B. RESOURCE ASSESSMENT

THE ASSESSMENT OF SOLAR ENERGY IN AN AFRICAN CONTEXT

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INTRODUCTION

A lot of lip service has been paid to the value of solar energy. Rather less effort has been devoted to the factual assessment of the actual value of solar energy in different territories, especially in the tropical world. The problem is of course difficult because of the sparseness of supporting scientific data in tropical countries. The value of solar energy can only be established if three pieces of information can be assembled and interrelated:

1. the amount of solar energy available per unit area on the differently orientated surfaces used to capture that energy;

2. the efficiency with which that energy can be harnessed in the different collection systems that can be used;

3. the capital costs of the collection system amortised on an annual basis together with the annual running and maintenance costs of the system.

The first factor is of course a variable quantity, so it is essential to explore the variability of the resource from month to month and from year to year. By dividing the annual costs by the annual yield, one can establish the average unit price of the energy produced. This price may then be compared with the price of the various fuels solar energy might displace. The value of the fuels that might be displaced varies considerably from place to place in a territory, as does the availability of the solar energy.

The costs of energy are often greater in rural areas because of the high costs of transportation of fuels, especially in regions with poor transportation infrastructures. A key problem in many parts of Africa arises from the overuse of the limited fuelwood resources to provide local energy for cooking and heating, which does so much to destroy the rural ecosystem (1). As energy is a centrally managed resource, there is a great tendency for governments to assume that energy systems are simply urban systems, so a systematic neglect of rural solutions develops. Rural electricity is very expensive, because the high distribution costs over big distances rule out grid systems, and diesel generators are used instead, producing high unit charges. If the adverse environmental impacts of excessive fuelwood consumption can be partially countered by solar energy systems, then the value of the associated environmental benefits must be thrown into the economic assessment on the positive side of the balance sheet.

Figure 1 attempts to illustrate the relative balance of these economic factors in areas of high insolation and low insolation competing in situations with different basic fuel costs. The competitiveness of solar energy systems clearly varies widely. Africa of course has many areas of high insolation combined with many areas of high fuel cost. The basic problem is to identify those ares showing the greatest potential, and to proceed to practical politics for achieving significant development on a sound economic basis.

The purpose of this paper is to discuss only the first of the above factors, namely quantifying the solar energy resource.

DATA REQUIREMENTS FOR SOLAR RADIATION APPLICATIONS

The data requirements for assessing the performance of solar systems obviously depend on the application. Quite sophisticated data requirements exist for complex installations like solar thermal power stations. Much simpler data will suffice for simple practical applications, like sun drying of crops and fish, water heating, and passive solar heating of buildings.

There is an important distinction to be made between focusing systems and non focusing systems. Focusing systems can only make use of the direct beam, while non focusing systems can also use the diffuse energy as well. The proportion of the solar energy which is diffuse will vary from climate to climate. However, in general, the proportion of diffuse radiation is higher than most people realise, especially in equatorial and other climates, where there is a lot of cloud.

There is another reason why knowledge of diffuse radiation is important. It is very difficult to estimate slope irradiation if the proportion of diffuse radiation in the horizontal surface radiation is not accurately known.

The variability of the energy supply also needs study. Assessments have to be made of the degree to which firm power can be supplied. The day to day variability of the supply can be compensated to some degree by appropriate storage policies for alternative energy. However to make such assessments a statistical foundation is essential. It is not enough to provide simply mean values.

The key problem is how to acquire such dat in practice at an economic cost. A review of the whole range of problems encountered was given by the author to the World Solar Congress in Perth **(2)**. Figure 2 extracted from that paper sets out the full range of studies that may be carried out. Any program however has to emerge by stages. In Africa it would appear that the immediate need is to make progress in the top half of the diagram, because work on slope irradiation, important for practical applications, can only proceed with full effectiveness from proper knowledge of the horizontal surface radiation climate.

SPECIAL PROBLEMS OF AFRICA

There are obviously a lot of special difficulties to be faced in the African region. For a start there is the shear scale of Africa, which, given the levels of wealth available, makes it difficult to achieve adequate instrumentation over the spatial areas involved. Further difficulties often arise due to the inadequate and often unreliable electricity supplies which may make it difficult to achieve continuous records using data logging equipment. There are added problems associated with high humidities, and, in the maritime areas, salt spray, which can seriously damage instruments. Instruments suitable for developed countries may prove unsatisfactory in remote areas. It would seem that a greater collaborative effort ought to be devoted to achieving more appropriate instrumentation for remote tropical areas. Such instrumentation might usefully be powered by solar cell systems to improve system reliability in remote areas beset with electricity supply problems.

