ill afford to overly depend on fossil fuels considering the high cost of imported petroleum products. India's fossil fuel resources are limited compared to global reserves. Table 7.3 provides an estimate of fossil fuel reserves in India.

The Indian economy has grown two and a half times over the past two decades but pollution control has not kept pace; industrial pollution has quadrupled over the same period. The Indian government has estimated the cost of environmental degradation at about 4.5% of GDP in recent years (FEI, 2002). Indiscriminate and inefficient burning of fuel wood in traditional cookers and in industries for thermal process heat has resulted in deforestation, environmental pollution and health hazards. Another significant problem is the generation of fly ash during the combustion of coal in power generation. In India with 70% of power generation being coal-based and the inherently high ash content of indigenous coal (more than 40% in some cases), 80–100 million tonnes of fly ash are produced every year. India stands second only to China in the quantum of fly ash generated every year. Currently, nearly 90% of fly ash generated is dumped as slurry in ash ponds, which requires huge amounts of water, resulting in creation of wasteland which also leads to leaching of heavy metals and soluble salts. Leakage from ash ponds to neighbouring fields and water bodies can lead to surface and groundwater pollution. The utilization of fly ash in India remains low at 10%, compared with utilization rates of 30%–100% internationally (TERI). The use of gasoline and diesel in the transport sector generates a number of pollutants like lead, carbon monoxide, toxic compounds such as benzene, and particulate matter which are discharged to the atmosphere along with vehicular exhaust gas. India is currently the fifth largest carbon emitter in the world, behind only the United States, Russia, China, and Japan; India's fossil-fuel carbon emissions are about the same as for the entirety of Africa. In the past decade alone, India's carbon emissions have increased by about 60%, and are about nine times higher than they were forty years ago (FEI, 2002). Much of this increase is due to India's increasing utilization of its coal resources for power generation. Carbon emissions are forecast to grow by about 3% annually through 2025, as against 1.9 % of the total world as shown in Table 7.4. To limit the disastrous effects of global warming, Indian as well as the world's CO<sub>2</sub> emissions would have to be cut by 50% (Arthus-Bertrand, 2003).

#### 7.2.3 Renewable energy trends

During the past decade, India has taken steps to utilise the immense potential for renewable energy sources. The goals of Indian energy planning include the promotion of decentralised energy technologies based on renewable resources in the medium term, and the promotion of energy supply systems based on renewable sources of energy in the long term. The latest projection by the Ministry of Non-conventional Energy Sources (MNES) is the plan of additional 12 GW capacity by 2012.

There is a large potential of renewable energy resource available in India, an estimated aggregate of over 100,000 MW, which needs to be harnessed in a planned and strategic manner to mitigate the gap between demand and supply. In the present scenario renewable energy is contributing to about 3.5% of the total installed electric capacity of about 3700 MW. It is planned to increase this contribution to 10% of the total power generation capacity by the year 2012.

Today India has the largest decentralized solar energy programme, the second largest biogas and improved stove programmes, and the fifth largest wind power programme in the world. Table 7.5 describes India's renewable energy potential and achievements (MNES, 2002-03).

However, only a fraction of the aggregate potential in renewables, and particularly solar energy, has been utilized so far. The achieved wind power capacity is less than 4 % of the potential from this source. Similarly, the respective installed biomass power and small hydropower capacities are about 2.4 % and 9.8 % of their potential.

#### 7.2.4 Solar PV progress in India

India lies in the sunny belt of the world. The scope for generating power and thermal applications using solar energy is huge. Most parts of India get 300 days of sunshine a year, which makes the country a very promising place for solar energy utilization (TERI, 2001). The daily average solar energy incident over India varies from 4-7 kWh/m<sup>2</sup> with the sunshine hours ranging between 2300 and 3200 per year, depending upon location (MNES, 2001). The technical potential of solar energy in India is huge. The country receives enough solar energy to generate more than 500,000 TWh per year of electricity, assuming 10 % conversion efficiency for PV modules. It is three orders of magnitude greater than the likely electricity demand for India by the year 2015.

The largest market for PV in India has been for applications such as telecom power, railway network, oil and gas sector, defense services and exports, with a currently installed aggregate capacity of 107 MW as shown in Fig. 7.5. The Indian PV industry today consists of nine companies that manufacture solar cells, 23 manufacture modules and about 60 companies that are in the business of systems integration. There is also a manufacturing capacity of about 2 million silicon wafers annually. The industry produced 11 MWp of modules in the year 1999, having a turnover of about US \$ 100 million. The national program initiated in the year 1975, is believed to be one of the largest demonstration PV program in the world today (TERI, 2001). In 2001 the annual production of solar modules accounted for 11MW capacity in India as shown in Fig. 7.2.

Electrification is one of the main infrastructure requirements for the overall rural development. There are about 80,000 unelectrified villages in the country. Of these villages, 18,000 cannot be electrified through extension of the conventional grid. A target for electrifying 5,000 such villages has been fixed for the Tenth National plan. So far, more than 2,700 villages and hamlets have been electrified mainly using solar photovoltaic systems (MNES, 2002-03).

#### 7.3 Proof of Concept and Economics of Solar Hydrogen

There are a number of solar hydrogen demonstration programs around the world- both for transport and building sector. With respect to the building sector, once again, several such international demonstration programmes may be cited. One such reference (Gosh et al, 2003) reports a ten-year operational experience. In the latter project, the technical feasibility of a self-sufficient energy supply system based on photovoltaic, battery and hydrogen storage was demonstrated for a public building: the Central Library in Forschungszentrum Jülich, Germany, for a period of 10 years. The overall efficiency based on the annual energy balance excluding the photovoltaic efficiency varied from 51% to 64%. The battery bank was able to supply energy to the load for three days in the absence of solar radiation. The battery delivered around 50-52 % of the demand. In addition, another 20-25% of the demand was supplied by the fuel cell, which indicates that the energy should be stored in long-term storage system. A high level of energetic

reliability with a relatively low battery capacity and hydrogen storage was thus demonstrated.

The economics of solar hydrogen in the proposed energy network can be categorised under three main areas i.e. PV electricity generation, hydrogen production through electrolysis and storage of hydrogen. Producing energy through PV is presently more expensive than conventional energy systems primarily due to high cost of PV technology. PV however has significant long-term potential because it has very desirable attributes and a great potential for radical reduction in cost. The cost of PV module has been decreasing steadily over the years. The cost of PV has dropped dramatically, from 7.4 US\$/W in 1987 to 2.5US\$/W in 2002 as shown in Fig. 7.6. Future forecasts indicate that cost of PV is likely to drop further over the coming years, approximately up to 0.8US\$/W by the year 2020 (Kurokawa, 2003).

