DEVELOPMENT AND UTILIZATION OF SOLAR ENERGY IN SAUDI ARABIA — REVIEW

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الخلاصة :

أدّى ازدياد النمو السكّاني في العالم، وسرعة استهلاك مخزون الوقود الاحفوري وكذلك ازدياد الوعي بالتأثير على البيئة أنْ يفكر العلماء ببدائل أخرى للطاقة تكون أكثر أمنا على الأرض. وقامت المملكة خلال العقدين الماضيين بتطوير العديد من المشاريع المتعلقة باستخدام الطاقة المتجددة. وتهدف هذه الدراسة إلى مراجعة المصادر المتاحة المتعلقه بتطوير واستخدام الطاقة الشمسية بالمملكة العربية السعودية. ووجدنا أن هناك مستقبلا للمزيد من العمل في مجال تطوير الأجهزة التي تعمل بالطاقة الشمسية، ومنها على سبيل التمثيل لا الحصر: الفرن الشمسي، وسخانات المياه بالطاقة الشمسية، وتجفيف المنتجات الزراعية، والإضاءة الشمسية، والتبريد الشمسي، والاتصالات الشمسية .

ABSTRACT

The growing population of the world, the fast depleting reserves of fossil fuels, and the awareness of environmental impact have lead the researchers to think of alternate sources of energy for a safer life on this earth. Like other industrialized and developing countries, the Kingdom of Saudi Arabia during the last two decades has undertaken many projects related to the development of renewable sources of energy. The objective of this study is to review the available literature related to the development and utilization of solar energy in the Kingdom of Saudi Arabia. The present review finds a potential for more work in the area of development of solar based devices like solar cookers, solar water heaters, solar drying of agricultural and other products, solar lighting, solar refrigeration, and solar communication to name a few.

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1. INTRODUCTION

The Kingdom of Saudi Arabia lies between latitudes 31°N and 17.5°N and longitudes 50°E and 36.6°E. The land elevation varies between 0 m and 2 600 m above the mean sea level. Complex terrain is found in the southwest region of the Kingdom. The east and the west coasts of the Kingdom are located on the Arabian Gulf and Red Sea, respectively. Two main seasons, winter and summer, are observed during the year. The daily average bright sunshine in the Kingdom is 8.89 hours and average global solar radiation on horizontal surfaces is 5 591 Whm^{-2}. These averages are based on the data collected at 41 solar radiation stations over a time period of approximately 10 years. The geographical locations of these solar radiation stations are shown in Figure 1. These stations have been under the supervision of the Department of Water Resources Development and the Ministry of Agriculture and Water of Saudi Arabia since 1970 (see Saudi Arabia Solar Radiation Atlas, hereafter SASRA [1], for more details).

