Regional Water Supply Planning with Renewable Energy Technologies: The Case of Senegal

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ABSTRACT

In order to plan for the installation of renewable energy technologies in the water supply sector in developing countries, an evaluation of the countries' renewable energy resources must first be made. It is then necessary to match the energy resources with the operating characteristics of the appropriate technologies. When these two stages have been completed, planning can proceed for a national program of renewable energy technology development. The example of Senegal is presented in terms of wind, solar and rainfall resources. Technologies considered are wind energy conversion systems (WECS), rainwater catchment systems (RWCS), hand pumps and solar pumping systems.

INTRODUCTION

There are many countries in the developing world that are in the process of changing their energy base to include a greater utilization of renewable energy technologies. In this transition period there is sometimes a tendency to look for a single answer to the complex problem of energy supply. This probably relates to the past experience where fossil fuels and their derivatives have often supplied most energy needs in conjunction with an electrical network. What is now becoming clear, is that renewable energy technologies provide a vast array of possibilities, often of small scale units. For a developing country one of the first planning issues to be solved is the pattern of dispersement of these diverse technologies.

This paper will discuss some principles of regional planning of renewable energy technologies in the domain of water supply for a developing country. A case history will be given for Senegal in West Africa.

CONVENTIONAL AND RENEWABLE ENERGY TECHNOLOGIES FOR RURAL WATER SUPPLY

There are important differences between conventional technologies, based on fossil fuels and large scale electrical networks as compared with renewable energy technologies. In the context of water supply for rural areas in developing countries the range of small-scale renewable energy technologies includes the following:

- Small scale hydro power systems.
- Gravity feed systems from springs or mountain streams.
- Hand pumps and wells.
- Rainwater catchment systems (RWCS).
- Wind power pumping systems.
- Stream pumping devices (turbines, hydrams).
- Solar pumping devices.

The major differences in the characteristics of conventional energy technologies and renewable energy technologies are the following:

CONVENTIONAL	RENEWABLE ENERGY
1. Large scale	1. Smaller scale
2. Standardized, uniform design	2. A great variety of design choices
3. Fairly sophisticated engineering	3. Generally simpler engineering
4. High quality materials needed for an internal combustion heat cycle	4. Possibility of using local materials with some of the renewable technologies (i.e. hand pumps, wells, RWCS).
5. Environmental pollution is often created	5. Generally less polluting
6. Consists of large networks serving large cities	6. Smaller units scattered in a rural countryside
7. Operation and maintenance (O/M) usually can only be done by skilled technicians.	7. Some aspects of O/M can be done by the users (gravity feed systems, hand pumps, RWCS).

In general, the application of renewable energy technologies is most appropriate in rural areas. Most de-

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veloping countries are mainly rural. Renewable energy (RE) technologies do not provide a single answer to rural energy needs, but instead a wide variety of possibilities.

The problem of matching the suitable RE technology to the variety of environmental conditions that can exist in a country requires careful planning. The conditions prevailing in the rural areas and the characteristics of the various available RE technologies must be well known before the proper match can be made. To illustrate this process, the case of Senegal is described.

SENEGAL

Senegal (Fig. 1) is located between the latitudes 12.5°-16.5° north of the equator. At the most western point of Africa, it falls within of rainfall zone of 200 mm-1500 mm per year and this includes the Sahel zone that has experienced severe drought conditions during the past 15 years. Four river systems exist in the country (the Senegal river, the Gambia river, the Cassamance river and the Sine-Saloum river system). Apart from these river sources and Lake Guier in the North, most of the country is dependent on the groundwater sources, which are abundant in the country though at a deep level [1]. Finally, the country is generally very flat so that it is not possible to use a drop in a flowing river as a power source.

Figure 1. Senegal in its West African context.

Senegal is situated at a cultural crossroads in Western Africa. It is here where the Arabic north meets the tropical south of Africa. The north of Senegal has desertic aspects while the south has tropical foliage, temperatures and rainfall. There is also a dramatic climatic variation from the windswept coastal areas to the inland, hotter and drier areas next to Mali and Mauritania.

Senegal has a scattered and rural population. The 1980 population was 5.7 million distributed over an area of about 200,000 km^2.