As stated above, hydrogen can be produced through a number of different technologies. All other technologies but electrolysis have associated carbon emission to various degrees that disqualify them as clean and environmentally friendly energy system. Electrolysis offers the main option for a zero carbon hydrogen economy that does not require sequestration. PV-based electrolysis is although slightly more expensive than wind-based electrolysis, it however has been preferred due to its consistency and higher reliability as compared to the latter. Industry based estimates indicate that the cost of PVbased electrolysis in 2000 was US\$41.8/GJ that is expected to drop down to US\$24.8/GJ by year 2010 (Dutton, 2002).

There are a number of technologies available for short-term and long-term storage. The three main options for hydrogen storage are compressed hydrogen, liquid hydrogen and metal hydrides. Long-term storage of hydrogen in any of the three forms is much more expensive than for short-term storage. Liquid hydrogen is the cheapest storage option that costs around 4.21US\$/GJ for short-term (1-3 days) storage. The cost for long-term storage (30 days) of liquid hydrogen is around US\$36.93/GJ (Dutton, 2002).

# 7.4 Proposed Energy Network for Key Urban Centres – A Modular Approach7.4.1 Data processing

To develop a proposal for sustained solar energy development in the six major cities of India, the very first task was to explore the radiation data sets that were available for those sites. The pattern of the availability of solar resource, in time, is important, as this dictates the design of energy production, transmission and storage systems.

Chennai, Delhi, Jodhpur, Kolkata, Mumbai, and Trivandrum were chosen in this study, because these are the chief metropolis of the Indian sub-continent. Furthermore, these sites are geographically and topographically different from each other as indicated in Table 7.6. The irradiance data from Chennai, Delhi and Mumbai were purchased by the research team from the India Meteorological Department expressly for the project under discussion. The radiation data sets of the other three sites were extracted from the Handbook of Solar Radiation (Mani, 1980). The present work employs detailed data sets of hourly global and diffuse values, day by day, for twelve months of each year over the period of 1990 to 1994 as procured from meteorological stations. On the other hand, datasets from the above mentioned handbook provide mean hourly values of the two irradiance components for the twelve months of the year based on observations made during the 10-year period 1958-1967. The data was quality controlled using the procedure described in Chapter 3.

#### 7.4.2 PV yield calculation

Hourly slope radiation values were calculated using a software tool from Muneer's monograph (Muneer, 2004). The computations were performed for five orientations using a PV area of 1 m<sup>2</sup> for each aspect, namely, east, southeast, south, southwest and west. Different combinations of tilts and azimuths were employed for the PV modules. A total of three cases were investigated details of which are shown in Table 7.7. The best set of orientations was worked out for each site in order to maximize the yield for a cost-effective arrangement of the PV array. For all of the three sites, case number 3 was found to provide the maximum slope irradiation as shown in Fig. 7.7. The energy yields were

then summed up over the five years and annual yield was calculated taking a conservative efficiency of 10% for the PV modules.

Using the case 3 orientation, hourly PV yield-profile for an average day of every month was calculated. Similar calculations were carried out for the mean-valued data for other three sites of Jodhpur, Kolkata and Trivandrum for which only monthly averaged data was available. This PV-yield profile was then set against the load profiles for the six cities based on the predicted energy trends for 2025 to determine the required PV module area.

Presently, the main concern was proposing a solar electricity network for each of the individual cities under consideration. However, a grid-connected solar electricity scenario can be a viable option for the future. The main reason being that it will smooth out the inherent fluctuations in solar radiation profile that are more site-specific and directly linked to the existing climatic conditions. Averaged global irradiance for the three locations of Chennai, Delhi and Mumbai were calculated for four seasonally distinct months. As expected, it was found that the site-integrated energy yield has a considerably more stable profile. In particular, for the month of July when most parts of India are affected by the seasonal monsoons and the irradiance trend vary widely, the overall average of the three cities is fairly stable. Figure 7.8 describes the global radiation profiles for Chennai, Delhi and Mumbai, with their overall average.

#### 7.4.3 The modular energy network

The present work proposes solar hydrogen based energy network to meet the future energy demand for the major cities of India. This modular approach presents a sustainable energy solution to the ever growing energy needs in a way that is more secure, stable and environmentally friendly. In the proposed energy network very largescale solar PV units are to be employed to generate electricity. Excessive solar electricity produced beyond the daytime needs is to be converted into hydrogen through electrolysis. The stored hydrogen is to meet energy requirements during nocturnal hours and also during heavily overcast conditions. Fuel cells are to be utilized to retrieve the energy

#### Chapter 7: Application: Sustainable Solar Electricity Provision for India in 2025

stored in the form of hydrogen. The proposed energy setup also exploits a fossil fuel power system as a backup to provide electricity in case the demand exceeds available solar electricity and/or hydrogen. Figure 7.9 provides functional details and flow chart for the energy supply and control mechanism for the proposed energy network. Present as well as projected cost scenarios for future have been provided for all the proposed technologies to evaluate the economical viability of the energy network.

Fossil fuel cost is expected to increase over the coming years as reported by numerous resources. Laherrère (2003) forecasts the crude oil price of 22US\$/barrel in 2003 to rise to 27US\$/barrel by 2025 that appears to be a rather conservative approach. Exxon as indicated by Zittel (2002), suggests a range of the crude oil cost for the year 2025 to lie between 22US\$ and 56US\$. Relying on these predicted costs of crude oil a range of the electricity cost in 2025 has been calculated. The electricity production cost (primarily fossil fuel based) in Delhi in the year 2003 was 7.6US cents/kWh while the projected cost of electricity in the year 2025 has been estimated to range from 9.3 cents/kWh to 19 cents/kWh with a mean value of 14.2 cents/kWh.

The cost analysis of the generation and transmission of solar PV electricity shows that the cost of PV cells is the most vital element. The worldwide market for PV has grown exponentially over last 20 years as PV cost has dropped dramatically, from 7US\$/W in 1988 to 3 US\$/W in 2000 (Kurokawa, 2003). The PV cost in 2003, 2.7US\$/W, is projected to drop down to less than 1 US\$/W by the year 2020. The trend described by Kurokawa (2003) leads to a PV cost of 0.6US\$/W by the year 2025. Based on 25-year service life for PV cells, the range of PV electricity production cost is calculated to be from 8.2 cents/kWh to 13.8 cents/kWh with a mean value of 11 cents/kWh. By 2025, the present day electrolysis cost of 15 US cents/kWh as reported by Padró (1999), is expected to drop down to 4 US cents/kWh. Hydrogen storage cost, for a facility size of 130 TJ, capable of supplying energy for 72 hours in case of continuous spell of overcast conditions, is projected to be equivalent to 0.49 US cents/kWh (Padró, 1999). By 2025, the present cost for proton exchange membrane fuel cells (PMEC), 4.3 US\$/W, is

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projected to drop down to 0.3 US\$/W (Fuel cells, 2003). Assuming a 10-year service life for fuel cells the net energy cost is estimated to be 0.52 US cents/kWh by the year 2025.

