Renewable Energy Potential in Sudan

Abdeen Mustafa Omer and Elfadil Braima
231 Denman Street
Nottingham NG7 3PS
Nottinghamshire
UNITED KINGDOM

ABSTRACT

Sudan is an agricultural country with fertile land, plenty of water resources, livestock, forestry resources and agricultural residues. An overview of the energy situation in Sudan is introduced with reference to the end uses and regional distribution. Energy sources are divided into two main types: conventional energy (biomass, petroleum products, and electricity); and non-conventional energy (solar, wind, hydro, etc.). Sudan possesses a relatively high abundance of solar radiation, and moderate wind speeds, hydro, and biomass energy resources. Application of new and renewable sources of energy available in Sudan is now a major issue in energy strategic planning as alternative to fossil conventional energy to provide part of the local energy demand. Sudan is an important case study in the context of renewable energy. It has a long history of meeting its energy needs through renewables. Sudan's renewables portfolio is broad and diverse, due in part to the country's wide range of climates and landscapes. Like many of the African leaders in renewable energy utilization, Sudan has a well-defined commitment to continue research, development, and implementation of new technologies. Sustainable low-carbon energy scenarios for the new century emphasize the untapped potential of renewable resources. Rural areas of Sudan can benefit from this transition. The increased availability of reliable and efficient energy services stimulates new development alternatives. It is concluded that renewable environmentally friendly energy must be encouraged, promoted, implemented, and demonstrated by full-scale plants especially for use in remote rural areas.

1. INTRODUCTION

Sudan is the largest country in the African continent, with a tropical climate, and an area of approximately 2.5 million km^2 (10^6 square miles). It lies between latitudes 3°N and 23°N; and longitudes 21° 45'E and 39°E. This large area enjoys a variety of climates, from desert regions in the north, to tropical in the south, and makes it a favourable environment for all activities of integrated agricultural investment from production to processing industries [1]. Sudan is a relatively sparsely populated country. The total population according to the 1996 census was 30 million inhabitants. The annual growth rate is 2.8%, and population density is 12 persons per square kilometer [2]. Sudan is rich in land and water resources [2]. Sudan has a predominately continental climate, which roughly divides into three climatological regions.

Region 1 is situated north of latitude 19°N. The summers are invariably hot (mean max. 41°C and mean min. 25°C) with large variation; low relative humidity averages (25%). Winters can be quite cool. Sunshine is very prevalent. Dust storms occur in summer. The climate is a typical desert climate where rain is infrequent and annual rainfall is 75 mm to 300 mm. The annual variation in temperature is large (max. and min. pattern corresponding to winter and summer). The fluctuations are due to the dry and rainy seasons.

Region 2 is situated south of latitude 19°N. The climate is a typical tropical continental climate. Region 3 comprises the areas along the Red Sea coast and eastern slopes of the Red Sea hills. The climate is basically as in region 1, but is affected by the maritime influence of the Red Sea.

Two main air movements determine the general nature of the climate. Firstly, a very dry air movement from the north that prevails throughout the year, but lacks uniformity. Secondly, a major flow of maritime origin that enters Sudan from the south carrying moisture and bringing rain. The extent of penetration into the country by airflow from the south determines the annual rainfall and its monthly distribution. The average monthly rainfall for Sudan indicates the decreasing trend in the rainfall, as well as in the duration, as one moves generally from the south towards the north and from east towards west.

The total size of the land of Sudan is 6 x 10^8 Feddans (Feddan = 1.038 acres = 0.42 hectares). The land use in the country is classified into four main categories. There are arable land (8.4 x 10^6 hectares), pasture (29.9 x 10^6 hectares), forest (108.3 x 10^6 hectares), and about 38.2 x 10^6 hectares used for other purposes.

Water resources are estimated at 84 x 10^9 cubic meters (m^3), this including the river Nile and its tributaries. Underground water is estimated at 26 x 10^{10} m^3, only 1% of this amount is currently being utilized. The annual average rainfall ranges from about 1 mm in the northern desert to about 1600 mm in the equatorial region. The total annual rainfall is estimated at 1093.2 x 10^9 m^3.

Sudan's economy remains essentially agricultural, with annual agricultural production, estimated as 15 x 10^6 tons mainly sugar, wheat, sorghum, cotton, millet, groundnut, sesame, tobacco, and fruits [2]. Sudan is also viewed as one of the potentially richest nations in livestock [2], approximately 103 x 10^6 heads (70 x 10^6 sheep and goats, 30 x 10^6 cattle, and 3 x 10^6 camels) [3]. Sudan has a great wealth of wild-life, birds, reptiles, and fish. Sudan possesses great potentialities for industrialization since it is rich in agricultural raw materials. Since the government realised the importance of industrialization for economic development, there were many attempts by the state to improve the performance of this sector through different industrial policies.

Energy is an essential factor in the development movement, since it stimulates and supports the economic growth and development. The energy crisis in mid seventies, and substantial increase in oil prices that followed, have put a heavy financial burden on the less developed countries (LDC's). Sudan is not an exception. The fossil fuels, especially oil and natural gas, are finite in extent, and should be regarded as depleting assets, and since that time the efforts are oriented to search for new sources of energy. Most of the policies are directed to establish sources of energy, many of which now face serious environmental and other constraints, rather than the biomass sources which are increasingly being regarded as a central part of long solutions to the energy environment dilemma. However, increasing energy service levels with the same environmental goals would imply stronger exploitation of biomass energy sources and stronger measures for exploiting the potential of energy conservation.

In recent years, Sudan has increased efforts to exploit renewable energy sources and reduce its dependence on oil. Wind, solar and biomass offers a variety of renewable options that are well suited to the African climate. A number of renewable energy initiatives are under way in Sudan that can contribute to rural development while also addressing climate mitigation.

2. ENERGY SITUATION

Sudan meets approximately 87% of its energy needs with biomass, while oil supplies 12%, and the remaining 1% are produced from hydro and thermal power as shown in Table 1. Tables 2 to 8 show energy profile, consumption, and distribution among different sectors in Sudan. Sudan like most of the oil importing countries suffered a lot from sharp increase of oil prices in the last decades. The oil bill consumes more than 50% of the income earnings. The household sector consumed 60% of the total electricity supplies [4]. The total annual energy consumed is approximately 11.7 x 10^6 tons of oil, with an estimated 43% lost in the conversion process [5]. The heavy dependence on biomass threatens the health and future of domestic forests, and the large quantities of oil purchased abroad causes Sudan to

Table 1 Annual Energy Consumption in Sudan From Different Energy Sources

Energy source	Percent (%)
Wood fuel	77.8%
Non-wood fuel	9.2%
Petroleum	12%
Electricity	1%

Table 2 Annual Energy Consumption Pattern in Sudan (10^6 mWh)

Sector	Energy (10^6 mWh)	Percent (%)
Residential	4640	77.2%
Transportation	610	10.0%
Industries	340	5.7%
Agricultural	151	2.5%
Others*	277	4.6%
Total	6018	100.0%

* Others are commercial, services, constructions and Quranic schools.