It is clear that Senegal offers the possibility of applying a wide range of renewable energy technologies, especially in the areas of wind and solar energy. In order to assess the energy potential of the country it is necessary to have detailed technical data of the country's energy resources.

Senegal offers the possibility of applying a wide range of renewable energy technologies

ENVIRONMENTAL DATA OF SENEGAL

Rainfall

There is a dramatic shift in rainfall patterns from north to south in the country (Fig. 2). The north of the country borders the desertic areas of Mauritania and has an annual rainfall of 300-500 mm/yr., whereas the southern portion of the country has rainfalls in the range of 1000-1500 mm/yr. Most rainfall falls during the period July-October which also corresponds with the hottest season of the year.

Temperatures

Annual average temperatures from 24°C at Dakar to 30°C at the eastern part of the country (Fig. 2). The seasonal fluctuations generally follow patterns of the northern hemisphere. The months November-March can be quite cool along the coast (20°C), and during the hot season, April-October, temperatures can reach into the 40's in the east of the country.

River Flows

The annual average river for the two main rivers are as follows [3]:

Senegal	738 m^3/s
Gambie	172 m^3/s

Because of the highly variable rainfall and minimal bush cover, the river variations are quite large as noted in the average monthly flows for the Sen-

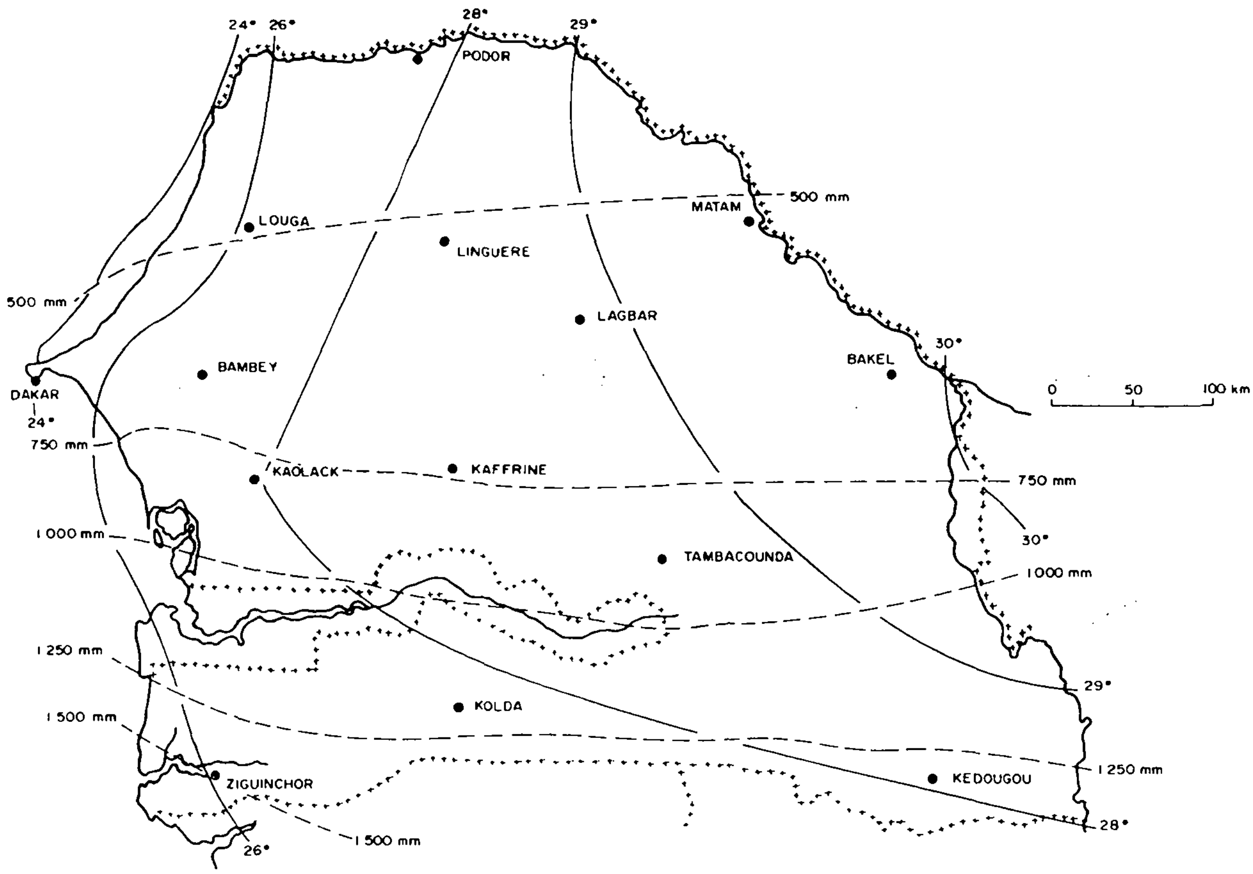

Figure 2. Annual Rainfall and Temperature Data for Senegal [2].

egal river (Table 1). Also 5-yr moving averages of this river flow reveal alternating high flow and low flow periods. Since 1969 the Senegal river has experienced successive low flows so that in 1984 the 5-yr moving mean flow was less than 300 m^3/s [4].

Table 1: Average monthly flows for the Senegal River (m^3/s) [3]

J	F	M	A	M	J	J	A	S	O	N	D