Another important practical difficulty is achieving adequate standards of calibration. Radiation measuring instruments are exposed throughout the year to strong sunlight, and often, at least in some seasons, to heavy rainfall with associated high humidities as well. In drier areas problems may also occur due to dust abrasion. The present standard technique of calibration by inter comparison against standard reference instruments produces acute difficulties in remote areas, and it is difficult and expensive to carry out such intercomparisons due to the large amounts of time required and the high cost of travel. More scientific effort needs to be given to techniques of calibration that are more self contained within specific site, but at the same time scientifically accurate. Unfortunately, because of these difficulties, many solar radiation records are relatively unreliable, though some rehabilitation of unreliably calibrated data can sometimes be achieved by studying noon irradiation values for days when cloudless conditions existed **(3)**.

The archiving of the data within suitable computational structures, with adequate quality control also needs attention, if effective use is to be made of the data in practical applications. The rapidly falling costs of computational systems will offer important benefits to all developing countries in making proper data processing so much more effective.

The basic fact is the best use has to be made of what is actually available, and it would be wrong to hold back programs of applications until such time, as a reliable data base is available. Attention is particularly drawn to the key W.M.O. publications in this area **(4) (5)**.

THE ATMOSPHERIC CLARITY IN AFRICA

Assessing the clarity of the atmosphere is very important in applied solar radiation studies. The atmosphere of many parts of Africa often contains large amounts of dust, especially in the dry season, and particularly so in the areas fringing on the vast deserts. The problems of rural development in these areas have tended to worsen the situation by removal of vegetation by overgrazing and fuel wood removal, so one must not make the assumption the air of Africa is necessarily very clear, simply because there is a lot of sunshine. High humidities also tend to produce skies in which a lot of scattering takes place. These effects can be assessed to some extent by looking carefully at the colour of the sky, and also examining the nature of the extinction of the sun's beam towards sunset. If there is a heavy dust burden, the sun's beam may be extinguished when the sun is still several degrees above the horizon, fading gradually through red until the image of the disc eventually disappears in the dusty sky. The colour of the sky lacks a full blueness throughout the day.

A very widely used measure of atmospheric clarity is the Linke Turbidity Factory T_L. The beam irradiance normal to the beam is determined by the following expression:

$$I_c = I_0 * K_d * \exp(-D_r * m * T_L)$$

where I_c = irradiance normal to the beam, watts per square metre
I_0 = the solar constant, 1367 W/m²
K_d = the correction to mean solar distance
D_r = the Rayleigh optical depth
m = the air mass corrected to station height.

The higher the value of T_L, the greater the attentuation. The lower the sun, the greater the air mass, so the low sun is considerably attenuated if the value of T_L is high.

The key W.M.O. publication on solar radiation applications **(4)** in fact suggests a very useful way for estimating the clarity of the atmosphere from subjective assessments of sky colour. In the absence of measurements, this provides a very useful methodology for people closely associated with a specific area. It is less suitable for outsiders, as knowledge of typical sky colour is established by residence and by observation.

THE IMPORTANCE OF DIFFUSE RADIATION MEASUREMENTS

The estimation of slope irradiation can only be carried out if diffuse radiation data can be obtained, either by measurement or by estimation. The measurement of diffuse radiation may be done either by using a shading disc which is driven to follow the sun's path. The alternative, which eliminates the need for continuous mechanical movement is the shading band. The shading band position has to be adjusted periodically to allow for seasonal changes in the sun's position relative to the equator. The shading band however obscures some of the sky and corrections have to be applied. The simplest assumption to adopt in making this correction is that the brightness of the sky is uniform. This assumption produces relatively large errors. Considerable effort had to be given in the European Community program to finding better methods of correction. The correction depends on the relative clarity of the sky. It also depends on the type of instrument. A summary of the CEC work may be found in a recent CEC publication **(6)**. It is desirable that scientific studies of such correctoins should be carried out at suitable scientific centres in Africa to check whether the same corrections are applicable as in Europe.