Table 3 Annual Biomass Energy Sources Available in Sudan (10^6 tons)

Source	Volume of biomass (10^6 tons)
Natural and cultivated forestry	2.9
Agricultural residues	5.2
Animal wastes	1.1
Water hyacinth and aquatic weeds	3.2
Total	13.4

Table 4 Annual Biomass Energy Consumption in Sudan (10^6 tons)

Sector	Volume of biomass (10^6 tons)	Percent of total (%)
Residential	4549	92.0%
Industries	169	3.4%
Others*	209	4.6%
Total	4927	100.0%

* Others are commercial, constructions and Quranic schools.

Table 5 Power Output of Present Hydropower Plants (10^6 Watts)

Station	Power (10^6 Watts)
Rosaries	275000
Sennar	15000
Khashm El Girba	13000
Total	303000

Table 6 Annual Electricity Consumption in Sudan (10^6 mWh)

Sector	Energy (10^6 mWh)	Percent of total (%)
Residential	48.0	60%
Transportation	3.2	4%
Industries	6.4	8%
Agricultural	22.4	28%
Total	80.0	100%

Table 7 Annual Petroleum Product Consumption in Sudan (10^6 mWh)

Sector	Energy (10^6 mWh)	Percent of total (%)
Residential	55	5.5%
Transportation	601	60.0%
Industries	138	13.8%
Agricultural	148	14.8%
Others*	60	5.9%
Total	1002	100.0%

* Others are commercial and services.

Table 8 Percentage of the Total Annual Electricity Consumption by States

States	Percent (%)
Khartoum, Central and East states	85.8%
Red Sea state	4.5%
Northern states	4.0%
Darfur states	3.1%
Kordofan states	2.3%
Southern states	0.3%

suffer from serious trade imbalances. Poverty and iniquity in the basic services are the major components that hindered rural development. None of the great goals of the international and national community peace, human rights, environment, and sustainable development will be achieved or even progressed unless being addressed now. Energy is a vital prime mover to the development whether in urban or rural areas. The rural energy needs are modest compared to urban. A shift to renewables would therefore help solve some of these problems while also providing the population with higher quality energy which will in turn, improve living standards and help reduce poverty. For proper rural development the following must be considered:

- Analyze the key potentials and constraints on development of rural energy;
- Assess the socio-technical information needs for decision-makers and planners in rural development;
- Utilize number of techniques and models supporting planning rural energy; and
- Design, import and interpret different types of surveys to collect relevant information and analyze them to be an input to planners.

Renewable energy technologies such as solar, wind, etc. become more important since there are local resources available and they are non-depletable source of energy. Renewable sources of energy are regional and site specific. The renewable energy strategy is well integrated in the National Energy Plan [6], and clearly spelled out in the National Energy Policy. However this alone is not enough. It has to be integrated in the regional development plans. The role of renewable energy is important in solving essential life problems especially in rural areas for people and their resource development [7]. A new renewable fuels program in Sudan aims to improve environmental standards while making better use of domestic resources, providing an economic stimulus to the rural economy, and reducing CO_2 emissions. This study discusses Sudan's current energy system, and describes plans for expanding and improving Sudan's emerging portfolio of renewable energy options.

The poor situations of conventional energy supplies to Sudanese people are characterised by high dependence on biomass woody fuels (firewood, and charcoal). More than 70% of the total Sudanese population live in rural and isolated communities characterised by extreme poverty and economical activity [8]. The unavailability and the acute shortages of the conventional energy supply (petroleum and electricity) to rural people forced them to use available alternative energy sources like biomass [9]. This situation caused serious environmental degradation beside the poor unsatisfactory services of some basic needs such as:

- Food security
- Water supply
- Health care
- Communications

In order to raise rural living standards, the per capita energy availability must be increased through better utilization of the local available energy resources (Table 9). The rural energy requirements are summarized in Table 10. The suitable energy source needed for the said rural requirements must be of diffuse low cost types rather than large central installation. Also, those technologies must be appropriate, environmentally, socially and economically acceptable. The urgent problem for rural people development is to increase the energy availability per capita. This is necessary to reduce the present level of extreme poverty and improve basic need services.

Due to the present limitations and sharp shortages or unavailability of both electricity and petroleum products to rural people, some renewable energy technologies based on utilizing locally

Table 9 Energy Sources for Rural Area

Source	Type
Solar energy	Solar thermal, Solar PV
Biomass energy	Woody fuels, Non woody fuels
Wind energy	Mechanical types, Electrical types
Mini & micro hydro	A mass water fall, Current flow of water
Geothermal	Hot water

Table 10 Energy Required in Rural Area

Rural energy	Activity
Domestic	Lighting, heating, cooking, cooling
Agricultural process	Land preparation, weaving, harvesting, sowing
Crop process and storage	Drying, grinding, refrigeration
Small and medium industries	Power machinery
Water pumping	Domestic use
Transport	Schools, clinics, communications, radio, televisions, etc.

available energy, materials and skills are alternative energy options to rural development [10]. These technologies are not for complete rural electrification (although they can), but they are applied as stand alone systems providing energy sources to some rural basic needs. It is necessary that a vigorous program for renewable energies should be set up immediately. The challenge is to provide a framework enabling markets to evolve along a path that favors environmentally sustainable products and transactions.

3. MAJOR ENERGY CONSUMING SECTORS

Sudan is still considered as one of the 25 most developing African countries. Agriculture is the backbone of economic and social development in Sudan. About 80% of the population depend on agriculture, and all other sectors are largely dependent on it. Agriculture contributes to about 41% of the gross national product (GNP) and 95% of all earnings. Agriculture determines for the last 30 years the degree of performance growth of the national economy.

3.1 Agricultural Sector

During the last decades agriculture had contributed about 41% to the country's GNP. This share remained stable until 1984-1985 when Sudan was seriously hit by drought and desertification, which led to food shortages and deforestation; and also, by socio-economic effects which caused the imposed civil war. The situation led to the drop of agricultural share to about 37%. Recent developments due to rehabilitation and improvement in agricultural sector in 1994 have raised the share to 41%. This share was reflected in providing raw materials to local industries and an increased export earnings besides raising the percentage of employment among population. This sector consumed 2.5% of the total energy consumption (28% from electricity, 14.8% from fossil fuels, and the rest from biomass fuels).

3.2 Industrial Sector

The industrial sector has mainly suffered from power shortage, which is the prime mover of the large, medium and small industries. The industrial sector has consumed 5.7% of the total energy consumption, distributed as follows: 55% from petroleum products, 13% from biomass and 32% from electricity.

3.3 Household Sector

The household sector is a major energy consumer. It consumed 92% of the total biomass consumption in form of firewood and charcoal. From electricity, this sector consumed 60% of the total consumption, and 5.5% of petroleum products.