A comparison of the present day costs of the technologies involved in proposed energy network with the projected costs for the year 2025 has been presented in Table 7.8. In the present study, Delhi's electricity demand in the year 2025 has been estimated based on its present load profile and India's total electricity demand in the year 2025 as reported by IEO (2003). Delhi's electricity demand has been calculated on the basis of its population proportion in India. This 'business as usual' demand is estimated to be 28.8 TWh. According to world energy statistics, India at present is consuming 19% of world's average per capita energy (WES). Assuming that due to its rapid economic growth, by the year 2025, India will consume 35% of world's average per capita energy, Delhi's electricity demand is estimated to be equal to 38.8 TWh. The latter scenario will represent a 'rapid economic growth' situation. The economics of the proposed energy network to meet Delhi's energy demand in the year 2025 with six different possible cost scenarios of involved technologies has been presented in Fig. 7.10. The cost scenarios describe the total cost of providing the electricity both for 'business as usual' and 'rapid economic growth' energy demand of Delhi, utilizing different viable combinations of fossil fuel and solar electricity at high, low and medium projected future costs. The electricity cost for the network has been plotted against increasing PV area. From Fig. 7.10 it is noted that with a low projected fossil fuel cost and a low projected PV cost (1, 1-1) the increase in PV area has only a slight bearing on the decrease in overall electricity generation cost. However, a significant decrease in overall cost can be observed even if the fossil fuel cost is medium like in the case m, l-2 with increase in PV area. The sharpest cost reduction is evident when PV cost tends to be low while fossil fuel cost is on the rise i.e. h, 1-1. With the continuing trends of consumption of fossil fuel and the environmental issues involved, it is highly likely that the fossil cost would witness a sharp rise in the future. By the year 2025, it is expected that with increasing global awareness and enhanced technologies, renewables will form a major portion of the energy matrix. Consequently, the PV technology if not cheaper would at least become competitive with the non-conventional energy resources in the market. Based on such

foresight, we thus have five scenarios strongly supporting our case (Fig. 7.10), which is: the total electricity cost would decrease considerably with a viable increase in the installed PV module area. Similarly, electricity network for the other major cities of India: Chennai, Jodhpur, Kolkata, Mumbai, and Trivandrum and the related cost analysis were generated. They are provided in Fig(s). 7.11, 7.12, 7.13, 7.14 and 7.15, respectively.

#### 7.5 Summary

India, already being an energy deficient country inevitably requires to explore new avenues of generating electricity in a sustainable way to meet the future energy and its related environmental challenges. The geographic location of India makes it a strong candidate for harnessing solar energy. Thus, solar PV is a potential technology to meet India's future energy demand and its associated environmental challenges. In present work, solar PV electricity has been described as the solution of future energy challenges. In the proposed energy network solar PV produced electricity is to be utilized to meet the energy demand during day hours. The solar generated electricity that is excessive of demand is to be stored in the form of hydrogen to be utilized during nocturnal hours and prolonged overcast conditions. The modular approach adopted to meet the year 2025 energy demand of six major cities in India: Chennai, Delhi, Jodhpur, Kolkata, Mumbai, and Trivandrum indicates that the suggested solar hydrogen based energy network has the capability of providing the energy requirements. Present as well as projected cost scenarios for 2025 have been provided for all the proposed technologies to evaluate the economical viability of the energy network under study. Based on the futuristic trends, it is foreseen that by the year 2025, the PV electricity would be more economical than the fossil-fuel electricity.

This study demonstrated the application of solar radiation data in proposing a future electricity network based on solar energy. It is seen through this work, that both knowledge of global as well as diffuse radiation is essential in order to calculate the hourly slope radiation and thus make optimum use of available solar energy (by selecting an optimal combination of tilt and orientation). Although, both global and diffuse radiation were provided for the presently used locations, the work can be extended for

cities/locations where diffuse radiation is not measured. The diffuse radiation models developed during the course of this project can be used to estimate the long-term radiation required to develop a solar-hydrogen energy network.



## Fig. 7.1 The six locations and the distribution of annual global solar irradiation across India, kWh/m<sup>2</sup> (reproduced; source: Mani, 1980)



Fig.7.2 Annual growth in PV module shipment, MW: World and Indian status



Fig.7.3 Indian sectoral composition of commercial energy consumption: 1999/2000



Fig.7.4 Energy, economic and population trends for India



Fig.7.5 Sector-wise use of PV modules: Total number of installed systems = 1,030,000; Aggregate capacity = 107 MW



Fig. 7.6 Historical and projected PV cost



Fig.7.7 Global horizontal and slope irradiation profiles for 14 April 1990 for Delhi: (Refer Table 7.7)





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\* l- low, m-medium, h- high, l- business as usual scenario, 2- rapid economic growth  $\cdot$  (notations: first-fossil fuel cost, second- PV electricity cost, third-demand scenario)

Fig.7.10 Cost comparisons for supply of fossil fuel and solar electricity for the year 2025: Delhi



Fig.7.11 Cost comparison for supply of fossil-fuel and solar electricity for the year 2025: Chennai



Fig.7.12 Cost comparison for supply of fossil-fuel and solar electricity for the year 2025: Jodhpur



Fig.7.13 Cost comparison for supply of fossil-fuel and solar electricity for the year 2025: Kolkata



Fig.7.14 Cost comparison for supply of fossil-fuel and solar electricity for the year 2025: Mumbai


Fig.7.15 Cost comparison for supply of fossil-fuel and solar electricity for the year 2025: Trivandrum

# Table 7.1 Economics and emissions of conventional technologies compared with solar electricity generation (Sims, 2004)

Power genearation technology	Carbon emissions	Emission savings	Generating costs
	(g C/kWh)	(g C/kWh)	(USc/kWh)
Pulverized coal- as base case	229	0	4.9
Integrated gasification combined cycle (IGCC) -coal	190-198	31-40	3.6-6.0
Pulverised coal + CO <sub>2</sub> capture	40-50	179-189	7.4-10.6
Combined cycle gas turbine (CCGT)- natural gas	103-122	107-126	4.9-6.9
CCGT gas + CO <sub>2</sub> capture	14-18	211-215	6.4-8.4
Solar thermal and solar PV	0	229	8.7-40.0