131	75.9	40.7	17.1	8.2	98.3	560	2248	3284	1601	539	249

HYDROGEOLOGY

The hydrogeology of Senegal is characterised by a vast aquifer, called the Maestrichtien which is found at a depth of 150-200 m. This aquifer covers most of Senegal and contains water of good quality under pressure. When pierced by deep boreholes the water typically rises in a tubed well to within 30-40 m of the surface. There are also two other geological strata above the Maestrichtien — the Paloeocene and the Eocene which often contain calcium deposits. Water is found in these aquifers but it is often high in salt content. Finally there is a more recent top layer called the Quatenaire made up of sands and clays. Water of reasonable quality can be found in this shallow aquifer. Water in this aquifer is often close to surface water sources like rivers but because of its limited capacity this aquifer often goes dry in the dry season.

A general picture of the depth to good water is given in Fig. 3, though it should be noted that there are variations due to local topography. For example, in the hilly region near Thies some boreholes pump water from a depth of 60-80 m.

Wind Patterns

In order to know the potential for wind power pumping it is necessary to know both the magnitude and the variation of the wind, since wind energy conversion systems (WECS) utilize high velocity winds much more effectively than lower velocity winds. However the average annual windspeed is useful since experience has shown that regions with a wind regime of 3 m/s can economically extract energy for wind powered pumping using multibladed units. Figure 3 gives the annual windspeed pattern for Senegal. Based on continuously recording instruments and statistical analysis, a cumulative frequency curve for Dakar (Fig. 4) can be derived, which enables one to determine the recuperable energy that can be extracted by a windmill of known characteristics.