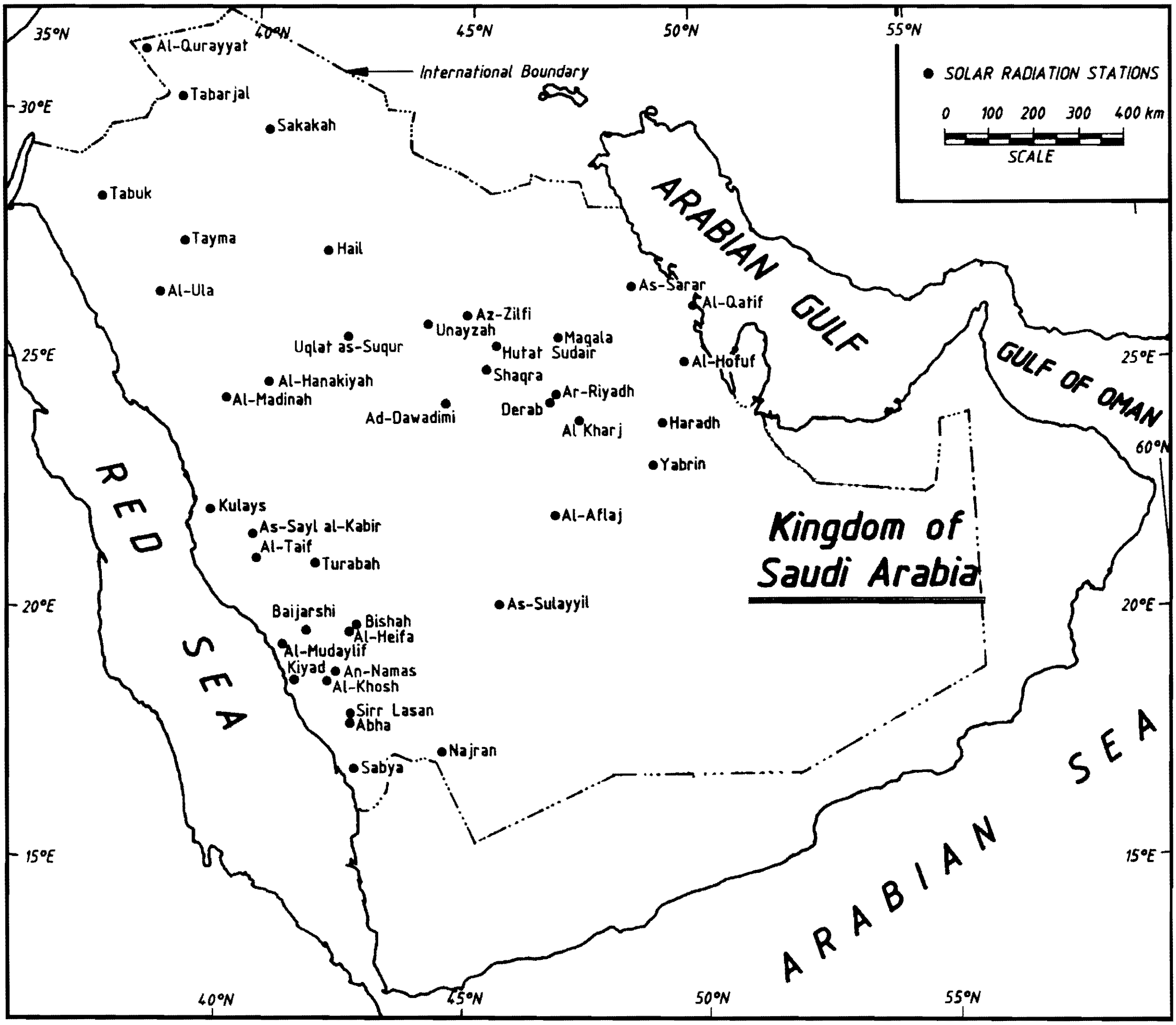

Figure 1. Map Showing the Locations of the Solar Radiation Stations in Saudi Arabia

The growing population on this earth and the fast depleting reserves of fossil fuels have led researchers in the fields of engineering, hydrology, meteorology, economy, and industry, and even politicians, to pursue the development and use of renewable energy resources like solar energy, wind power, biomass, and thermochemical recovery of energy. According to Winter [2], the population on this planet increases by about two million people every year. There were 5.5 billion people in 1992 and more than 6 billion are expected by 2000. Winter [2] also reported from Sadiq [3] that 60% of today's population lives in cities, and based on migration trends, the cities of the future will hold 80% of the world's population. Consequently, the energy demand of such a large number of inhabitants, the size of the cities, influx of supplies, and outpouring of wastes produced must be increased in proportion.

The population in Saudi Arabia faces no threat of such an increase of population nor of an energy crisis, lack of basic supplies, and outpouring of wastes produced. However, thinking in the direction of developing and using renewable energy resources for future use is indeed a good step. The Kingdom of Saudi Arabia is proud of having done a lot of work and of investing a good amount of money on the development of solar energy both experimentally and theoretically. Solar energy-based appliances are used at the Royal Commission of Yenbu and Jubail, Saudi Arabia. Almost all the residential buildings in these industrial cities are heated using solar energy-based devices. This study is aimed at reviewing the technical development cited in the literature on solar energy related topics like measurement, modeling, and appliances for Saudi Arabia. Accordingly, the authors have reviewed the available technical reports and papers on solar energy published in refereed journals and proceedings.

2. LITERATURE REVIEW

Accurate, detailed, long-term knowledge of the available global solar radiation and its components incident at a location on a horizontal surface in particular and at different tilt angles in general, is of prime importance for the design and development of solar energy conversion systems. These solar energy-based applications include solar water heating, solar fencing for controlling the movement of wild animals on wildlife game reserves (Jain *et al.* [4]), farming (Zahed and Elsayed [5]), solar distillation of drinking water, solar air heating, solar cooking, solar drying of agricultural produce and other products, solar lighting, solar refrigeration, solar water pumping, solar communication, and solar transport. Solar energy is also applied in heat budget and micro meteorological related studies (Topcu and Oney [6]). Saudi Arabia has a vast amount of land compared to its population. A significant population lives in rural areas far from major cities. These areas are either connected *via* an electrical supply grid or depend on independent diesel generating sets. In these areas, there is great potential for the use of solar-based applications.

In Saudi Arabia a good deal of work is reported in the literature on various aspects of solar energy such as its measurements, conversion, and utilization. In their earlier work, Sabbagh *et al.* [7] developed a correlation for the calculation of solar radiation by using solar radiation and sunshine duration data for Riyadh. Later, the same team, Sabbagh *et al.* [8], obtained an empirical formula which relates the daily total solar radiation to the sunshine duration, relative humidity, maximum temperature, latitudes, altitude, and the location of the place relative to the water surfaces. Their correlation is as follows:

$$Q = \alpha k e^{a} L^{a_1} \left(b_1 D^{b} + c_1 R^{c} + d_1 t^{d} \right) . \tag{1}$$

Where a, b, c, and d = 1, 1, 1/3, −1, respectively, are the factors and α, a_1,b_1,c_1, and d_1 = 1.53, 1, 1, and −1, respectively are the coefficients. The remaining terms K, L, D, R, and t are the latitude altitude factor of the place, latitude angle in radians, ratio of the bright sunshine hours relative to 12 hours, relative humidity, and maximum air temperature in °C, respectively. Sabbagh *et al.* [8] compared their relation for five locations within and nine locations outside the Kingdom and found good agreement with the observed values. They reported a maximum error of −8% for Taif and a minimum of −0.4% for Qatif. They also produced maps of global solar radiation over Saudi Arabia for two seasons. Later Nimmo and Said [9] presented the measured data on direct and total solar radiation for Dhahran. In 1983 the "Saudi Arabian Solar Radiation Atlas" SASRA [1] was developed by the Saudi Arabian National Center for Science and Technology which is now known as King Abdul Aziz City for Science and Technology. The maps showing the duration of sunshine and global solar radiation on horizontal surface presented in this atlas were developed using the data collected over the period from 1971 to 1980 at 41 locations.