SIMPLE METHODS FOR ESTIMATING DIFFUSE RADIATION

It is possible to estimate diffuse radiation from both global radiation or from sunshine. The dimensionless equations take either the form:

$$D/G = c+d^*(G/Go)$$

or

$$D/G = c'+d'(S/So)$$

where D/G is the ratio daily diffuse/daily global horizontal surface radiation
G/Go is the ratio of the daily global horizontal surface irradiation/global irradiation outside the atmosphere
S/So is the relative daily duration of bright sunshine
c, c', d and d' are linear regression coefficients.

The author studied the data from several African stations in 1960 **(7)**. The values of the constants c and d were found to vary with site, Table 1. This paper has just been independently reappraised against results of many other more recent formula and appears still to be a very reliable method at the monthly mean daily level **(8) (9)**.

ADDITIONAL SOURCES OF DATA RELATING TO SOLAR RADIATION

While very limited records may be available of actual radiation measurements, much more information exists on other relevant variables like sunshine and cloudiness. Today sophisticated information about cloudiness is available from satellites. Considerable work has already been carried out on this in many countries, for example in the Commission of the European Communities' program on Solar Radiation Data, Project F, Action 4.3. A book dealing with European work in this field is about to be published **(10)**. European work is continuing in this area with an emphasis on the Northern half of Africa. The few ground stations are very important in providing reference points of calibration to improve the reliability of a difficult technique. Difficulties in inadequate spatial coverage exist in Europe as well, and considerable expertise has been built up in developing the two European Solar Radiation Atlases, one for horizontal surfaces, the other for inclined surfaces **(11)**, **(12)**. A summary of the achievements of the first two four-year CEC programs may be found in reference **(13)**. The experience built up in this program in Europe is clearly applicable to other areas of the world, and steps have already been taken through the initiatives of the Commonwealth Science Council to organise programs evolving from this European experience in two major regions, Africa and the Caribbean.

THE EUROPEAN SOLAR RADIATION ATLASES

The production of these Atlases took considerable time. The broad decision to process essentially daily data was the basis of the horizontal surface Atlas. The raw data had to be reduced to a common pyrheliometric scale. All data was first converted to the World Radation Reference scale (WRR). Next a quality control process was applied to eliminate obviously unsuitable data. Problems of a systematic nature were found with some of the data for example, the Italian data measured with Robitzsch pyranographs were not in line with data from adjacent countries using more reliable instruments. Adjustments which varied from season to season had to be applied. This instrument, which is robust and independent of power supplies, is known to overrecord under conditions of high irradiation.

Tables were then prepared, on a month by month basis, of global mean irradiation, monthly mean maximum global irradiation, the extraterrestrial daily radiation averaged over the month, monthly mean daily sunshine, monthly mean astronomical daylength. Two dimensionless ratios were also included, G/Go and S/So.

The next stage was to systematically study the relationship on month by month basis of daily values of G/Go and S/So using the standard Angstrom linear regression formula:

$$G/Go = \quad a+b(S/So)$$

where a and b are regression coefficients, which depend on atmospheric clarity.

This process provided, for each site where observed data was available, values of a and b. These values were found to link fairly closely with the clarity of the atmosphere at different sites. Important new methods for estimating the clarity of the atmosphere from the sum of the Angstrom regression coefficients (a and b) have been evolved **(14)**. The values were subsequently used as an important part of the methodology for developing the inclined surface Atlas.

The next stage in the mapping process was to use the values of a and b in conjunction with sunshine data for a number of additional sites to estimate, from the sunshine data, values of the global irradiation again on a month by month basis. Values for several hundred sites were produced, and used to supplement the observed radiation data in the production of the horizontal surface irradiation maps.

Diagrams showing the annual mean course of global radiation for 124 stations for which observed data existed were extracted. Finally frequency distributions of global radiation for 49 stations were compiled. These give the mean monthly cumulative frequency distribution of daily irradiation above given thresholds, and also the mean monthly maximum number of consecutive days with daily irradiation above given thresholds.