Fuel	Consumption (MtoE)	Share of Total
Coal	180.8	55.6
Oil	97.7	30.0
Natural gas	25.4	7.8
Nuclear	4.4	1.4
Hydro	16.9	5.2
Total	325.1	100.0

#### Table 7.2 India's energy consumption by fuel (Year 2002)

#### Table 7.3 Indigenous fossil fuel reserves in India

Resource	Proved Reserves	Expected life of			
		reserves (years)			
Coal (MT)	84396	235			
Natural Gas (BCM)	760	26.9			
Oil (MT)	700	19.4			

Resource	India					Avg Annual %				
	History			Projections				change,		
								2001-2025		
	1999	2000	2001	2005	2010	2015	2020	2025	India	World
Coal	101	161	162	172	194	212	229	261	2.0	1.6
Oil	45	76	76	81	100	126	160	195	4.0	1.8
NG	7	12	12	19	27	37	46	50	6.1	2.8
Total	153	249	250	272	321	375	435	506	3.0	1.9

Table 7.4 (Million Metric Tons Carbon Equivalent) CO2 emissions by fuel use, reference case, 1990-2025

ENERGY SOURCES	POTENTIAL	ACHIEVEMENT	INDIA'S
		AS ON 31.12.2002	POSITION IN THE
			WORLD
Biogas Plants	12 million	3.37 million	Second
Improved Chulhas	120 million	33.9 million	Second
Wind	45,000 MW	1,702 MW	Fifth
Small Hydro	15,000 MW	1,463 MW	Tenth
Biomass	19,000 MW	468 MW	Fourth
Power/Cogeneration			
Biomass Gasifiers		53 MW	First
Solar PV	20 MW/sq. km	107 MW <sub>p</sub> *	Third
Waste-to-energy	2,500 MW	25 MW <sub>e</sub>	
Solar Water Heating	140 million sq.m	0.68 million sq.m	
	Collector Area	Collector Area	

#### Table 7.5 Renewable Energy Potential and Achievements in India (MNES, 2002-03)

\*Of this 46  $\ensuremath{\mathsf{MW}}_{\ensuremath{\mathsf{p}}}\xspace$  SPV products have been exported.

Location	Latitude, N	Longitude, E	Height, MASL	
New Delhi	28.6	77.2	236	
Jodhpur	26.3	73.02	224	
Calcutta	22.65	88.45	6	
Mumbai	19.12	72.85	14	
Chennai	13.00	80.18	16	
Trivandrum	8.48	76.95	64	

Table 7.6 Geography of the six cities chosen for the present study

	0	PV output with 10 % efficiency					
	Orientation	kWh/m2					
	Azimuth	Tilt	Delhi	Mumbai	Chennai		
Case 1	90	90					
	135	90					
	180	90					
	225	90					
	270	90	148	134	128		
Case 2	90	90					
	135	45					
	180	45					
	225	45					
	270	90	180	188	192		
Case 3	90	45		<u> </u>			
	135	45					
	180	45					
	225	45					
	270	45	205.6	5 216	228		

#### Table 7.7 Azimuth-tilt combinatorial sets and their respective PV energy yield

Technology/Cost	2003 (US cents/ kWh)	2025 (US cents/ kWh)		
		Low	Medium	High
Fossil Fuel	7.6	9.3	14.2	19.0
PV modules	3.7	8.2	11.0	13.8
Electrolysis	15.0	-	4.0	-
H <sub>2</sub> Storage	1.9	-	0.49	-
Fuel Cells	7.45	-	0.52	-

# Table 7.8 Cost analysis of proposed technologies

# **CHAPTER 8**

## CONCLUSIONS

Energy is a crucial commodity of modern age pertinent to the socio-economic wellbeing and integrity of any society. Increasing concerns about insecurity and vulnerability of supply of the fossil fuels and the many and diverse ways they are causing damage to our ecology, has motivated a gradual but steady reform in current energy mix. Sustainable development demands increasing reliance on renewable energy resources. Solar energy, traditionally been in use since man's existence, is now gaining impact as the fuel of the 'future' with a huge potential to meet the energy demands of the world at any one time. Utilization of sun's energy requires the understanding of the pattern of its availability on earth's surface. It is a well known fact that solar resource or solar radiation varies spatially as well as temporally across the face of the earth. Hence, resource assessment is a preliminary step for all solar applications. In other words, design and simulation of solar energy projects requires knowledge of solar data. Solar radiation measurements are an expensive affair. Therefore, the lack of availability of ready-to-use solar radiation data at the site of interest calls for the need to estimate radiation. Calculation of radiation received by tilted surfaces, the most common manifestation of a solar application, needs both diffuse and direct components. This accentuates estimating any one of them from more commonly measured global radiation to get the third component as the difference of two. Such models are diverse and innumerable.

This research was conducted with the primary goal to produce more accurate yet computationally simple diffuse radiation models. The approach involved improving the estimation by incorporating commonly available meteorological parameters to traditional clearness index- diffuse ratio models.

#### 8.1 Originality of contribution

Clearness index remains by large as the single most influential parameter in characterizing diffuse ratio and thus effecting the estimation of diffuse radiation. However, this fact doesn't preclude the investigation of other potential parameters that can improve the accuracy of estimation.

Sunshine duration, cloud cover and air mass have individually been the subject of interests in the past. The current research project, however, was developed with a view to explore and inter-compare the influence of these parameters on diffuse ratio on a substantial basis. This approach has a practical basis: the fact that there is greater number of meteorological stations measuring sunshine duration, cloud cover, temperature, etc. than there are for solar radiation measurement (Gul et al, 1998).

Original contribution within the context of presented research can be identified in the following sub-sections:

*Database:* No single study has been conducted in solar radiation modelling history (to the author's best knowledge) that uses such wide spread locations, with latitude ranging from 51° N to 13 ° N.

*Approach:* No previous study was found in literature that combined the effect of sunshine fraction, cloud cover and air mass, or even the two of them, in the same model.

*Temporal scale:* Most of the previous researches that took global radiation and sunshine fraction in account were monthly averaged values or in some cases daily. Multi-parameter models for hourly values estimation are considerably scarce. Most of the daily radiation models developed in the past were strictly site-specific, unlike the presently proposed models.

*Methodology:* The models developed here are invariably different than the multiparameter models, available in literature, generally defined by first degree empirical equation with subsequent parameters following a serial order. The current regression modelling uses additional descriptors like sunshine fraction, cloud cover and air mass as sub-functions within clearness index for the latter as a function of diffuse ratio. Optimization is performed at every level, from varying degrees within a single parameter qualification to inter-comparison between the three proposed variables.