Since 1984 a good deal of work has been done on solar energy at the King Fahd University of Petroleum and Minerals (KFUPM). The research topics involved measurements of solar radiation, solar pond technology, solar water heaters, flat plate solar collector testing facility, and plastic degradation. Smith [10 and 11] studied the structure of Arabian heat low using an automated surface station within the interior of Saudi Arabian's Empty Quarter during June 1981 to collect continuous measurements of radiative fluxes, state parameters, and the subsurface thermal profiles. Smith [10] reported that the properties of the desert are remarkable in terms of their regular diurnal periodicity. He also found that the almost pure rhythmic nature of the surface radiation budget differentiates between an extremely dry desert and moist coastal regions. He further observed a more than 2 to 1 difference between near-infrared and short-wave directional reflectance. In his second part of the study, Smith [11] states that in terms of the large scale radiative fields, the Arabian Empty Quarter exhibits the high albedo characteristics of another principal heat source region within the southwest monsoon domain (the Tibetan Plateau), as well as the extensive monsoon cloud system. Bakhsh *et al.* [12] developed a simple correlation for the estimation of the ratio of hourly diffuse and global radiation received on a horizontal surface for Dhahran. This correlation was developed using hourly diffuse and global solar radiation data for a 15 month period. The authors compared their correlation with the existing correlations of Orgill and Holland [13] and Erbs *et al.* [14] and found good agreement. A report entitled "Solar Radiation Monitoring at Dhahran" [15] was also compiled by the Energy Resource Division of the Research Institute of the King Fahd University of Petroleum and Minerals, Dhahran. This report contains the details of the above solar radiation and meteorological parameters monitoring station. The paper of Bahel *et al.* [16] also describes in detail the operation and maintenance of the above mentioned automatic data acquisition system for the measurement of solar radiation and meteorological parameters at Dhahran, Saudi Arabia

Srinivasan *et al.* [17] reported a seasonally dependent correlation for the estimation of the daily ratio of diffuse to total radiation received on a horizontal surface by using insulation measurements at Dhahran and found good agreement when compared with some of the existing correlations. The authors observed lower values of diffuse fraction in winter than in summer. Their observation conforms with the dry and relatively less dusty winter season at Dhahran, which leads to a reduced diffuse fraction. Furthermore, the amount of scattered radiation depends on the air mass which varies from 1.52 in summer to 2.47 in winter at Dhahran. The work of Bahel *et al.* [18] was devoted to the measurement of bright sunshine duration and development of a linear correlation between monthly average daily global solar radiation and the sunshine duration for Dhahran, Saudi Arabia. The linear type of correlation which Bahel *et al.* [18] obtained for Dhahran is as follows:

$$\frac{H}{H_0} = 0.175 + 0.552\left(\frac{S}{S_0}\right) . \tag{2}$$

Where H is the monthly average daily global solar radiation falling on a horizontal surface; S is the monthly average daily duration of bright sunshine; H_0 is the monthly average value of extraterrestrial radiation; and S_0 is the maximum possible sunshine duration. They found better than 4% agreement between estimated and measured global solar radiation on an annual basis. The authors concluded that for arid and semi-arid climates like Saudi Arabia, the values of Angstrom coefficients a and b vary from 0.16 to 0.42 and 0.335 to 0.56 respectively.

Abdelrahman and Elhadidy [19] utilized the total solar radiation data measured at Dhahran on a surface inclined at 26° from horizontal for a period of one year between March 1984 to April 1985 to test three models for the calculation of total solar radiation on inclined surfaces. These included one isotropic model of Liu and Jordan [20] and two anisotropic models of Klucher [21] and Hay [22]. These models were evaluated on the basis of statistical error tests using the root mean square error (RMSE) and mean bias error (MBE). They concluded that the choice of a particular model should be based on location, inclination of the surface, and time. They also concluded that for a hot arid region, isotropic models are more accurate for tilt angle values around the latitude of the location. Srinivasan *et al.* [23] concluded that Bahel *et al's.* [18] model produced the best estimates of global solar radiation for arid and semi-arid regions. The universal models of Sayigh [8] and Rietveld [24] were found to be the next best estimators. These conclusions were based on the statistical comparison of the correlations of Rietveld [23], Bahel *et al.* [18], Sayigh [25], Reddy [26], and Barbaro *et al.* [27]. The authors compared these models for eight stations in different countries between latitudes 19.58°N to 33.33°N. Bahel *et al.* [28] used monthly average daily values of global solar radiation and hours of bright sunshine for 48 locations around the world with varied meteorological conditions and found the following non-linear fit of the third order using the least square method.

$$\frac{H}{H_0} = 0.16 + 0.87\left(\frac{S}{S_0}\right) - 0.61\left(\frac{S}{S_0}\right)^2 + 0.34\left(\frac{S}{S_0}\right)^3 . \tag{3}$$

The authors evaluated Equation (3) along with the universally accepted models of Rietveld [24] and Hay [29] in terms of RMSE and MBE for all 48 locations and found Equation (3) to produce the best estimates of global solar radiation for a majority of stations. The values of global radiation obtained from Equation (3), on an average, deviated from measured ones only by 5% for all the stations. As claimed by Bahel *et al.* [28], the difference between the predicted and measured values varied between 2–8%.