Solar Radiation

Senegal is in an area of high solar radiation, but be-

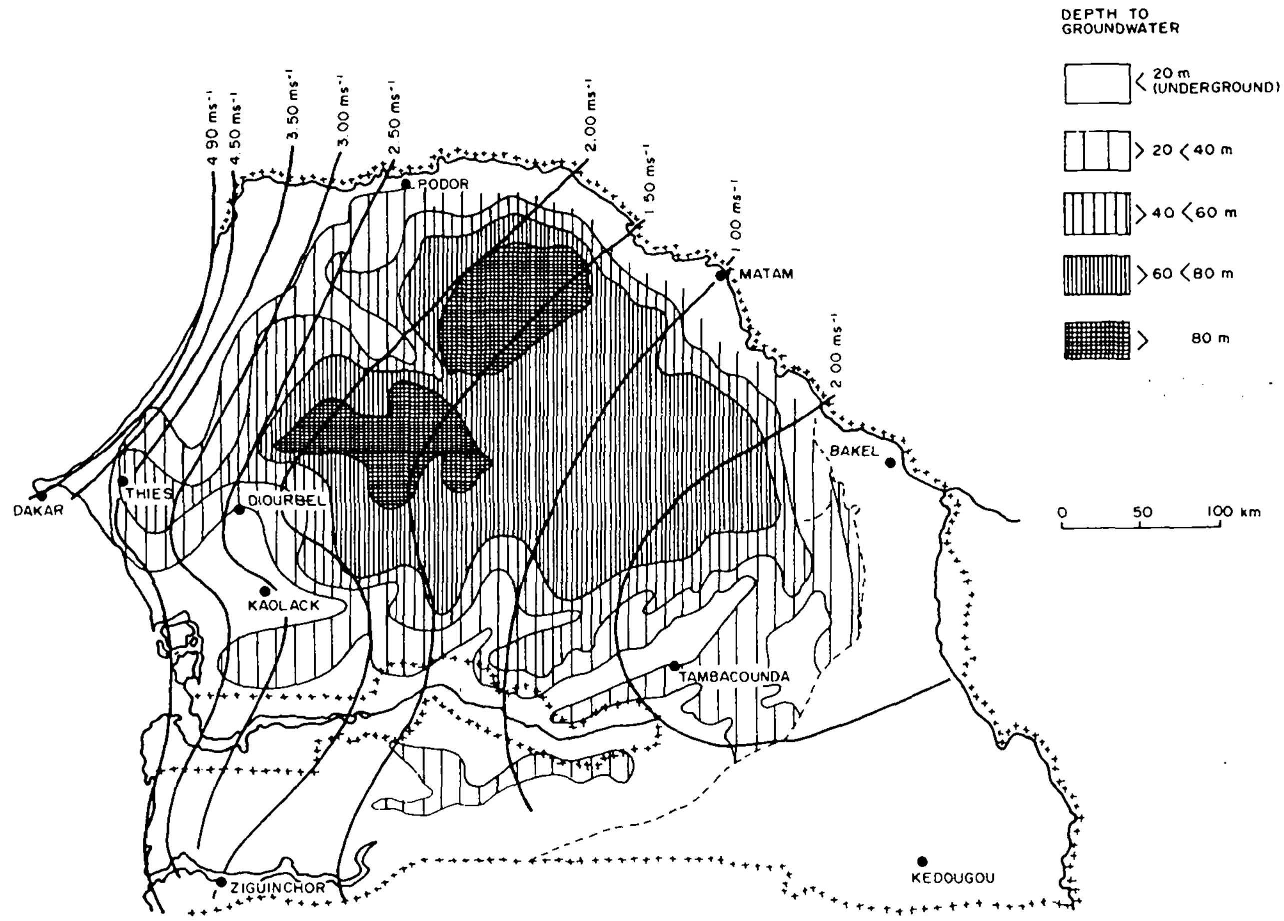

Figure 3. Depth to groundwater and Average Annual Windspeeds in Senegal.

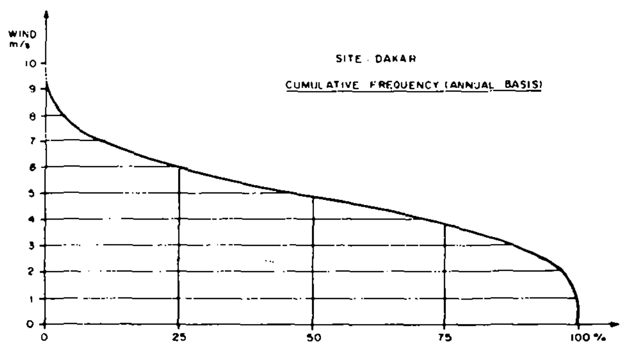

Figure 4. Cumulative Frequency Curve of Windspeeds [2].

cause the network of solar recording stations is limited the spatial variation throughout the country is not known precisely (Fig. 5). The range of solar radiation in the country is between 1600-2200 Kwh/m^2/yr (4.4-6.0 Kwh/m^2/day). In general, the annual variation is ± 15% as demonstrated by the Dakar data [2].

Before installing solar technologies, it is important to know the duration of time that the solar radiation is above a starting threshold (about 300 w/m^2 for photovoltaic pumping units). By means of cumulative frequency curves it is possible to compute the solar energy that can be extracted by various existing technologies. Finally there is the problem of cloudy days when insufficient solar radiation exists and some kind of energy storage needs to be designed. To plan for this eventuality, probability graphs of the number of consecutive cloudy days need to be derived.

Summary

By gathering all available environmental data — meteorological, hydrological and hydrogeological, an assessment of the ability of a country to support renewable energies can be made. However, before a proper match between technology and environment can be made, it is necessary to know the main operating characteristics of the technologies that one intends to install.