3.4. Transportation Sector

The transportation sector (railways, ships, boats, etc.) was not efficient for the last two decades because of serious damage to its infrastructure (roads, workshops, and maintenance centers, etc.). It consumed 10% of the total energy consumption and utilized 60% of the total petroleum products supplied.

4. RENEWABLE ENERGY RESOURCES

At present, the energy (heat, light, etc.) needed by most people in Sudan is easily provided by firewood. Cooking is largely done by wood from forests or its derivative, charcoal. Cattle dung and agricultural waste are being used to a lesser extent. Human, animal, and diesel or gasoline engines provide mechanical power. Some cooking and lighting are done by kerosene. It should be recognized that this situation is unlikely to be changed in the next one or two decades. However, there is a need to increase energy availability and to find alternatives to the rapidly decreasing wood supplies in many rural areas. It is necessary that a vigorous program reaching into alternative renewable energies should be set up immediately. There should be much more realism in the formation of such program, e.g., it is no use providing a solar powered pump at a price competitive with a diesel for someone who cannot ever afford a diesel engine. The renewable energy technology systems (RETs) are simple, locally available, clean energy, reliable and sustainable.

Specialists on RET applications carried out socio-economic and environmental studies. The output of the studies pointed out that RETs are acceptable to the people and have measured remarkable impacts on the social life, economical activities and rural environment [11, 12].

4.1. Solar Energy

Sunlight is the driving force behind many of the renewable energy technologies. The worldwide potential for utilizing this resource, both directly by means of the solar technologies and indirectly by means of bio-fuels, wind and hydro technologies is vast [13 and 14].

Sudan has been considered as one of the best countries for exploiting solar energy. Sunshine duration ranges from 8.5 to 11 hours per day, with high level of solar radiation regime at an average of 20 to 24 $MJm^{-2} day^{-1}$ on the horizontal surface as shown in Table 11 and Fig. 1. The annual daily mean global radiation ranges from 3.05 to 7.62 $kWhm^{-2} day^{-1}$. Sudan has an average of 7-9 $GJm^{-2} year^{1}$, equivalent to 436-639 $Wm^{-2} year^{1}$ [15].

The country strives hard to make use of technologies related to renewable sources in rural areas where it is appropriate and applicable. Sudan already has well-established solar thermal applications. The most promising solar energy technologies are related to thermal systems; industrial solar water heaters in the residential sector and in larger social institutions, such as nurseries, hospitals, and schools. Solar cookers, solar dryers for peanut crops, solar stills, solar driven cold storage to store fruits and vegetables, solar collectors, solar water desalination, solar ovens and solar commercial bakers. Solar photovoltaic systems (PV) are used for lighting, solar refrigeration to store vaccines for human and animal use, water pumping, battery charging, communication network, microwave receiver stations, radio systems in airports, VHF and beacon radio systems in airports, and educational solar TV posts in some villages [16].

4.2. Wind Energy

The use of wind as a source of power has a long history in Sudan. Wind power has been used for water pumping, corn grinding and for power to small industries. In areas of low population density where implementation of a central power system would be uneconomical, the decentralized utilization of wind energy can provide a substantial contribution to development [17, 18 and 19]. A program of wind power for generating electricity as well as for pumping water appears to be attractive for rural development, e.g., lights, radios, televisions. Wind electric generators can be utilized to meet the power requirements of isolated settlements.

Wind energy is found to match well with the demand pattern of the loads, high load during the day for illumination loads at night. Wind is a considerable resource in Sudan (Table 11), where the annual average wind speeds exceeds 5 ms^{-1} in most parts of the country, north latitude 12°N (at the

Table 11 Correlation of Solar Radiation with other Weather Parameters (Yearly Averages)

Stations in Sudan	Mean temp. (°C)	Sunshine duration (h)	Solar radiation (MJm^{-2} day^{-1})	Wind velocity (ms^{-1})	Relative humidity (%)
Port Sudan	28.4	9.0	20.87	5.1	65
Shambat	29.7	9.9	22.82	4.5	31
Wadi Medani	28.4	9.8	22.84	4.5	40
El Fasher	25.8	9.6	22.80	3.4	33
Abu Na'ama	28.2	8.8	21.90	3.1	46
Ghazala Gawazat	27.2	9.3	21.72	3.0	43
Malakal	27.9	7.8	19.90	2.8	54
Juba	27.6	7.8	19.59	1.5	66
Dongola	27.2	10.5	24.06	4.6	27
Toker	28.8	7.3	17.60	4.1	53
Hudeiba	29.3	10.0	22.37	4.0	25
Aroma	29.1	9.6	21.40	4.2	37
El Showak	26.3	9.7	22.90	4.1	39
Zalingei	24.5	8.8	22.98	2.7	39
Babanusa	28.2	8.9	21.73	2.8	48
Kadugli	27.5	8.5	21.30	2.7	48

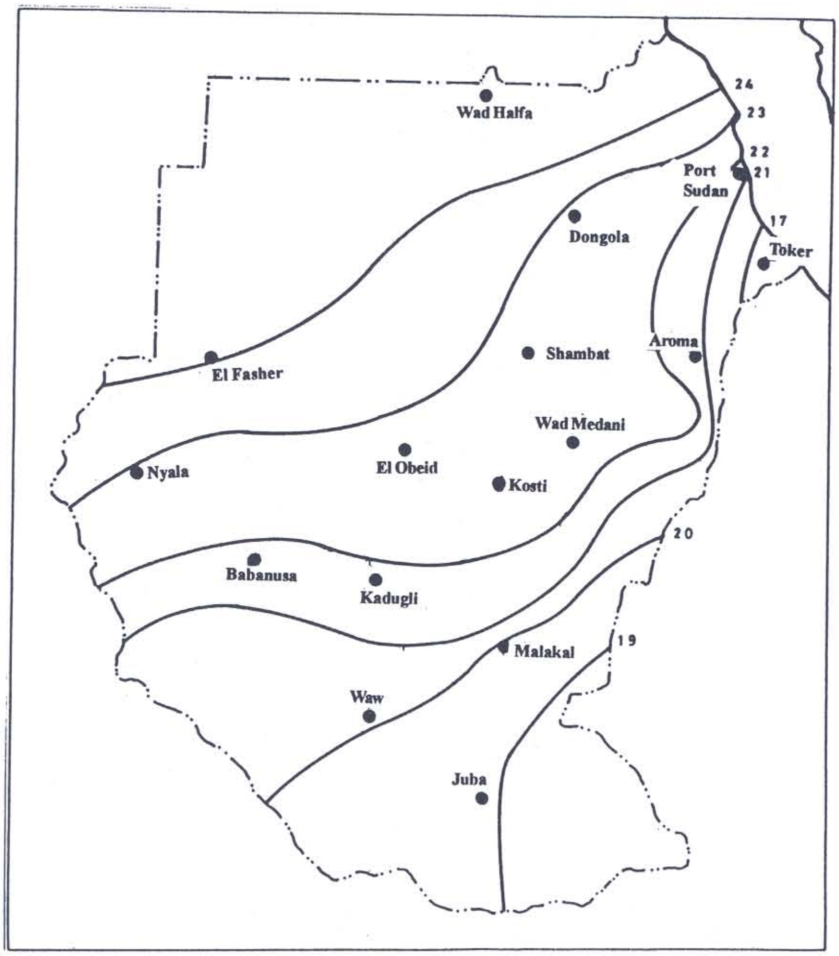

Fig. 1. Yearly average global solar radiation over Sudan ($MJm^{-2}day^{-1}$).

coastal area along the Red Sea), and along the Nile valley (from Wadi Halfa to Khartoum, and south of Khartoum covering the El Gezira area). The southern regions have the poorest potential because of the prevailing low wind speeds as shown in Fig. 2.