In another attempt, Bahel [30] used the monthly average daily values of diffuse radiation, global radiation, and clearness index for 40 locations from 15 countries and found a fourth order best fit equation using the least square method. The equation is given here:

$$\frac{H_d}{H} = 1.6932 - 8.2262K_t + 25.5532K_t^2 - 37.87K_t^3 + 19.8178K_t^4 \; . \tag{4}$$

Where H_d, H, and K_t are the diffuse radiation, global radiation, and clearness index respectively. Statistical tests were made for the root-mean-square error (RMSE) and mean-bias error (MBE) to compare the accuracy of eight relations including Equation (4). In another study, Bahel *et al.* [31] evaluated the statistical performance of four correlations, namely Rietveld [24], Hay [29], Glover–McCulloch [32], and Bahel *et al.* [18] (Equation (2)) for estimating the monthly average daily horizontal global radiation. They utilized the sunshine duration and global solar radiation data for 140 locations around the world with varied meteorological and geographical conditions for calculating RMSE and MBE. They concluded that Rietveld's [24] equation generally gives the best estimates; Hay's [29] correlation was the next best; and Glover–McCulloch's [32] relation was found to give the maximum error.

For better estimates of clear sky radiation, Kruss *et al.* [33] applied the ASHRAE [34] technique for the estimation of solar radiation reaching a horizontal surface under average clear sky conditions to estimate the direct, diffuse, and total radiation components. With the ASHRAE [34] technique the authors found a month to month error of 6% for total radiation, 20% for direct, and 50% for diffuse component. These errors between the measured and estimated values of total, direct, and diffuse components were reduced to 1%, 3%, and 3% respectively with the new Julian day polynomials of ASHRAE coefficients A, B, and C developed by the authors for Dhahran. Elhadidy *et al.* [35] reported measured values of ultraviolet radiation for a period of 3 years between January 1985 to December 1987 at Dhahran. The dependence of ultraviolet radiation on the clearness index was investigated in terms of the ratio of ultraviolet radiation to total horizontal radiation. They concluded that this ratio remained constant (a value of 3.45%) for a clearness index above 0.65, but varied significantly for a clearness index below 0.65. The authors also mentioned that cloudy and rainy days reduce the total radiation more than the ultraviolet, while the opposite is true for dusty days. In another work, Elhadidy [36] studied global energy in different spectral bands at Dhahran. His analysis showed that cloud cover has almost no effect on the ratio of the band to total solar radiation and that rainfall increases the percentage of radiation of certain bands, namely 385–500 nm, 500–530 nm, and 630–690 nm, and decreases for the 690–2800 nm band. Sand storms displayed the opposite trend. Smaller changes in the monthly values of band radiation over the year were reported. In a recent paper Elhadidy and Shaahid [37] presented the influence of Kuwait's 1991 oil fire smoke cloud on incident total horizontal solar radiation by using measurements made at the automatic solar radiation and meteorological monitoring station in Dhahran. Their results have shown that the global horizontal irradiance on smoky days was 70–87% of that on clear/non-smoky days and that the clearness index was about 50%.

A good deal of work on solar energy related topics done by researchers at King Abdulaziz University is found in the literature. For Makkah, Khogali *et al.* [38] presented the analysis of measured wind and solar energy data for possible use of these two renewable energies in this city. Khogali and Al-Bar [39] studied solar ultraviolet radiation and total global radiation for 17 months from 1987 to 1988 for a solar radiation station in Makkah. The solar apparatus and pyrheliometers for the measurements of solar radiation were installed on the roof of the physics department building at Umm Al-Qura University in Makkah and the automatic data recording/acquisition system in a control room of the building. They found the annual mean of the daily ultraviolet radiation for 1987 to be 200 ± 33 Whm^{-2}. The monthly average values varied from a minimum of 147 Whm^{-2} in December to a maximum of 252 Whm^{-2} in April. The authors proposed the following empirical type of correlation for the estimation of ultraviolet radiation:

$$H_v = 806 + 0.032H + 0.577H_0 - 222.3\;\cos(Z) - 4.103\;O_3 \; . \tag{5}$$

Where H_v, H, and H_0 are the monthly average daily values of ultraviolet, global, and extraterrestrial solar radiation on horizontal surfaces respectively; cos(Z) is the solar zenith angle; and O_3 is the ozone content in matm cm. They found that the ratio of ultraviolet to total global radiation varied from a maximum of 0.043 to a minimum of 0.028. The authors also analyzed the hourly values of ultraviolet radiation and applied multiple regression to obtain the coefficients of the following equation:

$$I_v = A + B\,I + C\cos(Z)\,. \tag{6}$$

Where I_v and I are the ultraviolet radiation and hourly values of solar radiation respectively and A, B, and C are the regression coefficients.