*Evaluation:* Much of the evaluation of previously-developed hourly radiation models is based on comparing the monthly averages. Such an averaging masks the significantly larger scatter and deviation resulting from comparison of hourly measured and computed values. Therefore, it virtually improves the model accuracy in contrast to hour-by-hour evaluation. In the present study, all the statistical indicators are evaluated on hourly computed values. Most of the daily radiation models in literature were validated or rather tested against the same data as they were derived from. Whereas, in this research project daily models are validated against independent data, either originating from a different site or different time period. Statistical approach: Introduction of an innovative comparative index, called Accuracy Score (AS) which scores up the credits of all currently used statistical indicators to provide a common and unique ground of inter-comparison between all the models. The literature was extensively reviewed; however, no single study involved such a comprehensive statistical evaluation. Most of them used the popular MBD and RMSD and some additionally used  $R^2$ . Whereas, this research additionally utilized skewness and kurtosis of error distribution and other comparative indices such as sum of deviation (SD) and t-statistic.

#### 8.2 Summary of Conclusions

Major points of conclusion that can be drawn from the research analyses are as follows:

Qualitative investigation of the proposed parameter as additional descriptors:

- The conventional k-k<sub>t</sub> model for diffuse irradiation estimation produces a wide scatter and therefore, in itself is unsatisfactory.
- In qualitative investigation, it was found that while SF showed a strong bearing, followed closely by CC, m on the other hand was a weak parameter for general estimation of diffuse radiation due to its inherent subjective nature.
- Air mass effect was analysed for clear sky data based on two sites and it was found that for clear skies it has more significance than under all-sky conditions.
- Since, clear sky data is of interest for numerous solar energy projects, investigation was carried out to recognize the best criterion for its identification. It was found that the SF>=0.9 filter provides the best means of selecting clear sky data under the present scope.

#### Hourly modelling of diffuse radiation:

- Generally, models, which included all the parameters, gave highest accuracy scores.
- An optimum level solution for some sites was to propose one of the 'bivariate' model forms that yielded reasonable accuracy and at the same time involved minimal intricacy. For example, for an Indian site (Chennai), both Japanese sites (Fukuoka and Sapporo) and the UK site (Bracknell) the optimum model was found to be a (kt, SF, m) model. Likewise, for Madrid a bivariate model (kt, SF, CC) was the optimum.

*Note:* Since  $k_t$  is an essential parameter in all models, a bivariate model refers to the number of parameters besides  $k_t$ .

- It was also noted that incorporation of SF to the k-kt relationship among all three parameters had the most significant effect on the model's performance for all sites. All the proposed individual site models essentially have SF as one of the additional parameters.
- On a quantitative scale, it was found that the proposed models improved the accuracy of diffuse radiation estimation by more than 50% (based on the Accuracy score system) in most cases over the k-k<sub>t</sub> counterparts.
- These models were found to be site-specific. While proposed hourly models are site-oriented to a large extent, they can have the same parameter combination for a whole region and a tendency for their coefficients to be generalized over locations with similar meteorological and climatic characteristics. It is to be noted that the *model-types* are fairly consistent for neighbouring stations or locations with similar climates. Hence, an overall optimum model was recommended for each of the given countries.

The above generalization is quite an optimistic approach. This needs further verification and possibly slight adjustment of coefficients to suit the requirements of different locations. This is a yet another extensive exercise and was therefore, considered out of the scope of current project. Unlike daily regression models, validation against independent sites is not performed for hourly radiation.

#### Daily modelling of diffuse radiation:

- It was found that a model based on K<sub>t</sub> and CF or a multivariate model such as K<sub>t</sub>, SF and CF performs better than a model based on K<sub>t</sub> alone *within the same data set*. In other words, incorporation of SF and CF in K-K<sub>t</sub> models yields greater accuracy of estimation, particularly if they are used to fill the gaps within the measured data series, i.e. to estimate diffuse irradiance where it was not measured due to station shut down or other such operational issues.
- However, these models were found to be site-specific and in some cases timespecific too, owing to the poorly maintained meteorological standards and systematic inevitable errors associated with such parameters.
- After an exhaustive evaluation, it was established that SF, like in hourly models, is the most influential parameter next to K<sub>t</sub>, in order to produce daily diffuse radiation models with general applicability and increased accuracy.
- It was also observed that SF incorporation improves the estimation particularly at the high end of measured diffuse radiation with no subjugation trend unlike that presented by the other two parameters, K<sub>t</sub> and CF.
- The validation process revealed that additional parameter such as CF is redundant if daily diffuse radiation is to be estimated in *another location*.
- A higher performing model (K<sub>t</sub>, SF in this case) from one site which yields reasonably improved results for other sites within that region was selected. This model could then be reliably proposed as a *regional* model.
- All the proposed regional-models, involving only SF as additional parameter, differ only in degree of correlation of the two parameters.
- If daily diffuse irradiation is to be estimated at a site belonging to a region
  where no such daily model has been developed, it is both wise and reasonable
  to use a well-established K-K<sub>t</sub> model developed elsewhere. However, if a KK<sub>t</sub>, SF model is available in literature for that region, it would not only suffice
  to use that model to estimate diffuse radiation but will give better estimates
  than the locally developed K-K<sub>t</sub> model.
- This section also demonstrated the subjective nature of various statistical tests used within solar radiation modelling. Therefore, one of the conclusions drawn here is that a good research analysis should encompass all the major evaluation methods to establish a criterion of selection for the best model.

#### In a nut-shell:

In this research multivariate solar radiation models involving one or more of the following parameters viz. SF, CC and m, were established. Significant improvements over the typical K-  $K_t$  model were achieved indisputably for all sites (belonging to Asia and Europe) and for both hourly and daily time scales. It is also concluded herein that the effect of sunshine fraction on k-k<sub>t</sub> relationship is general and not restricted to a single site.

#### Comparing the hourly- and daily-based models:

Hourly models have invariably and inevitably large scatter. Since hour-by-hour radiation involves many intricacies, hourly models with all the 4 or at least 3 of the parameters were found to be optimum i.e. significant improvement overweighed the model complexity. With daily models, however, a two-parameter model proved to be optimum. Thus, two important conclusions can be drawn from the above trend:

- The improvement in accuracy with multi-parameterisation decreases with increase in temporal frame. In other words, while a (k<sub>t</sub>, SF, CC/m) model for hourly is preferred, a (K<sub>t</sub>, SF) model is proposed as optimum for daily diffuse estimation.
- 2) Hourly models are inherently site-specific and may lead to inaccurate estimation if used elsewhere. However, the proposed daily model on the other hand can fairly and reliably be used as standard for a region. This is in a way related to the point 1, since *the more parameter-intensive a model is the less likely it is to be generalized*. An obvious reason for this trend is the fact that more measured parameters entail greater uncertainty and those uncertainties are linked to the meteorological measuring standards which vary from not only region to region, but often time to time.