In Sudan, wind energy is currently used mainly for water pumping as shown in Table 12. Wind has not yet been significantly exploited for power generation. Experience in wind energy in Sudan started in the 1950's, where 250 wind pumps from Australian government, had been installed in El Gezira Agricultural Scheme (Southern Cross Wind Pumps). These machines gradually disappeared due to a lack of spare parts and maintenance skills combined with stiff competition from relatively cheap diesel pumps. However, the government has recently begun to recognize the need to reintroduce wind pump

Table 12 Number of Wind Pumps Installed for Irrigation in Sudan

Location	No. of pumps
Tuti island	2
Jebel Awlia	1
Soba	4
Shambat	4 (one was locally manufactured)
Toker (eastern Sudan)	2 (both locally manufactured)
Karima (northern Sudan)	2 (both locally manufactured)
Total	15

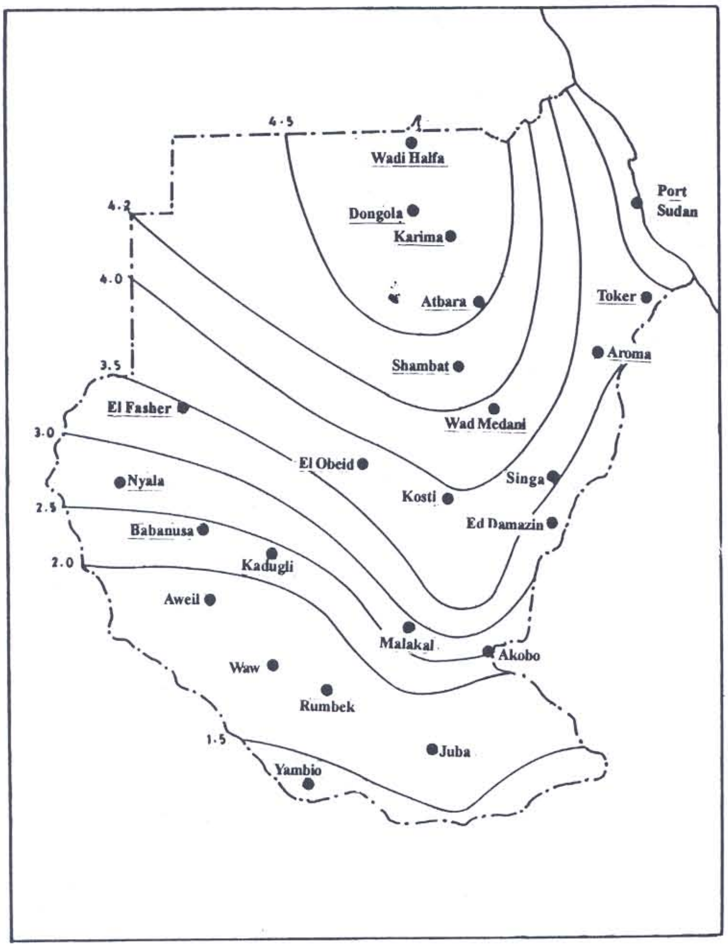

Fig. 2. Annual average wind speeds of Sudan (ms^{-1}).

technology to reduce the country's dependence on foreign oil. This would increase economic security, given high and/or fluctuating oil prices, and would help to reduce the trade deficit. Using wind power also allows for pumping in rural areas where transportation of oil might be difficult.

In the last 15 years the Energy Research Institute (ERI) installed 15 Consultancy Services Wind Energy Developing Countries (CWD 5000 mm diameter) wind pumps around Khartoum area, Northern state, and Eastern state. Now ERI with cooperation of Sudanese Agricultural Bank (SAB) plans to use 60 wind pumps for water pumping in agricultural schemes. However, due to lack of financial support, these wind pumps have not been manufactured yet.

A sizing of wind pump for drinking and irrigation purposes usually requires an estimation of hourly, daily, weekly, and monthly average output. The method for making such estimation is combining data on the wind pump at various hourly average wind speeds with data from a wind velocity distribution histogram (or numerical information on the number of hours in the month that wind blows within predefined speed). The result is given in Table 13, which gives the expected output of wind pump in various wind speeds, and the statistical average number of hours that the wind blows within each speed range.

Generally it is concluded that wind pump systems have a potential to fulfill water lifting needs, both in Khartoum area and even in remote rural areas, for irrigated agriculture and water supply for human and livestock needs. This conclusion is based on:

- Studies of several agencies dealing with the feasibility of wind pumps [28, 29].
- The history of water pumping in the Gezira region for drinking purposes [30, 31].
- The national policy of Sudan vis a vis wind energy [6, 11].

Sudan is rich in wind; mean wind speeds of 4.5 ms^{-1} are available over 50% of Sudan, which is well suited for water lifting and intermittent power requirements, while there is one region in the eastern part of Sudan that has a wind speed of 6 ms^{-1} which is suitable for power production. In areas where there is wind energy potential but no connection to the electric grid the challenge is simplicity of design, and higher efficiency [20]. Because of this potential for fulfilment of rural water pumping needs, it is recommended to continue the development of wind pumping in Sudan.

The most practical location to start with seems to be the northern regions because of a combination of:

- Favorable wind energy potential;
- Shallow groundwater level, i.e. 5 m to 10 m depth; and
- Existing institutional infrastructures.

The research and development in the field of wind machines should be directed towards utilizing local skills and local available materials. Local production of wind machines should be encouraged in both public and private organizations.

4.3. Biomass Resources

Agriculture is the source of a considerable sum of hard currency that is needed for the control of balance of payment in the country's budget. It is also the major source of raw materials for local industry. Biomass resources play a significant role in energy supply in Sudan as in all other developing countries. Biomass resources should be divided into residues or dedicated resources, the latter including firewood and charcoal from forest resources as shown in Table 14. Approximately 13.8 x 10^6 m^3 of biomass are consumed per year. To avoid resource depletion, Sudan is currently undergoing a reforestation program of 1.05 x 10^6 hectares.