Due to the importance of atmospheric turbidity in the measurements of spectral solar radiation data, Abdelrehman and Nimmo [40 and 41] measured the turbidity and analyzed it for Dhahran, Saudi Arabia. The measurements of atmospheric turbidity were made by using broad band Schott filters OGI, RG2, and RG8 arranged on a ratable disk and mounted on an Epply Normal Incidence Pyrhelio-meter. Abdelrehman and Nimmo [40] also used the Beer–Lambert relation for the estimation of optical depth, which in turn was used to calculate the Angstrom coefficients of turbidity. The authors observed a high monthly variation in the values of both total and spectral broad band and direct radiation in Dhahran. They also concluded that the wave-length exponent of the turbidity equation varies from one season to another and as well as within the season, which implies that a frequent change occurs in size distribution and concentration of aerosol in Dhahran. Abdelrahman *et al.* [42] used normal radiation data at different bands for a period of one year between July 1980 and June 1981 at Dhahran for the determination of aerosol optical depth and atmospheric turbidity coefficients (*i.e.* Linke factor and Angstrom coefficient) for a desert climate. The authors found higher values of atmospheric turbidity coefficients for the desert climate of Dhahran than the temperate climate of Avignon (France) and Potsdam(Germany). They [42] reported that the extinction effect depends on the aerosol particle size, the relation between the Linke factor, and the Angstrom coefficient of turbidity was linear and the atmospheric turbidity was highly dependent on local weather conditions (*i.e.* wind speed, wind direction, and to some extent on the ambient temperature).

Elsayed [43] and Elsayed and Al-Turki [44] derived relations for monthly average daily and instantaneous shading factors of any element in a flat plate collector field caused by the relative position of other collectors located in the successive southern row. Elsayed [43] found that the expression for monthly average shading factor depends on the site latitude angle, month of the year, length and width of each collector (if different in size), spacing between successive rows of collectors, number of collectors in a row, and the magnitude of tilt angle for each collector. Elsayed [43] has shown a graphical representation of shading factor over a wide range of its independent variables. These graphs and analytical expressions of shading factor assist in improving the accuracy of predicting the monthly average daily radiation received by a collector field. A theoretical analysis on Heliostat minimum radial spacing was studied by Al-Rabghi and Elsayed [45] for different blocking and no shadowing conditions. Elsayed and Beirutty [46] developed a shielded collector model for the prediction of solar irradiance falling on a tilted flat plate collector in a field of solar collectors. Their model takes into account the effects of several factors like shielding effect by adjacent collectors beside other commonly considered effects. In order to account for shielding effects, expressions are derived for configuration factors between a flat collector, shielded by one or more collectors in the preceding rows, and the ground and the sky. The analytical expressions of these configuration factors are found to depend on the dimensions of each collector (width and length), tilt angle, spacing between collector rows, and the relative position of the collector with respect to the shielding collectors in the preceding row.

In another study, Elsayed *et al.* [47] obtained an analytical expression for estimating the instantaneous usefulness efficiency of a heliostat surface and developed a procedure to calculate the usefulness efficiency for overlapping of blocking and shadowing on a heliostat surface. They concluded that the local yearly average daily usefulness efficiency depends on site latitude angles, radial distance from the tower measured in tower heights, heliostat azimuth angle, and the radial spacing between heliostats. They also developed charts for local yearly average daily usefulness efficiency for latitudes 0, 15, 30, and 45°N. These charts are useful for the calculation of reflected radiation from a given cell. Elsayed and Fathalah [48] used a new technique, known as separation of variables/superposition, to calculate the flux density distribution on receiver surface. This method is applicable to both focusing and nonfocusing heliostats, and also accounts for any sun shape, error distribution (due to tracking, imperfect reflecting surfaces *etc.*), blocking, and shadowing on heliostat surface and various geometries of receiver planes. Elsayed *et al.* [49] designed and manufactured an experimental facility to measure the solar flux density distribution on a central flat receiver due to a single heliostat. A two stepping motor was used to control the tracking mechanism of the heliostat (for tilt and azimuth angles). To measure the solar density distribution on the receiver surface, a miniature solar sensor was mounted on the platform of the traversing mechanism. A computer program was written to control the heliostat tracking and traversing mechanisms to the points of a preselected grid and to record the solar flux density distribution on the receiver plane. They observed two types of images on the receiver plane, namely apparent and mirror reflected. The results indicated that the apparent and mirror reflected radiation images may have different limb darkening angles. The authors mentioned that further work is to be done to investigate this phenomenon. The experimental results of their experiments were in good agreement with the mathematical model results of Elsayed and Fathalah [48]. In their book, Elsayed *et al.* [50] presented various aspects of design of solar thermal systems. This book presents the design of solar thermal systems using mathematical modeling and adds considerably to engineering expertise. Topics related to design of solar water heaters, swimming pool heating systems, space heating, and solar desalination systems are covered in detail in this book. Rehman *et al.* [51] used the empirical type of parameterization scheme for the calculations of solar radiative fluxes and atmospheric heating or cooling rates in the troposphere by using observed upper air meteorological data. They compared the diurnal variation of annually averaged solar radiation fluxes reaching the ground with observed values of solar radiation flux at Dhahran and found good agreement between the two.