From application point of view, the diffuse radiation models should *ideally* be siteindependent. This is a near-impractical goal due to the fact that diffuse irradiance varies with many factors that are characteristic of a particular site and are difficult to be generalized. Nevertheless, there is always a scope to standardize the models for locations of similar climates, turbidity level, etc.

#### 8.3 Potential Future Work

The avenues for possible future research can be classified as follows: *Improvement in measurement standard* 

Measurement uncertainties are passed on and therefore, add to the modelling uncertainties. Models developed or validated on the basis of existing measured data are limited at best to the prevalent measurement uncertainties. To put it simply, even the best model can only be as accurate as the data it is derived from. High quality radiation measurements should be conducted at least in select places so that models based on more reliable data can be developed.

# Cloud type is necessary for complete assessment of cloudiness and therefore concrete parameterization for diffuse radiation.

The variability in amount and type of cloud has a dominant role on the value of diffuse fraction (Bhattacharya et al, 1996). Cloud changes the diffuse fraction by affecting diffuse and beam radiation in a multiplicity of ways. For example, broken clouds may primarily enhance the beam radiation; scattered clouds on the sky dome may enhance the diffuse irradiance and leave the beam irradiance unaffected (Skartviet et al, 1998). In this research we only took into account traditional cloud cover observation. It would be interesting to investigate the influence of a more robust cloud cover-based parameter that gives information not only on the amount but also another equally significant aspect of cloud i.e. the cloud type. Incorporation of comprehensive cloud information can lead to better model estimates.

### Aerosols are yet another important criterion for diffuse radiation estimation.

Another possible avenue and likely candidate in characterizing diffuse radiation is the aerosol loading often parameterized by turbidity. Turbidity is an important extinction affecting direct and diffuse component of solar radiation under clear skies (Gueymard, 2005). Future studies should explore this parameter and compare it with sunshine fraction and cloud cover. It would be worthwhile to develop the models with turbidity as an additional descriptor; however this exercise can only be carried out for fewer stations as turbidity information is largely limited.

Characterization of diffuse radiation is a challenging task. The phenomenon of scattered radiation or diffuse radiation in the atmosphere is very complex and varied.

Unlike direct radiation which depends only on the extinction property of the atmosphere, diffuse radiation characterization requires knowledge of the details of extinction, like scattering and absorption (Halthore, 1999). More so, numerous factors determining the quantity of diffuse radiation change continuously in time and space (Bhattcharya et al, 1996).

Nevertheless, there is a need for continual efforts towards improving the accuracy of estimation which is an essential qualification for precise and correct design and simulation studies. It would be worthwhile to quote the remark by Myers (2005), "the challenge for solar radiation models in the 21st century is to reduce the uncertainty in measured data, as well as develop more robust models (i.e., fewer input parameters and smaller residuals, under a wider variety of conditions)."

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Note: All the web-links provided herein, were last accessed in March 2006, unless stated otherwise.

# APPENDICES

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# **APPENDIX** A

## **GLOSSARY OF TERMS**

#### A.1 Climatological, Radiation and Energy Terminology

Air mass - the relative path length of the direct solar beam radiance through the atmosphere. When the sun is directly above a sea-level location the path length is defined as air mass 1 (m=1.0). It is not synonymous with solar noon because the sun is usually not directly overhead at solar noon in most seasons and locations. When the angle of the sun from zenith (directly overhead) increases, the air mass increases approximately by the secant of the zenith angle.



**Albedo** - the fraction of solar radiation that is reflected. The solar energy community defines albedo as the fraction of solar radiation that is reflected from the ground, ground cover, and bodies of water on the surface of the earth. Astronomers and meteorologists include reflectance by clouds and air. To reduce confusion, some solar researchers use the term *ground reflectance*.

**Aerosols -** are any small particles (particles ranging from 0.1 to 1+ microns in diameter) that tend to stay in the air, such as smoke, dust, salt, and pollen and follow the motion of an air stream. All suspended particles showing variation in volume,
distribution, size, form and material composition are aerosols. They are either of terrestrial or marine origin.

Atmospheric Turbidity - haziness in the atmosphere due to aerosols such as dust (particles ranging from 0.1 to 1+ microns in diameter). If turbidity is zero, the sky has no dust. A sun photometer is used to measure atmospheric turbidity.

**Azimuth Angle** - the angular displacement of the projection of beam radiation on the horizontal plane from a reference direction (usually North, although some solar scientists measure the solar azimuth angle from due South).

**Circumsolar Radiation** - the amount of solar radiation emanating from a circle, having a radius of between 2.5 and 3.5 degrees, in the sky centred on the sun's disk. The radius depends on the type of instrument being used to measure the direct normal irradiance.

**Clearness Index** (k<sub>t</sub>) - the ratio of monthly average, daily or hourly *global radiation* on a horizontal surface to the monthly average, daily or hourly horizontal *extraterrestrial radiation*. It is employed as normalization tool for global horizontal radiation because k<sub>t</sub> removes the effect of low sun angle and reduces the scale of values to between 0 and 1. It gives the depletion of the incoming global radiation by the atmosphere and, therefore, indicates both the level of availability of solar irradiance at the surface of the earth and the changes in atmospheric conditions. The clearness index is also used to denote sky conditions namely,  $k_t < 0.2$  suggests an overcast sky,  $0.2 < k_t < 0.7$  indicates partly cloudy skies and  $k_t > 0.7$  presents clear sky conditions.

**Cloud Cover** - the fraction of the sky dome covered by clouds. This fraction is typically expressed either as tenths (1/10, ..., 10/10) or eighths (1/8, ..., 8/8). Some researchers refer to this as **cloud amount**, to clarify the distinction from *cloud type*, which is the nature of the cloud cover.

**Cloud Type** - the type of clouds (e.g., altostratus, cumulonimbus) that form each layer of the sky dome.

**Declination** – the angular position of the sun at solar noon (i.e., when the sun is on local meridian) with respect to the plane of the equator, north positive.

**Diffuse Radiation** – the solar radiation received from the sun after its direction has been changed by scattering by the atmosphere. In the absence of atmosphere, there should be almost no diffuse sky radiation. A turbid atmosphere or reflections from clouds produce high values of diffuse radiation. Because it comes from all regions of the sky, it is also referred to as **sky radiation**.