OPERATING CHARACTERISTICS OF RENEWABLE ENERGY — WATER SUPPLY TECHNOLOGIES

In any given region it is necessary to select the technologies that may be appropriate to the region. Having selected the list of possible technologies, one can proceed to select the most appropriate technologies

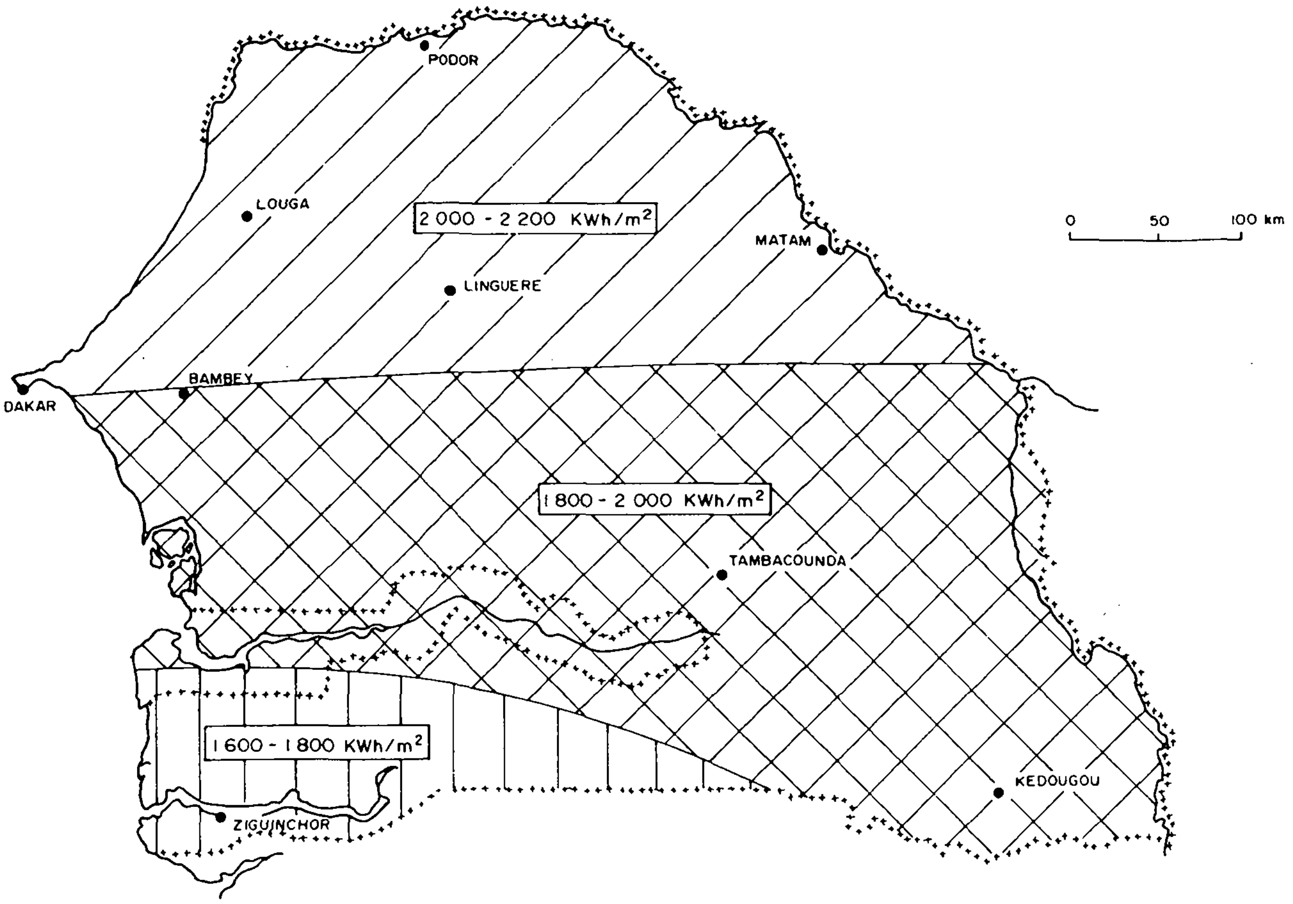

Figure 5. Solar Radiation in Senegal [2].

for given regions in the country.