Zaki *et al.* [52] presented a model for a simple solar still assisted by an external solar collector for improving solar distillation yield. The collector and the still were coupled to form a natural circulation closed loop where the energy was dumped into the still to enhance the water evaporation process. They solved governing coupled heat and momentum balance equations for a quasi-steady state condition with temperature dependent physical properties. They found that for a coupled still, fresh water productivity increases as the solar collector area of the assisting device increases. For an ideal system, *i.e.* with zero thermal inertia, a linear variation between the fresh water productivity and the solar flux was experienced. The comparison showed good agreement between the model predictions (with thermal inertia) and the experimental values. Without considering thermal inertia, the model predicted much higher values of temperatures than the actual ones. Experimental work related to concentrator assisted solar stills can be found in Zaki *et al.* [53], Fattani [54], and Al-Ghamdi [55]. Fattani *et al.* [56] studied both theoretically and experimentally the possibility of improving the daily yield of a simple basin type solar still by enhancing the vapor condensation process on a coupled condensing surface. Their mathematical model predicted the limits of the yield improvement as well as effect of thermal inertia. The analysis showed that yield improvement depends on the heat removal rate by the condenser and on brine depth, which determines the thermal inertia of the still. They concluded that the use of a condensing surface provided an excellent means for vapor removal. Abu-Abdou [57] solved a set of equations describing the spatial and temporal variation of water temperature in a continuous-flow thin-film solar still to study the sensitivity of some major variables in the system. Their analysis showed that for a small water mass in the storage tank, steady periodic conditions were established within 24 hours while for larger masses, a second day may be needed. The enhanced convective heat transfer between the absorbing liner and the water flow was found to improve the productivity over that of a basin still. Zahed and Elsayed [5] presented a thin-layer mathematical model for a natural ventilation solar kiln. This model is capable of predicting the instantaneous and long-term performance of the kiln using either real or mathematically modeled weather data and solar irradiance data. The model prediction showed that the operational efficiency of the solar dryer using a bi-directional pattern of air flow in the kiln was better than the unidirectional pattern of air flow. The maximum product temperature was higher in summer than in winter, spring, and fall. The kiln dimensions affect the drying process, and lastly, the increased thermal capacity of the kiln produced good drying results over the year.

Nimmo and Said [58] carried out a study related to the effect of dust accumulation on the surfaces of flat plate thermal collectors and photovoltaic panels. Their results showed a 26% and 40% decrease in the efficiency of thermal and photovoltaic panels respectively as a result of several months of accumulation of dust on the panels. Shoboskshy and Hussein [59] experimentally studied the effect of five kinds of dust particulate matters having different physical properties on the surface of photovoltaic cells. The experiments were carried out in a laboratory using a solar simulator consisting of three tungsten halogen 1 000 W lamps, different types of dust of known materials, and the photovoltaic panel consisting of 33 commercial silicon cells model M73. They found that fine particulates deteriorate the performance of photovoltaic cells more than coarser particulates. Of the five dust types investigated, cement was found to reduce the short circuit current and output power while carbon particulate resulted in the worst deterioration of performance when deposited on the surface of photovoltaic cells. It was also concluded that the effect of dust particulate on the performance of a photovoltaic cell can no longer be correlated to the period of exposure to the atmosphere at a given site as suggested by many investigators. The authors emphasized that more work is needed in order to include the optical characteristics of the dust under varying solar intensities and its effect on photovoltaic cells.

Nimmo and Litka [60] studied an operating industrial acetone reclamation system to determine whether or not to install solar collectors to supply a part of the thermal energy required. They obtained an annual fuel saving of up to 31%, but their economic analysis showed that the installation of the solar system would not be practical. The technical paper of Said and Nimmo [61] describes in detail the development of the flat plate solar collector facility at KFUPM, Dhahran, Saudi Arabia. This facility was developed on the basis of the United States National Bureau of Standards recommendations. The facility, which can accommodate two 4 ft × 8 ft flat plate collectors at a time, was tested for four types of collectors. The performance curves and the characteristic design parameters for all the four types of collectors were discussed. Finally, the authors made some relevant observations on the need of standardized testing in the Middle East.

Olwi *et al.* [62] explored a new means for cooling power plants through passive dry cooling utilizing convection and infrared radiation from a covered cooling pond, such that evaporation was suppressed. They obtained a total heat rejection of 150 Wm^{-2} on average for 24 hour operation of the cooling system. They also demonstrated the potential of using covered ponds as a cooling system of power plants in arid areas where water is scarce. The authors observed that the conduction to the ground does not contribute more than 4% of the total heat rejection and hence a simple once through pond should be constructed. Convection, on the other hand contributed up to 60% of the overall heat rejection and hence the pond should be constructed in a windy location. Sabbagh *et al.* [63] explored the use of radiative cooling for power plants and large refrigeration plants in inland arid areas. Their work consists of small scale experiments, mathematical models, a survey of the suitable materials, and a prototype experiment. They designed, constructed, and tested a prototype experimental pond covered with a painted white aluminum sheet. The pond measured of 10m x 25m x 1m dimensions. The authors showed the validity of a covered cooling pond under hot summer conditions. They even expected better cooling efficiency in dry inland conditions than in coastal or humid locations. In the night an average 50 Wm^{-2} of heat rejection was achieved by radiation. The pond cover should be of a material having good conductivity, good weather resisting properties, and should be painted white because most white coatings have good reflectivity to solar radiation and good resistivity to thermal radiation. The pond cover should be in complete contact with the water and should float on the surface of the water. Their experimental results were comparable with their model work.