This Atlas provides a model which should be of considerable value to others attempting to achieve similar goals in other parts of the world, like Africa. Inter country collaboration proved very important, as radiation patterns are not related to geographic boundaries. The CEC Atlas contains data for a number of countries in the Soviet block, and successfully crosses the barriers too easily set by accepted contemporary politics. The same crossing of barriers will be necessary to produce appropriate maps of solar radiation in Africa.

DEVELOPING A METHODOLOGY FOR INCLINED SURFACE RADIATION PREDICTIONS

A substantial research effort had to go into the development of the European Solar Radiation Atlas for Inclined Surfaces. There are few centres where measured inclined surface radiation data are available. Furthermore, if such measurements are made, the results are limited to surfaces of specific tilt and orientation. Solar designers require data for any slope and orientation they may wish to specify. Considerable difficulties therefore stood in the way of the development of an inclined surface radiation Atlas for Europe.

Any method evolved had to accept the limitations of the input data base. This input data base was the data in the CEC European Solar Radiation Atlas Vol 1.

The input data used to develop by numerical modelling the inclined surface Atlas were:

1. Monthly mean daily global radiation on a horizontal surface
2. Monthly mean values of the daily duration of bright sunshine
3. Monthly mean values of the monthly maximum values of daily global radiation on the horizontal surface
4. Monthly mean maximum duration of bright sunshine
5. Values of the monthly Angstrom regression coefficients a and b, taken out at the daily level.

Observed monthly mean daily data were available for 102 sites in Europe. In order to perform the slope calculations, a method had first to be evolved to convert the daily horizontal surface data to the hourly level, and the diffuse radiation had to be separated from the beam, also at the hourly level. Then a model had to be developed to estimate slope irradiances from horizontal surface values. The limited number of observed inclined data sets data available were used to check the accuracy of the modelling process.

The problem of the non uniformity of the radiance of the sky had to be addressed in the slope modelling process. A clear sky model was developed first and then an overcast sky model. The monthly mean slope model was derived from them, using the relative duration of bright sunshine as the basis for splitting the sky irradiation contribution into a clear sky and grey sky component in the computational process. The actual relationships are quite complex, but the steps involved are described in full detail in the specially published CEC book **(15).**

CLEAR SKY RADIANCE MODEL

A turbidity sensitive radiance model was evolved, which described the main features of the brightness pattern of the clear sky, the aureole around the sun, the ring brightening effect around the horizon, the point of low radiance at 90° to the solar position on the solar azimuth. Once a radiance model has been established, by numerical integration it is possible to determine the relationships between slope diffuse irradiance and horizontal surface diffuse irradiance for any slope and orientation **(16).**

OVERCAST DAY RADIANCE AND RADIATION MODEL

The work on this part of the project was carried out by Professor Krochmann and his colleagues in Berlin **(17).** The Moon and Spencer formulation, long standard in daylighting studies for estimating mean overcast sky luminance distributions, was verified as also appropriate for overcast sky radiance distribution prediction. Statistical relationships between horizontal surface overcast day irradiation and solar altitude were established. Once again, making suitable allowances for ground reflected energy, a complete solution could be obtained. There appears to be no reason why the Moon and Spencer overcast day formula should not hold in the African continent. However, it is likely, because of the different types of cloud associated with overcast days in Africa, especially in the Equatorial region, that the European overcast day radiation formula may need modification.

MONTHLY MEAN HOURLY SLOPE IRRADIATION MODEL

The hourly slope irradiation model has three components, the beam, the sky diffuse and the ground reflected diffuse. The first component is easily determined by simple trigonometry from the horizontal surface beam values. Estimation of the ground reflected component is based on the global horizontal surface irradiation. The key decision is the choice of ground albedo. In Europe a value of 0.20 was adopted as standard. However, in Africa, the strong seasonality of rainfall has to be considered, and the ground albedo in drier areas could be substantially higher for a significant part of the year.