In Senegal, the following renewable energy technologies for water extraction are considered appropriate:

- Solar pumping
- Wind power pumping
- Hand pumps
- Rainwater catchment systems

Hand Pumps

Hand pumps are now being manufactured in many different sizes and designs [5]. In general, a human can supply 50-70 watts of power (P_{input}) and hand pump efficiencies are in the range of 60-70% so that using the power equation

$$P_{hyd} = \text{efficiency} \times P_{input}$$
$$9.81\ Qh = 0.65 \times 60 = 39$$
$$\therefore\ Qh \cong 4.00$$

in which P_{hyd} = hydraulic power
Q = flow (ℓ/s)
h = head (m)

Generally when the head exceeds 50 m, and thus the flow available is less than 0.08 ℓ/s, hand pumps are not a viable technology. Rural hand pumps usually can operate between 6-12 hours per day and supply populations in the range of 100-400 persons, depending on the depth to groundwater and the type of hand pump employed.

Rainwater Catchment Systems (RWCS)

In order to be viable, RWCS require

- a significant rainfall, without long dry periods.
- the presence of impermeable roof tops
- the eventual construction of a reservoir tank

The rainfall in the southern half of the country would justify the exploitation of RWCS. To estimate the potential, it is necessary to know the impermeable roof area per person. The annual rainfall x roof area/person will give the average annual rainfall that can be trapped by a system. This supply needs to be compared with the demand, which for rural areas can be estimated at 40 ℓ/p/day x 365 days

$$= 14.6\ m^3/\text{person/year}$$

RWCS often cannot supply all the domestic water needs, but they can supplement other sources of water supply especially during the rainy season, which is also the busy farming season. The amount of water (m^3/person) to be supplied from other sources

= Demand − Supply

* $= 14.6 - \dfrac{\text{RF(mm)} \times \text{Roof area/person } (m^2)}{1000}$

Wind Power Pumping

The power in the wind (P_w) is a function of the velocity cubed as follows:

$$P_w = \frac{1}{2} \varrho V^3 A$$

in which ϱ = mass density of air (kg/m^3)
V = velocity of wind (m/s)
A = cross sectional area exposed to wind (m^2)

The power that can be extracted from the wind is given by

$$P_e = C_p \frac{1}{2} \varrho V^3 A$$

in which C_p represents the coefficient of performance of the windmill. The above demonstrates that high bursts of wind are most important in extracting energy, though of course winds of tornado proportions ($V \geq 20$ m/s) are dangerous, and thus braking devices are required on wind energy conversion systems (WECS).

The amount of energy that can be extracted from the wind is a function of the machine efficiency as expressed by C_p. Betz has calculated that for an ideal machine C_p cannot exceed 0.37, so it is possible to calculate the maximum wind energy that can be extracted, as has been done in Senegal [2]. The value of C_p for the multi-bladed windmills utilized in Senegal ranges between 0.2-0.3.

Solar Pumping

There are two main methods to utilize solar energy for water pumping.

One can use a thermodynamic system which uses solar energy to cause a change of state in a working fluid and thus work can be done on a piston or turbine, which in turn drives a water pump. This method has been tried in developing countries and has found to be too complicated, expensive and difficult to maintain.

The preferred method of solar pumping nowadays is to use panels of photovoltaic (PV) cells which generate electricity to drive an immersed motor-pump system. These systems are being widely tested and applied in the Sahel areas of Africa.

In general, the PV panels are the most reliable aspect of the system although the efficiency does drop with increasing temperature and some deterioration occurs with time (5-10% in 5 yrs.). The life expectancy of such panels is of the order of 10-15 years, but the newer models claim a 20 year life expectancy.

The preferred method of solar pumping nowadays is to use panels of photovoltaic cells

The main concern with PV pumping systems is their cost. A recent World Bank sponsored study has compared solar pumping systems with other energy options in terms of their cost [6]. Solar pumping systems are presently quite expensive (about $5-8(US) per watt for the PV panels), but their cost is dropping and is expected to drop in the future. At present, small scale solar applications are an economical way of pumping water in remote regions. A recent report gives the following criteria for solar pumping feasibility:

> "For rural water supply applications, solar pumping systems are becoming cost competitive compared to diesel pumps where the average daily energy equivalent is less than 250 m^4 (for example 25 m^3/day through a head of 10 m) and where the monthly average solar irradiation is greater than 10 MJ/m^2 per day" [7].