A salt gradient solar pond with stabilizing density gradients is an economical, simple, and reliable long-term low temperature energy collecting and storage system. The energy collected is useful in industrial process heat, district heating and cooling, and producing electricity when combined with an electricity conversion system. In order to utilize salt gradient pond technology in Saudi Arabia, a thorough literature review on this topic with special reference to its use in the Sabkha Areas was made by Nimmo and Rudesill [64]. The study revealed that salt gradient solar pond (SGSP) technology coupled with the extensive sabkha areas in the Gulf region has a great potential of large scale thermal and electric power production. Furthermore, the sabkhas are preferred sites due to relatively low alternative land use, easy excavation, and availability of saline ground water about a meter below the ground surface. Later, Elhadidy *et al.* [65] investigated both theoretically and experimentally the thermal behavior of salt gradient solar ponds with heat removal from side walls and bottom heat losses. They used a two dimensional unsteady numerical model developed at the Research Institute of the King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia for the theoretical analysis of an outdoor small scale sodium chloride pond. Their theoretical results, for the average storage zone temperature, were found to be in good agreement with the experimental and local climatic data for Dhahran. The study concluded that top heat loss was the major loss from the pond; the physical properties of the surrounding earth have considerable impact on the pond's ultimate temperature rise; the degree of natural convection expected in the storage zone depends strongly on the values and location of the heat removal; and side wall and bottom heat losses have a considerable effect on the performance of the pond and hence should not be neglected.

The experimental setup of SGSP at Dhahran and its results were presented in an internal report (Elhadidy *et al.* [66]) of the Research Institute. A 2m diameter and 1m deep sodium chloride salt gradient solar pond was operated for nine months and measurements of density and temperature profiles were made. Within a period of 2 weeks, the pond reached a storage zone temperature of about 55°C. Elhadidy [67 and 68] described in these internal project reports the development of a two-dimensional conduction analysis model to perform parametric studies and thermal performance design calculations for axisymmetric and rectangular ponds with high aspect ratios. This model is capable of handling the transient conduction case coupling a one dimensional treatment of the pond and ground beneath the pond with a two dimensional treatment of surrounding side walls. The model also included the bottom absorptance or reflectance of the radiation, varying earth properties, dependence of density on concentration and temperature, and heat removal from the storage zone at time varying rates at different distances from the pond bottom. Elhadidy and Nimmo [69] used the above model to study the dependence of the pond's thermal efficiency, calculated as the ratio of heat removal to incident radiation, on the average storage zone temperature, which was calculated from the computed temperature profiles. They found that the brine properties ($MgCl_2$ *versus* NaCl), the pond shape, and the storage zone thickness have relatively smaller effect on the pond's thermal efficiency than the earth properties, gradient zone thickness, bottom absorbtivity, and pond radius to depth ratio. Their analysis also showed that a thin gradient zone produced the best efficiency at large heat removal rates and lower average storage zone temperatures, while a thick gradient zone produced best efficiency at lower heat removal rates and large storage zone temperatures.

Nimmo and Elhadidy [70] provided a brief description on the design of various types of solar ponds available in the literature and the progress made at the Research Institute on various aspects of solar pond technology. Elhadidy and Nimmo [71] used the model reported by Elhadidy *et al.* [65] to study the thermal performance of finite solar ponds by taking into consideration the heat loss through the bottom and side walls of the pond. Their results showed that the ratio of the temperature response of finite ponds to that of infinite ponds varies nonlinearly with the ratio of the pond depth to radius or pond depth to half width for axisymmetric or rectangular ponds, respectively. They also concluded that the temperature ratio depends on the surrounding earth properties and on the pond storage zone thickness. As mentioned earlier, further detailed analysis was carried out on the experimental data collected during the operation of a 2.1m diameter and 1.2m deep salt gradient solar pond by Elhadidy *et al.* [72]. The authors noticed that the morning and afternoon vertical temperature scans as well as traces from stationary thermocouples located at the bottom and 10 cm from the bottom of the pond show the effect of heat loss and radiation absorption from the bottom. Their study further showed that the convective cells which occurred in the nonconvective zone were about 5cm thick and were able to restore themselves or self-heal. In another study, Elhadidy and Nimmo [73] used the computer model developed at the Research Institute to calculate the concentration gradient required to stabilize the temperature gradient in the salt gradient solar pond with heat removal from the bottom and side walls of the pond. Their results revealed that a higher salt concentration was required than previously suggested.

Khalifa *et al.* [74] studied various types of solar cookers and extensively analyzed the amount of energy involved in cooking meat. They presented the results of four types of solar cookers showing the performance efficiencies of each type. An application-oriented work was done by Khalifa *et al.* [75 and 76] in which they presented the design and development of a solar cooker for outdoor and indoor use. In their study, they introduced the concept of insulated and vapor-tight pots and applied to the oven point focus and heat pipe cookers. They used a flat-plate cooker with heat pipes which does not require tracking and allows cooking in the shade or indoors. Khalifa *et al.* [77] constructed and tested a novel-portable cooker named "The Mina Oven". It features a vapor tight pot and an integral collection with plaps. Another cooker comprised of a parabolic dish focused at a glazed and insulated receiver, named " The Arafat Cooker", was also tested. These cookers were able to cook one kilogram of food per square meter of solar collection area in 25–45 minutes between 10.00 a.m. to 4.00 p.m. The study concluded that the compact, simple, and portable Mina Oven prevents spillage, minimizes cooking time, and the projected area of the pot does not need to be enlarged for increased power input. On the other hand the insulated, focusing type cookers like "The Arafat Cooker" which minimizes heat loss can be used for frying, baking, grilling, and roasting. Furthermore, the heat pipe solar cookers allow cooking in the kitchen and hence are wind insensitive, are simple to operate and maintain, do not require tracking, are sturdy, and have a permanent fixture for year round operation.