**Direct Normal Irradiance** – also referred to as **beam radiation**, is the amount of solar radiation from the direction of the sun without being scattered by the atmosphere.

**Diffuse ratio**/ **fraction** (k) - the ratio of monthly average, daily or hourly *diffuse radiation* on a horizontal surface to the monthly average, daily or hourly horizontal *global radiation*. It is used to denote the depletion of the diffuse component due to the concentration of the atmospheric aerosols and the presence of clouds. Along with  $k_t$ , it has been used to establish sky conditions at various places. Diffuse ratio is also referred to as **cloudiness index** by some solar researchers.

**Extraterrestrial Radiation** - also known as "top-of-atmosphere" (TOA) irradiance, is the amount of global horizontal radiation that a location on Earth would receive if there were no atmosphere or clouds (i.e., in outer space). It is used as the reference value against which actual solar energy measurements are compared.

**Fuel Cells** – are electrochemical devices that convert the fuel's chemical energy into electrical energy directly, without combustion, with high electrical efficiency and low pollutant emissions. Fuels cells represent a new type of power generation technology that offers modularity, efficient operation across a range of load conditions, and opportunities for integration into co-generation systems.

**Global Horizontal Radiation** - total solar radiation; the sum of direct, diffuse and ground-reflected radiation. However, because ground reflected radiation is usually insignificant compared to direct and diffuse, for all practical purposes global radiation is said to be the sum of direct and diffuse radiation only.

**Greenhouse Effect** - the warming of the Earth by the atmosphere because of water vapour and certain gases, which absorb and emit infrared radiation or heat. Thus, the high-energy photons such as light and ultraviolet radiation are passed through the atmosphere to the Earth, which tends to absorb them and emit lower-energy photons which are then captured in the atmosphere and partially sent back to Earth. As the presence of infrared absorbers rises in the atmosphere, the more solar energy is retained as heat in the atmosphere and on the surface of the Earth. Because glass also passes light and tends to absorb and reflect heat, this effect is compared to that of a greenhouse.

**Greenhouse Gas Emissions (GHG)** – gases, like, carbon dioxide, methane and halocarbons e.g. CFCs, HFCs and PFCs that are responsible to produce *greenhouse effect*.

**Hour Angle** – also known as solar hour angle, is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15 ° per hour, morning negative, afternoon positive.

**Humidity** - the weight of water per unit weight of moisture free gas. Relative humidity (RH) is the percentage ratio of the partial pressure of the vapour to the vapour pressure of water at the existing temperature.

**Hybrid Power Systems** – are based on the principle of 'complimentary' where two or more types of energy systems compliment each other to give a reliable and costeffective energy service to the end-user. Typically, hybrid systems can be formed between a renewable energy based and fossil fuel based generator or between two renewable energy based generators. PV combined with diesel or fuel cell generation, PV combined with wind generation, or wind combined with diesel generation, are some examples for hybrid systems. **Illuminance** - solar radiation in the visible region of the solar spectrum to which the human eye responds.

**Irradiance** – the rate at which radiant energy is incident on a surface, per unit area of surface.

**Irradiation** – the incident energy per unit area on a surface, found by integration over a specified time, usually an hour or a day. **Insolation** is a term applying specifically to solar energy irradiation. However, since it is so much similar to word 'insulation', its use is almost obscure now.

**Latitude** - the angular distance from the equator to the pole. The equator is 0°, the North Pole is 90° North, and the South Pole is 90° South.

**Local Apparent Time** - the time of day based strictly on the *longitude* of the locality and not on "blocky" time zones. For example, when it is 12:00 Pacific Standard Time (USA) (assumed to be 120° West Longitude), it is 11:51 Local Apparent Time in Seattle, Washington (USA), at 122° 18' West Longitude.

**Longitude** - the East-West angular distance of a locality from the Prime Meridian. The Prime Meridian is the location of the Greenwich Observatory in England and all points North and South of it.

**Longwave Radiation - infrared radiation**, radiation with wavelengths greater than those of the visible light (at about 8000 Angstroms or 800 nanometres (nm)) but shorter than those of microwaves (at about 1,000,000 Angstroms or 800,000 nm). Longwave radiation is associated with heat energy.

**Model** - a way to represent a system for the purposes of reproducing, simplifying, analyzing, or understanding it. The term referred here is the *computer* model, which uses global radiation as input and calculates the corresponding set of diffuse radiation.

**Optical Depth** - (technically known as the **relative aerosol optical depth**) usually considered to be synonymous with the *airmass*, is the approximate number of aerosols in a path through the atmosphere relative to the standard number of aerosols in a vertical path through a clean, dry atmosphere at sea level.

**Orientation** - the direction that a solar energy collector faces. The two components of orientation are the *tilt angle* and the *azimuth angle*.

**Photovoltaic** Array - a *photovoltaic module* or set of modules used for converting solar radiation to energy.

**Photovoltaic Module** - a unit comprising of several *photovoltaic cells* that is the principal unit of photovoltaic array. A photovoltaic module's size is on the order of 1  $m^2$ , although its size is governed by convenience and application.

**Photovoltaic/Solar Cell** - a single semi-conducting element of small size (for example, 1 cm<sup>2</sup>) that absorbs light or other bands of the electromagnetic spectrum and emits electricity.

**Precipitable Water** - the amount of water in a vertical column of atmosphere. The unit of measure is typically the depth to which the water would fill the vertical column if it were condensed to a liquid. For example, 6 cm of precipitable water (in the absence of clouds) indicates a very moist atmosphere. Precipitable water is often used as a synonym for water vapour.

**Renewable Energy** - there is no formal definition for this term. Typical usage defines it as any energy source that is replenished at least as fast as it is used. Standard examples are solar, wind, hydroelectric, and biomass products.

**Shading Disk** - a disk mounted on a solar tracking device, which blocks the beam irradiance, so as to allow a *pyranometer* to measure only the *diffuse sky radiation*.

**Shadow Band** - a metal strip which blocks the direct normal radiation so as to allow a pyranometer to measure only the *diffuse sky radiation*.

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**Shortwave Radiation** - the principal portion of the solar spectrum that spans from approximately 300 nanometers (nm) to 4000 nm in the electromagnetic spectrum.

**Sky Dome** - refers to the appearance of the entire sky, from horizon to zenith in all directions.

**Solar Altitude** – the angle between the horizontal and the line to the sun, i.e., the complement of the *zenith angle*.

**Solar Constant** - although not strictly constant, this number is the amount of solar power flux that passes through the mean Earth orbit. In other words, it is the sun's energy, per unit time, received on a unit area of surface perpendicular to the direction of propagation of the radiation, at mean earth-sun distance, outside of the atmosphere. The currently accepted value is  $1367 \text{ W/m}^2$  with an uncertainty of the order of 1%. Note that Earth-based instruments record lower values of solar power flux because of atmospheric attenuation.