Biomass residues are more economically exploitable and more environmentally benign than dedicated biomass resources. There exist a variety of readily available sources in Sudan, including agricultural residues such as sugar cane bagasse, and molasse, cotton stalks, groundnut shells, tree/ forest residues, aquatic weeds, and various animal wastes as shown in Table 3.

Table 13 Wind Speeds Versus Wind Pump Discharges

Wind speeds (ms^{-1})	Annual duration (h)	Output rate (m^3h^{-1})
3.0	600	0.3
3.5	500	1.4
4.0	500	2.3
4.5	400	3.0
5.0	500	3.7
5.5	450	4.3
6.0	450	4.7
6.5	300	5.2
7.0	300	5.7

Table 14 Annual Biomass Energy Consumption Pattern in Sudan (10^3 m^3)

Sector	Firewood	Charcoal	Total	Percent (%)
Residential	6148	6071	12219	88.5%
Industrial	1050	12	1062	7.7%
Commercial	32	284	316	2.3%
Quranic schools	209	0	209	1.5%
Total	7439	6367	13806	-
Percent (%)	54%	46%		100.0%

Direct burning of fuelwood and crop residues constitutes the main usage of biomass in Sudan, as is the case with many developing countries. However, the direct burning of biomass in an inefficient manner causes economic loss and adversely affects human health. In order to address the problem of inefficiency, research centers around the country are investigating the viability of converting the resource to a more useful form, namely solid briquettes and fuel gas. Briquetting is the formation of a char (an energy-dense solid fuel source) from otherwise wasted agricultural and forestry residues. One of the disadvantages of wood fuel is that it is bulky and therefore requires the transportation of large volumes. Briquette formation allows for a more energy-dense fuel to be delivered, thus reducing the transportation cost and making the resource more competitive. It also adds some uniformity, which makes the fuel more compatible with systems that are sensitive to the specific fuel input [21].

Briquetting of agricultural residues in Sudan started since 1980, where a small briquetting plant used groundnut shells in Khartoum. The second plant was introduced in Kordofan (western Sudan) with a capacity of 2 tons per hour (i.e., maximum 2000 tons per season). Another, prototype unit was installed in Nyala with a capacity of 0.5 tons per hour (i.e., 600 tons per season). In central Sudan, a briquetting plant of cotton stalks was installed at Wad El Shafie with a capacity of 2 tons per hour (i.e., 2000 tons per season). The ongoing project in New Halfa is constructed to produce 1200 tons per season of bagasse briquettes [22]. A number of factories have been built for carbonisation of agricultural residues, namely cotton stalks. The products are now commercialized. More than 2000 families have been trained to produce their cooking charcoal from the cotton stalks.

In Sudan, most urban households burn charcoal on traditional square "Canun" stove that has very low fuel-to-heat conversion efficiencies. The following prototypes were all tried and tested in Sudan:

- The metal clad Kenyan Jiko,
- The vermiculite lined traditional Kenyan Jiko,
- The all-ceramic Jiko in square metal box,
- The open draft Dugga stoves,

- The controlled draft Dugga stoves, and
- The Umeme Jiko "Canun Al Jadeed"

The following local traditional stoves were tested, improved, invested, and commercially used in Sudan [23]:
- Traditional muddy stoves,
- Bucket stoves, and
- Tin stoves.

Another area in which rural energy availability could be secured where woody fuels have become scarce, are the improvements of traditional cookers and ovens to raise the efficiency of fuel saving. The rural development is essential and economically important since it will eventually lead to better standards of living, people's settlement, and self sufficiency in the following:
- Food and water supplies,
- Better services in education and health care, and
- Good communication modes.

Gasification is based on the formation of a fuel gas (mostly CO and H_2) by partially oxidizing raw solid fuel at high temperatures in the presence of steam. The technology, initially developed for use with charcoal as fuel input, can also make use of wood chips, groundnut shells, sugar cane bagasse, and other similar fuels to generate capacities from 3 kW to 100 kW for biomass systems. Three gasifier designs have been developed to make use of the diversity of fuel inputs and to meet the requirements of the product gas output (degree of cleanliness, composition, heating value, etc.) [23, 32 and 33].

Furthermore, Sudan is investigating the potential to make use of more and more of its waste. Household waste, vegetable market waste and waste from the cotton stalks, leather, pulp and paper industries can be used to produce useful energy either by direct incineration, gasification, digestion (biogas production), fermentation, or cogeneration.

The use of biomass through direct combustion has long been and still is the most common mode of biomass utilization as shown in Tables 15, 16, and 17. Examples for dry (thermo-chemical) conversion processes are charcoal making from wood (slow pyrolysis), gasification of forest and agricultural residues (fast pyrolysis), and of course, direct combustion in stoves, furnaces, etc. Wet processes require substantial amount of water to be mixed with the biomass.

4.4. Biogas Technology

Presently, Sudan uses a significant amount of kerosene, diesel, firewood, and charcoal for cooking in many rural areas. Biogas technology was introduced to Sudan in mid-1970s when GTZ designed a unit as part of a project for water hyacinth control in central Sudan. Anaerobic digesters producing biogas (methane) offer a sustainable alternative fuel for cooking that is appropriate and economic in rural areas. In Sudan, there are currently over 200 installed biogas units, covering a wide range of scales appropriate to family, community, or industrial uses. The agricultural residues and animal wastes are the main sources of feedstock for larger scale biogas plants.

There are in practice two main types of biogas plants that have been developed in Sudan; the fixed dome digester, which is commonly called the Chinese digester (120 units each with volumes 7 m^3 to 15 m^3). The other type with floating gasholder known as Indian digester (80 units each with volumes 5 m^3 to 10 m^3). The solid waste from biogas plants adds economic value by providing valuable fertilizer as by products.

Biogas technology does not only provide fuel, but is also important for comprehensive utilization of biomass forestry, animal husbandry, fishery, development of the agricultural economy, protecting the environment, realizing agricultural recycling, as well as improving the sanitary conditions in

Table 15 Biomass Residues, Current Use, and General Availability

Type of residue	Current use / availability
Wood industry waste	No residues available
Vegetable crop residues	Animal feed
Food processing residue	Energy needs
Sorghum, millet, wheat residues	Fodder, and building materials
Groundnut shells	Fodder, brick making, direct fining oil mills
Cotton stalks	Domestic fuel considerable amounts available for short period
Sugar, bagasse, molasses	Fodder, energy need, ethanol production (surplus available)
Manure	Fertilizer, brick making, plastering (Zibala)

Table 16 Effective Biomass Resource Utilization

Subject	Tools	Constraints
Utilization and land clearance for agriculture expansion	• Stumpage fees • Control • Extension • Conversion • Technology	• Policy • Fuel-wood planning • Lack of extension • Institutional
Utilization of agricultural residues	• Briquetting • Carbonisation • Carbonization and briquetting • Fermentation • Gasification	• Capital • Pricing • Policy and legislation • Social acceptability

Table 17 Agricultural Residues Routes for Development

Source	Process	Product	End use
Agricultural residues	Direct	Combustion	Rural poor Urban household Industrial use
	Processing	Briquettes	Industrial use Limited household use
	Processing	Carbonization (small scale)	Rural household (self sufficiency)
	Carbonization	Briquettes Carbonized	Urban fuel
	Fermentation	Biogas	Energy services Household Industry
Agricultural, and animal residues	Direct	Combustion	(save or less efficiency as wood) (similar end use devices or improved)
	Briquettes	Direct combustion Carbonized	Use Briquettes use
	Carbonization	Briquettes	Use
	Carbonization Fermentation	Biogas	

rural areas. The introduction of biogas technology on a wide scale has implications for macro planning such as the allocation of government investment and effects on the balance of payments. Factors that determine the rate of acceptance of biogas plants, such as credit facilities and technical backup services, are likely to have to be planned as part of general macro-policy, as do the allocation of research and development funds [21].