Khalifa *et al.* [77] presented the results of successful cooking in Pyrex pots utilizing an absorption plate. In another paper Khalifa *et al.* [78] used a new oven type cooker that allowed heating from the sides and the bottom and supplied the solar energy *via* a spiral concentrator. Their simulation results were in good agreement with the experimental observations. Olwi and Khalifa [79] used a fourth order Runga–Kutta algorithm to solve the set of differential equations to perform the computer simulation of the solar pressure cooker by treating each element as a separate parameter. Further, Olwi and Khalifa [80] used mathematical model to study the performance of the solar grill and compared the model results with their experimental data. Taha *et al.* [81 and 82] tested the spiral concentrator *versus* the Fresnel reflector in terms of the geometrical relationships and design procedures. They found good agreement between the results of the spiral concentrator and the parabolic dish concentrator. Habeebullah *et al.* [83] developed transient heat balance equations and solved them using the numerical integration technique to predict the thermal behavior of a concentrating type solar cooker. The mathematical model considers the effects of the transient nature of solar radiation and wind speed variation. The model results showed the great advantage of using a glass-sided oven over the conventional bare receiver pot. The theoretical analysis further showed that the oven type receiving pot has both a higher fluid temperature and overall receiver efficiency compared to the bare receiver type working under similar conditions. The authors proposed that a lightweight insulated oven should be developed to enhance the use of the concentrating type of cookers.

Abdelrahman and Al-Ansari [84] in their paper described the development of a domestic solar water heating system (DSWHS) program at the Research Institute of the King Fahd University of Petroleum and Minerals, Dhahran. This program included the collector testing facility, the complete system testing under simulated water drawoff, complete system testing under real use, and design and fabrication of a system suitable for Saudi Arabia. The results showed that DSWH systems are reliable and trouble free if proper materials are selected and system components are assembled carefully. Abderrahman *et al.* [85] carried out thermal performance tests on a commercial thermosyphon solar domestic hot water system consisting of an effective flat plate collector area of $3.76m^2$, a 300 liter storage tank, and an electric auxiliary heater. The primary objectives of this study were to determine system daily solar fraction and thermal efficiency. The secondary objectives were to find out recovery rate in the storage tank for solar and electric combined input and for solar input alone, and finally, to measure the collector array efficiency. The test results showed a yearly average solar fraction of 77.5% and thermal efficiency of 31%. Abderrahman and Al-Ansari [86] described in more detail the procedures for the installation of the above mentioned DSWH system including hoisting the components, orienting the collectors, retrofitting the existing gas fired system, and commissioning. This system was installed in a house with five family members and test runs were made. It was shown that the lowest solar contribution was 76% (January) and maximum 99% (June) in the total energy input. The maximum and minimum average daily hot water consumption was 179 and 51 liters in February and June respectively. The system was maintained consistently during the test year, and there was no interruption in hot water supply. Al-Ansari and Abdelrahman [87] presented the adaptation of solar technology in Saudi Arabia with special emphasis on technical, environmental, and economical constraints. Bahel *et al.* [88] demonstrated the potential of Heat Recovery Water Heating (HRWH) in the hot and humid climates of the Gulf area. The HRWH system was installed and tested in a typical Saudi single family residence in Dhahran, Saudi Arabia. The above system produced about a 75% saving in annual energy required for heating water. The heat recovery process improved the coefficient of performance of the cooling cycle up to 30% of the condensing load.

Hamid *et al.* [89] studied the effect of meteorological parameters in general and ultraviolet radiation in particular on plastic. In this study, the linear low-density polyethylene (LLDPE) samples were exposed to the natural environment of Dhahran, Saudi Arabia. The characterization of degraded samples was carried out by differential scanning calorimetry (DSC). Hamid *et al.* [90] reported the effect of ultraviolet radiation on greenhouse and mulch films exposed to the natural environment of five locations in the Kingdom. They concluded that the growth in the carbonyl group in the exposed films was due to ultraviolet radiation absorption. Javed and Hamid [91] studied the weathering effect on plastic films by mounting them on a model greenhouse and aluminum exposure racks at the Dhahran plastic exposure facility. The authors found that the films exposed on the model greenhouse showed a higher rate of photo-oxidative degradation in terms of higher carbonyl growth, higher percent crystallinity, and higher drop in mechanical properties than those exposed on aluminum racks.

3. CONCLUSIONS

The available material on solar energy development for the Kingdom of Saudi Arabia was thoroughly reviewed and authors observed the following:

1. A good deal of work is reported in the literature on the development of solar energy conversion and its utilization for Saudi Arabian climatic conditions.
2. The economical aspects of solar energy for commercial use in the Kingdom need more attention.
3. An effort should also be made on the commercial use of solar cookers, water heaters, street lights, water pumping, communications, and solar kilns for drying of agricultural and other products in remote areas of the Kingdom.
4. Diffuse radiation, ultraviolet radiation, and other components of solar radiation need more attention both in terms of modeling and measurements.
5. Various aspects of salt gradient solar ponds, both in terms of modeling and experiments, have been studied in the Western and Eastern regions of Saudi Arabia.
6. For better understanding of the availability of global solar radiation and sunshine duration over Saudi Arabia, further research work is being carried out by the authors.

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