Solar Radiation - Solar radiation refers to the energy emanating from the sun.

**Solar Time** – also referred to as **apparent solar time**, is the time based on the apparent angular motion of the sun across the sky, with solar noon the time the sun crosses the meridian of the observer. Solar time does not coincide with local clock time. However, the former is to be used in all solar geometry calculations.

**Sunshine Duration** - the length of time for which the sun casts an obvious shadow or when a *Campbell-Stokes sunshine recorder* is recording.

**Sunshine Fraction -** the ratio of measured bright sunshine to the total possible bright sunshine in a given time period such as an hour or a day. For instance, daily sunshine fraction is obtained by dividing the total recorded sunshine duration in a day by the day length.

**Sun Position** - the location of the sun in the sky, expressed in terms of azimuth angle and zenith angle.

**Tilt/ Tilt Angle -** the angle the collector or any other surface makes from the horizontal.

**Turbidity** - a measure of the opacity of the atmosphere. A perfectly clear sky has a turbidity of 0, and a perfectly opaque sky has a turbidity of 1. Turbidity is affected by air molecules and aerosols.

**Zenith Angle** - the angle between the direction of interest (of the sun, for example) and the zenith (directly overhead).

#### A.2 Statistical Terminology

Average and Weighted Average - the simple arithmetic average is expressed as the sum of a series of values divided by the total number of values in the series. This type of average is fine as long as all values have equal relevance. A weighted average is a special type of average that takes into account the proportional relevance of each component, rather than treating each component equally.

**Correlation** – is the degree of relationship between variables. It seeks to determine how well a linear or other model describes the relationship between variables.

**Histogram** – is a type of plot that illustrates the distribution of a variable within a specified range.

**Regression** – is a mathematical technique of fitting linear or non-linear models between a dependent and a set of independent variables.

**Scatter Plot** - a graph that uses a coordinate plane to show the relationship between two variables. Each point on the plot represents a unique set of values of the two variables.

**Standard Deviation** ( $\sigma$ ) - is by far the most important of the measures of dispersion, i.e. the degree to which numerical data tend to spread about an average value. It is defined as the root mean square of the deviations from the mean.

Please note that definitions of terms such as **coefficient of determination**, **kurtosis**, **mean bias error**, **root mean square error** and **skewness** are provided in the main text in the relevant chapter and therefore, not re-represented herein.

## APPENDIX B

# UK METEOROLOGICAL OFFICE SOLAR RADIATION STATIONS

Table C1: List of UK stations (84) measuring global radiation, out of which only 9 measure diffuse radiation (Source: Muneer, 2004)

SUNDERLAND	SUTTON BONINGTON	RYEMEADS
WEST FREUGH	SHAWBURY	FILTON
DUNDRENNAN	ABERDARON	LONDON*
DURHAM	COLTISHALL	LONG ASHT ON
ALDERGROVE*	LAKE VYRNWY	ST.ATHAN
SHAP	WITTERING	BRACKNELL MODLE*
HILLSBOROUGH	EDGBASTON	MANSTON
LECONFIELD	WINTERBOURNE	HERNE BAY
ST ANGELO	GOGERDDAN	WISLEY
LEEDS	COVENTRY	KENLEY
LEEMING	MONKS WOOD	EAST MALLING
BRAMHAM	CHURCH LAWFORD	ODIHAM
CAWOOD	BROOMS BARN	CHARLWOOD
CHURCH FENT ON	SHOBDON	LISCOMBE
PRESTON	BEDFORD	HERST MONCEUX
MANCHESTER	ABERPORTH*	THORNEY ISLAND
VALLEY	WATTISHAM	NORTH WYKE
WADDINGTON	WOBURN	EFFORD
HARWARDEN	LITTLE RISSINGTON	BODMIN
NOTTINGHAM	ROTHAMSTED	CAMBORNE*
HOLBEACH	HODDESDON	JERSEY++
	SUNDERLAND WEST FREUGH DUNDRENNAN DURHAM ALDERGROVE* SHAP HILLSBOROUGH LECONFIELD ST ANGELO LEEDS LEEMING BRAMHAM CAWOOD CHURCH FENTON PRESTON MANCHEST ER VALLEY WADDINGTON HARWARDEN NOTT INGHAM HOLBEACH	SUNDERLANDSUTTON BONINGTONWEST FREUGHSHAWBURYDUNDRENNANABERDARONDURHAMCOLT ISHALLALDERGROVE*LAKE VYRNWYSHAPWITTERINGHILLSBOROUGHEDGBAST ONLECONFIELDWINT ERBOURNEST ANGELOGOGERDDANLEEDSCOVENTRYLEEMINGMONKS WOODBRAMHAMCHURCH LAWFORDCAWOODBROOMS BARNCHURCH FENTONSHOBDONPRESTONBEDFORDMANCHESTERABERP ORTH*VALLEYWATTISHAMWADDINGTONKOTHAMST EDHOLBEACHHODDESDON

\* These stations additionally record hourly sky-diffuse irradiation

+ Only daily integrated global irradiation recorded

++ Only daily integrated global and sky-diffuse irradiation recorded

## **APPENDIX C**

## LIST OF PUBLICATIONS

#### **Journal Articles**

1. Muneer, T, Asif, M and Munawwar, S. 2005. Sustainable production of solar electricity with particular reference to the Indian economy. Renewable and Sustainable Energy Reviews, 9, pp.444–473.

2. Muneer, T, Grassie, T, Munawwar, S and Lior, N. 2005. Editorial introduction. Energy, 30, pp.1499–1500.

3. Muneer, T, Younes, S and Munawwar, S. Discourses on solar radiation modeling. Renewable Energy & Sustainable Energy reviews (article in press, available online).

4. Muneer, T, and Munawwar, S. 2006. Potential for improvement in estimation of solar diffuse irradiance. Energy Conversion Management, 47 (1), pp. 68-86.

5. Muneer, T, and Munawwar, S. 2006. Improved accuracy models for hourly diffuse solar radiation. Journal of Solar Energy Engineering, 128, pp. 104-117.

### **Conference** Articles

1. Muneer, T, and Munawwar, S and Younes, S. May 2005. Exploration of meteorological parameters based solar radiation models. SOLARIS-05 conference proceedings, Athens (Greece).

2. Munawwar, S and Muneer, T. August 2005. Improvement in estimation of hourly solar diffuse irradiance. ISES 2005 Solar World Congress proceedings, Orlando (USA).