4.5. Sugar Cane Biomass

Residuals from the sugar cane industry represent by far the most important source of current and potential biomass resources in Sudan. The sugar industry in Sudan goes back fifty years and Sudan has been one of the world's leading sugar producers. Sugar cane plantations cover one-fifth of the arable land in Sudan. In addition to raw sugar, Sudan enterprises produce and utilize many valuable cane co-products for feed, food, energy and fibre. At present, there are five sugar factories as illustrated in Table 18.

Sugar cane bagasse and sugar cane residues already provide a significant amount of biomass for electricity production, but the potential is much higher with advanced cogeneration technologies. Most sugar factories in Sudan, as elsewhere in the developing world, can produce about 15 kWh to 30 kWh per ton of cane. If all factories were fitted with biomass gasifier-combined cycle systems, 400 kWh to 800 kWh of electricity could be produced per ton of cane, enough to satisfy all of Sudan's current electricity demand. Some of sugar plants are near electric grids (Kenana, El Genaid and Sennar) and others have their own grids.

In Sudan there are no alcohol distilleries since 1983. Three factories were closed due to Islamic Laws. The current circumstances suggest that Sudan should consider expanding production for use as transportation fuel, but this option has not yet been pursued. The alcohol is used for a variety of applications, mainly for medical purposes and rum production. Blending with gasoline would also have direct environmental advantages by substituting for lead as an octane enhancer.

Table 18 Sugarcane Bagasse Available
Sudan (10^3 tons)

Factory	Design capacity	Yearly bagasse
Kenana	300	266
El Genaid	60	53
New Halfa	75	65
Sennar	100	58
Asalaia	100	60
Total	635	502

4.5. Hydropower

Hydropower plants are classified by their rated capacity, such as, micro (< 50 kW); mini (50 kW to 500 kW); small (500 kW to 5 MW); and large (> 5 MW). The plants and the 10^6 W generated by the plants are given in Table 5, accounting for about 1% of the total power available in Sudan where hydropower potential is promising. A number of prospective areas have been identified by surveys and studies have been carried out for exploration of mini-hydropower resources in the country. Mini and micro hydro can be utilized or are being utilized in two ways:

- Using the water falls from 1 m to 100 m; power can be generated up to 100 kW.

- Using the current flow of the Nile river, i.e., the speed of the Nile river current. This can be used in run-of-the-river turbines (current river turbines), and then water can be pumped from the Nile to the riverside farms. There are more than 200 suitable sites for utilization of current river turbines along the Blue Nile and the main Nile [24].

The total potential of mini-hydro is 67000 mWh for southern region, 3785 mWh in Jebel Marra area, and 44895 mWh in El Gezira and El Managil canals. Small-scale hydro plants (under 5 mW) are more environmentally benign than the large-scale hydro projects that often involve huge dams and permanent restructuring of the landscape. These smaller plants are perfectly suited for some regions of Sudan where there is plenty of rainfall and a mountainous or hilly landscape such as Jebel Marra. Table 8 lists the current distribution of electric power for different states in Sudan (mainly from hydro 55%, and thermal generation 45%). The hydropower is consumed in Khartoum, Central and East states.

4.6. Geothermal Energy

In Sudan geothermal resources have been identified [25], and the following sites are expected to have a significant potential:

- Volcanic Jebel Marra area,
- The Red Sea littoral (Suwakin area),
- Volcanic territories, and
- Some other remote areas.

Scientific studies are needed on the above sites for the geothermal energy availability, and then the economic, and social studies can be done.

5. ACHIEVEMENTS AND THE FUTURE

In 1991, Sudan created the Ministry of Higher Education and Scientific Research (MHESR) and was given responsibility for all matters relating to non-conventional/renewable energy. It undertakes the role of renewable energy policymaking, planning, promotion, and coordination. In recent years Energy Research Institute (ERI)-National Centre for Research (NCR)-MHESR has overseen the development of a broad base of technologies including biogas plants, solar thermal and PV systems, wind turbines, small and micro hydropower units, energy from urban and industrial wastes, and even improved cooking stoves. Table 19 summarizes the current status of renewable energy development in Sudan.

Under the present federal system, Sudan is divided into 26 states. This made regional development planning a more important tool for the utilization of natural resources particularly planning for the utilization of renewable energy sources. The role of renewable energy is big in solving essential live problems especially in rural areas for people and their resource development like the availing of energy for the medical services for people and animal, provision of water, education, communication and rural small industries. Consequently the energy plan includes:

- Installation of 200 solar pumps in the rural areas every year to achieve self-sufficiency of drinking water in areas suitable for solar applications;
- Utilization of solar energy for telecommunications to cover by the end of the plan all existing airports, the railway stations, the remote hospitals and microwave stations through the installation of 300 units;
- Lighting of rural areas at a level of 2 mW every year (8 mW for 10 years of the program);
- Popularise the use of solar refrigerators by the installation of 300 units per year for vaccines and medicines preservation for human beings and animals;
- Supply distilled water by producing 1000 m^3 of distilled water for the medical purposes every year;

Table 19 Renewable Energy Achievements in Sudan

Source/system	Status (units, as of July 2000)
Industrial solar heaters (16 m^2 to 80 m^2)	150
Solar cookers	2000
Solar stills (1 m^2 to 10 m^2)	100
Solar dryers	10
PV solar refrigerators (120 W to 250 W)	200
PV communication systems	30
PV solar water pumps (1.5 kW to 5.5 kW)	120
PV solar lighting systems (40 W to 1.5 kW)	1000
Wind pumps (diameters 2.4 m to 7.4 m)	25
Wind generators (research facilities)	4
Biomass gasifiers	3
Improved stoves	25000
Briquetting plants (600 to 2000 tons per season)	5
Biogas plants	200
Current driven turbines	10

- Solar water heating in hotels, hospitals, and relevant industries through the installation of 500 units every year;
- Disseminate the use of solar cookers in the northern states for household use through the production of 1000 units every year;
- Production of 60 wind pumps for Sudan rural areas;
- Production of 200 current driven pumps per year;
- Installation of 50 biogas units per year; and
- Support research and development for:
  - Biomass gasifiers (stand-alone),
  - Biomass combustion/gasifier,
  - Bagasse based cogeneration,
  - Ethanol production from sugar cane,
  - Floating pumps,
  - Wind generators,
  - Solar collectors, and
  - Solar dryers.