The modelling difficulties are centred on the diffuse radiation estimates for slopes. In preparing the CEC Inclined Surface Radiation Atlas, it was assumed that the diffuse sky contribution could be split into two parts, by using the relative sunshine duration. The blue part was assumed to be proportional to the product of the 4° relative sunshine duration and the clear sky value. This part was converted to the slope values using the clear sky model. The clear sky horizontal blue component was subtracted from the hourly horizontal diffuse to give the overcast/partially cloudy sky grey component. This was converted to the slope value using the Moon and Spencer radiance formula. The sum of the two components is the mean sky component on the slope. It was assumed there were no directional effects for the overcast sky contribution, but further studies are showing that this assumption is not entirely satisfactory **(18) (19).**

THE EUROPEAN SOLAR RADIATION ATLAS VOL. II INCLINED SURFACES

The final production of the Atlas itself was a team effort. Inclined surface radiation tables were first prepared in the Department of Buildng Science, University of Sheffield for 102 sites in Europe. These tables give monthly mean values of daily global radiation and diffuse radiation on a range of inclined planes. The tables, which are published in the Atlas, also give the estimated clear day daily global and diffuse radiation on the same slopes. The input data is included in the Tables and also the normalisation factors used to match the theoretical horizontal values to the observed values. These Tables were then used by R DOgniaux and G Preuveneers (Institut Royal Meteorologique de Belgique), together with associated information, like the Horizontal Surface maps in Volume I, to draw monthly maps for the European region covered by the tables drawing isolines of inclined surface irradation. The Atlas also provides information about the radiation transmitted through single and double vertical clear glazing for the 102 sites. Data on solar radiation on overcast days is also provided for a range of slopes. This was assumed to be independent of orientation. A brief explanatory text is provided at the beginning. The detailed computational methodology however is not provided in the Atlas itself, which is primarily a source of data.

ASSOCIATED BOOK AND SCIENTIFIC COMPUTING PROGRAMS

The full scientific studies together with all the detailed computational procedures are being published in book form by the CEC. The book also contains additional prediction procedures for daylighting studies. It also enables radiance studies of the overcast, clear and monthly mean skies to be carried out. A manual method for computing hourly solar radiation using the CEC Atlas procedure is provided. The Department of Building Science in the University of Sheffield has developed a series of colloquial programs for systematically carrying out the computations. This contains an input base for 101 European sites. This makes it a simple process to carry out predictions for any site in the data base for any slope and orientation. Facilities for interposing one or two sheets of glass of any required normal incidence transmittance are included. These allow all the directional characteristics of glass on solar radiation transmission to be assessed.

An alternative version of the program suitable for African conditions has been developed. This uses the WMO technique described in reference 4 to estimate the turbidity. A sample output for Bulawayo is attached as Table 3 showing the estimated slope irradiance on an equator facing surface.

STATISTICAL STUDIES OF THE DISTRIBUTION OF SOLAR RADIATION

Another practical requirement for solar energy application is knowledge of the statistical distributions of solar energy in different months of the year. Liu and Jordan developed a simple but widely adopted method that enables estimates of the statistical distribution of daily global radiation to be estimated from the monthly mean values of the atmospheric transmittance **(20)**. The method is however based on American observations. The author has studied the validity of the US method for the UK and found important differences **(21)**. He has been able to show that better predictions can result if proper attention is paid to the clarity of the atmosphere using the sum of the Angstrom (a+b) as a simple measure of turbidity. He has also been able to show how reasonably accurate statistical distributions for sloping surfaces ean be derived very simply, using the inclined surface European Solar Radiation Atlas tables as inputs. There is no space to discuss these issues further here, but clearly study of the statistical distributions of daily radiation data in different parts of Africa merits considerable further study.

ADAPTING THE METHODS TO AFRICA

By extensive and positive collaborative effort involving many different groups of scientists from different countries in the European Community, an entirely new type of Atlas has been successfully evolved. The scientific procedures involved have been fully documentd and a start has been made on making more widely available the detailed computational procedures using the techniques of modern information technology.

The program of the Commonwealth Science Council for solar radiation data studies in Africa is essentially trying to build on the experience of the European project described in outline above. It is clear a two stage program is required. The development of the work on horizontal surfaces has to come first, because the estimation of inclined surface radiation is dependent on the availability of horizontal surface data on which to base the slope estimates. Detailed slope studies at appropriate centres can follow. There should be many benefits from such a program of collaboration. Reaching an understanding of the most appropriate physical parameters to adopt for variables like the Linke Turbidity Factor should emerge. A better understanding should be reached concerning the diffuse radiation climate of Africa. There should be improved knowledge of the statistics of solar radiation, with improved formulae for making estimates in the absence of detailed measurements. This should lay the foundation for more reliable assessments of the economics of solar energy applications. It should also provide designers with the information they really need.

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