The above cost figures include the cost of maintenance of both diesel and solar pumping systems. Solar pumping systems have experienced significant maintenance problems in West Africa [8, 9]. However, maintenance procedures are being improved. A recent report from Mali [9] describes in detail maintenance procedures and their costs, which for that area averaged about US$0.08 per m^3 of water delivered in 1986 [10].

The typical efficiency from the solar electrical input to hydraulic output is 30-45 per cent. However the total efficiency of the system (solar energy input-hydraulic output) is of the order of 5% so that at present rather extensive panel arrays are needed even for small sized systems (Fig. 6).

At present solar pumping units find a niche between hand pumps for smaller applications and diesel-motor pumping systems for larger applications (Fig. 7). In fact, these applications do not need to be competitive. A solar pumping device can be installed to provide a basic water flow, with hand pumps (for small systems) and diesel motor-pumps (for larger systems) providing the surplus water in excess of solar pumping supply.

Summary

Having determined the environmental setting of a region in terms of its ability to support renewable energy technologies and knowing the main operating parameters of the appropriate renewable energy technologies, it is then possible to prepare a plan of energy development for a region or a country. To illustrate this process the example of Senegal is described.

MAJOR ENERGY REGIONS IN SENEGAL

Senegal can be divided into major energy regions as follows:

NUMBER OF PERSONS	NUMBER OF CATTLE	IRRIGATED SURFACE	FLOW IN m^3/DAY
10 000	5 000	3,2	200
5 000	2 500	1,6	100
2 500	1 250	0,8	50
1 000	500	0,3	20
500	250	0,16	10
250	125	0,08	5
20 l/d/pers	40 l/d/head	60 m^3/ha/d	

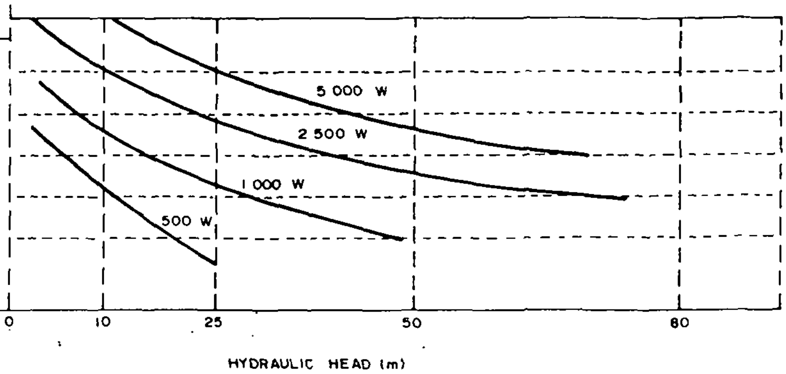

Figure 6. A Typical Design Chart for Small Scale Solar Pumping Systems [11].

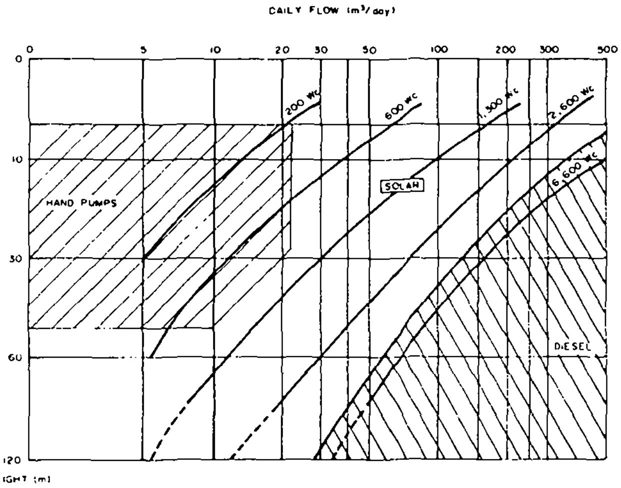

Figure 7. Pumping Regimes in terms of Head and Discharge [11].

Coastal region

This region which extends from the northern border with Mauritania to the southern border with Gambia is about 50 km in width. In this region the average annual wind speed is ≥ 3m/s and the water table is usually within 40 m of the surface.