6. PRIVATIZATION AND PRICE LIBERALIZATION IN ENERGY SOURCE SUPPLIES

The strategy of price liberalization and privatization in some products of agriculture, industry and energy sectors has been implemented over the last two years and has had a positive result on government deficit and restriction of imports. The investment law approved recently has good statements and rules on the above strategy in particular to agriculture and industry areas.

The privatization and price liberalization in energy fields has to re-structure (but not fully). Availability and adequate energy supplies to the major productive sectors. The result is that, the present situation of energy supplies is for better than ten years ago. The investment law has also encouraged the participation of investors from the national level as well as from partner countries to invest in energy sources supply such as:

- Petroleum products (import in particular) in the northern states.
- Electricity generation (in some states) through providing large diesel engine units.

The implementation of electricity price liberalization has to some extent release the National Electricity Corporation (NEC) from the heavy dependency of government subsidies, and a noticeable improved of NEC management and electricity supplies are achieved.

7. ENVIRONMENTAL ASPECTS

From Tables 20 and 21 it is noticed that 92% of CO_2 emissions in Sudan were from land-use change. The per capita CO_2 emission was estimated at 0.15 x 10^3 tons, which is considered very low compared to average of Africa which is 1.03 x 10^3 tons per capita CO_2 (world per capita is 4.21 x 10^3 tons) [26]. Gas flaring is the practice of burning off gas released in the process of petroleum extraction and processing, and the CO_2 emission from this is negligible. Due to increasing momentum in oil industry, oil products and the future increase in petroleum products consumption in Sudan the per capita CO_2 emission will be increased. It is expected in the coming decades that the emissions of greenhouse gases from the oil industry and use will certainly increase by a large amount if certain measures of mitigation are not under taken.

7.1. Petroleum Industry Pollution and Greenhouse Gases Emissions

The activities of oil exploration in Sudan began in late 1950s in the coastal areas of Red Sea. The results of exploration indicated that there is considerable amount of natural and liquefied gases in Suwakin and Bashair, and the quantities were estimated between 45 to 326 x 10^9 cubic meters. Considering the increasing oil industry activities in Sudan such as production, refining and export/consumption, as well as the entire fuel cycle (exploration, extraction, preparation/transformation, transportation, storage) pollution including the increase in greenhouse gases, the petroleum industry will be very significant in the forthcoming future. In 1997 about 2 x 10^9 tons of petroleum products were burned in Sudan. This amount will be doubled in the year 2010. There is a shortage of information concerning greenhouse gases in Sudan [26 and 27].

Table 20 Annual Amount of Emissions from Industrial Processes (10^6 tons)

Emissions	10^6 tons
Liquid	3320
Gas	0
Gas flaring	0
Cement manufacturing	84
Total	3404
Per capita CO_2 emissions	0.15

Table 21 Annual Greenhouse Gas Emissions from Different Sources (10^6 tons)

CO_2 emission from land use change	CH_4 from anthropogenic sources				Chlorofluorocarbons
	Solid waste	Oil & gas production	Agriculture	Livestock	
3800	47	N.A.	1	1100	N.A.

7.2. Mitigation Measures

Potential mitigation measures to decrease greenhouse gas (GHG) emissions from the oil industry and minimize the threat of global climate change may include the following:

- Controlling GHG emissions by improving the efficiency of energy use and changing equipment and operating procedures;
- Controlling GHG emission detection techniques in oil production, transportation and refining processes in Sudan;
- More efficient use of energy-intensive materials and changes in consumption patterns;
- A shift to low carbon fuels, especially in designing new refineries;
- Development of alternative energy sources (e.g., biomass, solar, wind, hydro-electrical and cogeneration);
- Development of effective environment standards, policies, laws and regulations particularly in the field of oil industry; and
- Activating and supporting environmental and pollution control activities within the Ministry of Energy and Mining (MEM) to effectively cope with the evolving oil industry in Sudan.

8. RECOMMENDATIONS

1. Embark on energy conservation and pollution reduction to be undertaken without delay:
   - To save on fossil fuel for premium users for export;
   - To accelerate development of new and/or remote lands otherwise deprived of conventional energy sources; and
   - As a preventive measure against shortage of future energy supply against prospective national energy demand.
2. Launch public awareness campaigns among investors particularly small-scale entrepreneurs and end users of renewable energy technologies to highlight their importance and benefits;
3. Utilize the resources in real development which will serve the noble ends of peace and progress instead of wasting them to wars and the arms industry;
4. Develop policies and capabilities of institutions and manpower for long term and more effective solutions. The energy crisis is a national issue and does not only concern the energy sector, therefore the country has to learn to live with and endure the crisis;
5. Invest in research and development through the existing specialized bodies, e.g., Energy Research Institute (ERI);
6. Encourage co-operation between nations, a fact which will be much easier in this era of information and communications revolution;

7. Encourage the household sector to use renewable energy technologies instead of conventional energy by providing incentives from the government;
8. Promote research and development, demonstration and adaptation of renewable energy resources (solar, wind, biomass, and mini-hydro, etc.) among national, regional, and international organizations which seek clean, safe, and abundant energy sources;
9. Execute joint investments between the private sector and the financing entities to disseminate the renewables with technical support from the research and development entities;
10. Promote the general acceptance of renewable energy strategies by supporting comprehensive economic energy analysis taking into account the environmental benefits;
11. Enforce laws regulating and encouraging businesses, tax concessions both to investors and customers and most of all, a sustained, coordinated and well-planned official publicity campaign to enlight, inform and educate the public. In most of the developing countries, the governments acknowledge that renewable energy can resolve many pressing problems. Yet, the matter stops at this level. More action therefore should be taken beyond acknowledgement;
12. Propose solar and wind pumps to replace diesel engines in the predominant irrigation areas to avoid fuel problems (e.g., uncertain availability and skyrocketing prices);
13. Emphasize local manufacture of renewable energy devices whenever possible since limited funding is the main constraint in commercialization and dissemination of the technology. Low cost and reliable devices have to be provided;
14. Encourage training opportunities to personnel at different levels in donor countries and other developing countries to make use of their wide experience in application and commercialization of renewable energy technologies; and
15. Encourage the private sector to assemble, install, repair and manufacture renewable energy devices via investment encouragement and more flexible licensing procedures.

9. CONCLUSIONS

Sudan is an agricultural country and has good resources of energy from agricultural residues, forestry resources and animal wastes. Sudan has an excellent annual mean solar radiation of 5.44 kWh m^{-2} day^{-1} which could be of strategic importance in substituting for oil, electricity, wood and charcoal and in assisting in rural development and improving the quality of life in rural areas.

Sudan is rich in wind; about 50% of Sudan's area is suitable for electricity generation (annual average wind speed is more than 5 ms^{-1}) and 75% of Sudan's area is suitable for water pumping (annual average wind speed of 3 ms^{-1} to 5 ms^{-1}).

Energy is one of the key factors for the development of the national economy. The use of renewable energy resources could play an important role in this context, especially with regard to responsible and sustainable development. It represents an excellent opportunity to offer a higher standard of living to the local people, and will save local and regional resources. Implementation of renewable energy technologies offers a chance for economic improvement by creating a market for producing companies, maintenance and repair services. Production of bio-fuels such as ethanol from sugar cane takes advantage of year-round cultivation potential in a tropical country like Sudan.

Benefits extend from local to regional to national to global. Local rural economies benefit through new economic opportunities and employment in the agricultural sector. Urban regions benefit through cleaner air and health improvements. The nation benefits through substituting domestic resources for costly imported gasoline. The world benefits from reduced CO_2 emissions.

In a country with a high population density, there are extreme pressures on energy and waste systems, which can stunt the country's economic growth. However, Sudan has recognized the potential to alleviate some of these problems by promoting renewable energy and utilizing its vast and diverse climate, landscape, and resources, and by coupling its solutions for waste disposal with its solutions for energy production. Thus, Sudan may stand at the forefront of the global renewable energy community, and presents an example of how non-conventional energy strategies may be implemented.

Biogas plants offer renewable options that are relatively inexpensive and well suited to rural areas. Hydropower will continue to play a role in smaller-scale energy supply. There is also potential for expanding wind and solar applications in Sudan, particularly in rural areas.

Energy efficiency brings health, productivity, safety, comfort and savings to the homeowner, as well as local and global environmental benefits.

10. REFERENCES

1. Omer, A.M. 1995. Rainfall patterns in Sudan. *NETWAS News* 2(7): 4-7.
2. Omer, A.M. 1998. Sudan energy background; an overview. *Renewable Energy* 14 (1-4): 467-472.
3. Omer, A.M. 1999. *Sudan Experience in Biomass Energy*. Khartoum, Sudan.
4. Energy Research Institute (ERI). 1987. *Renewable Energy Resources Potential in Sudan*. Khartoum, Sudan.
5. Omer, A.M. 1997. *Review of Hydropower in Sudan*. Khartoum, Sudan.
6. National Energy Administration (NEA). 1985. *The National Energy Plan 1985-2000*. Khartoum, Sudan.
7. Omer, A.M. 1994. Renewable energy technology applications in the Sudan. In *Proceedings of the 3rd World Renewable Energy Congress*. Reading, UK, 11-16 September. Oxford: Elsevier Science Ltd.
8. Omer, A.M. 1996. Renewable energy potential and future prospect in Sudan. *Agriculture and Development in Arab World* 3(1): 4-13.
9. Omer, A.M. 1996. Biogas technology and environment. *Regional Energy News* 2(4): 2-5.
10. Omer, A.M. 1995. Solar energy technology applications in the Sudan. In *Proceedings of the 1st Jordanian Mechanical Engineering Conference*. Amman, Jordan, 25-28 June. Amman: Jordanian Mechanical Engineering Association.
11. National Energy Administration (NEA). 1983. *Renewable Energy Assessment for the Sudan*. Khartoum, Sudan.
12. National Energy Administration (NEA). 1983. *A Pre-investment Study for Fuel Production from Agricultural Wastes for Power Generation and Household Consumption*. Khartoum, Sudan.
13. Duffie, J. A., and Beckman, W. A. 1980. *Solar Engineering of Thermal Process*. New York: Wiley Interscience.
14. Kirtikara, K. 1983. Solar radiation and measurement. In *Proceedings of Seminar on Solar Energy and Applications*. Bangkok, Thailand.
15. Omer, A. M. 1990. Solar Atlas for Sudan. P. G. Thesis. University of Khartoum (UOK), Khartoum, Sudan.
16. Omer, A. M. 1996. Solar energy potential and future prospect in Sudan. In *Proceedings of the 4th World Renewable Energy Congress*. Denver, USA, 15-21 June. Oxford: Elsevier Science Ltd.
17. Omer, A. M. 1997. Compilation and evaluation of solar and wind energy resources in Sudan. *Renewable Energy* 12(1): 39-69.
18. Omer, A. M. 1998. Horizons of using wind energy and establishing wind stations in Sudan. *Dirasat* 25(3): 545-552.
19. Omer, A.M. 1993. Wind speeds and wind power potential in Sudan. In *Proceedings of the 4th Arab International Solar Energy Conference*. Amman, Jordan, 20-25 November. Amman: Renewable Energy Research Centre.
20. Joop, V.M.; Paul, H.; and Omer, A.M. 1987. *Evaluation of Sudan Wind Energy Project*. The Netherlands: CWD-ERC.
21. Omer, A.M. 1999. *Biomass Energy Potential and Future Prospect in Sudan*. Khartoum, Sudan.

22. National Energy Administration (NEA). 1991. *Energy Handbook*. Khartoum, Sudan.
23. Elamin, S.M.E. 1995. Towards Participative Approach for the Design of Appropriate Energy Technology in Sudan Rural Settings. M.Sc. Thesis. University of Khartoum (UOK). Khartoum, Sudan.
24. Omer, A.M. 1998. *Renewable Energy Potential and Environmentally Appropriate Technologies in Sudan*. Khartoum, Sudan.
25. Omer, A.M. 1998. Renewable energy resources in Sudan. In *Proceedings of the 5th World Renewable Energy Congress*. Florence, Italy, 19-25 September. Oxford: Elsevier Science Ltd.
26. World Resource Institute (WRI). 1994. *World Resources: A Guide to the Global Environment, People and the Environment*.
27. UNIDO. 1997. Changing Courses Sustainable Industrial Development, as a Response to Agenda 21. Vienna, Austria.
28. Eisa E.I.; Costa Ing J.L.; Hoevenaars Ir J.; and Schermerhorn Ir R.E. 1987. Sudan Wind Energy Project Phase 1. 1985-1986. CWD-(SWP). Khartoum, Sudan.
29. Posoriski R.; and Rahman A. 1984. Case studies of the wind potential and its utilisation for water pumping in North Sudan. Special Energy Program (SEP). Khartoum, Sudan.
30. Hamid, Y.H.; and Jansen, W.A.M. 1981. Wind energy in Sudan. CWD Report 81-2. The Netherlands.
31. Abu Baker, E.H. 1988. The boundary layer wind regime at a representative tropical Africa region-Central Sudan. Ph.D. Thesis. Eindhoven University of Technology, The Netherlands.
32. Ali, G.E.; and Ali, S.S. 1993. *Sudan Biomass Energy Issue and Options*. Khartoum: Energy Research Institute (ERI).
33. Ali, S.S. 1997. A preinvestment study for the fuel production from agricultural wastes for power generation and household consumption. Khartoum, Sudan.