River regions

This represents the land bordering the Senegal river and the Gambia river in the Tambacounda region. The river flow is abundant, though variable with a noticeable flood cycle. For most of this region the wind energy is limited (≤ 3 m/s). The solar radiation is abundant being in the range 2000-2200 Kwh/m^2/yr along the Senegal river and 1800-2000 Kwh/m^2/yr along the Gambia river. Water tables within a few kilometres of these rivers are usually within 30 m.

Central Bushland — Pastoral Area

The region is characterized by a high solar radiation, reduced wind speeds and limited rainfall. This area is in fact the driest and least productive area of the country. It has been hardest hit by the recent drought conditions. It is also the area where the depth to the water table is the greatest, thus making pumping of groundwater most difficult.

Southern Cassamance Region

This region receives the largest amount of rainfall (1000-1500 mm/yr). The vegetation is tropical in this area. The wind speeds are reduced, and the groundwater is near the surface (mostly ≤ 20 m). The Cassamance river flows through this region.

Summary

When choosing the technology for a site, it is obvious that very windy sites tend to favor wind power pumping and very sunny sites tend to favour solar pumping. However, a precise quantitative comparison based on cost is still required to make the most economic choice. In order to be economically competitive the annual cost (Capital + O/M costs) computed over the lifetime of the technology per volume of water delivered should be the lowest of all other choices.

At present solar pumping does not benefit from economics of scale to a great extent because of the dominant cost of the solar PV panels. The first Kw of power costs nearly as much as the hundredth Kw of power. For this reason, solar plants tend to be most economical for small systems, although this situation is expected to change with decreasing PV panel costs. At present, solar systems of less than 1 Kwh/day are clearly economic, whereas systems in the range 1-10 Kwh/day can be competitive but the initial capital costs can be prohibitive for small rural areas. Systems great-

At present solar pumping does not benefit from economics of scale

er than 10 Kwh/day are not yet viable with solar pumping systems.

Another factor that can influence cost comparisons is the depth to which groundwater needs to be pumped. Studies have shown [6] that whereas hand pumps are most economical for lower lifts, wind and solar technologies become more economical as the depths to the water table reaches the range of 20-30 m.

A PLAN FOR RURAL WATER SUPPLY ENERGY DEVELOPMENT FOR SENEGAL

Considering the major regions existing in Senegal, the following is proposed as a pattern of rural technology development for Senegal:

Coastal Regions

The wind regime is very favourable for the exploitation of wind power, therefore the installation of WECS in the region should be given first priority. In fact windmills are already being installed in this region.

As a second priority, hand pumps can find an application for scattered small settlements in this region where the water demands are not high, and the water table occurs within 40 m.

River Regions

Areas along the river regions are now being used for irrigated farming. At present most of these areas are being irrigated with diesel driven motor pumps units. However, the solar radiation in this area is very favourable to solar pumping. At present solar pumping at lower lifts are quite economical for irrigated farming. Recent estimates [7] state that irrigated farming is now economical where the peak daily energy equivalent is less than about 150 m^4 and where the minimum monthly average solar irradiation is greater than about 15 $MJ/m^2/day$ [7]. In these Sahel regions the radiation exceeds this minimum limit. For direct pumping from the river, the lift is in the order of 5 m so that 30 m^3 can be economically pumped by solar means. This means that small irrigated plots (of the order of ½ ha) can be economically irrigated with solar pumping.

Along the river edges water can often be found at modest depths of 20-30 m. In this range hand pumps can be envisioned for domestic water supply for small scale farmers.

Central Bush Land — Pastoral Area

In this area water is usually found at large depths. The wind regime is not very favourable to wind power development and rainfall is relatively sparse. This means that WECS and hand pump exploitation will be difficult. Rainwater catchment systems will only have a limited application and in any case impermeable roof tops are rare in this region.

The region has abundant solar radiation but at present solar pumping units are limited to depths of about 20-30 m [6] although experimental work is being done on units that may be able to pump from depths of 60-80 m [12].

Presently diesel-driven pumping units are the most appropriate means of obtaining water in this region. As a result of past experiences in this fragile ecozone, some control will need to be placed on the rate of extraction of water. If excessive water is available, cattle can multiply too fast and denude the scant grass cover, thus exacerbating the problems of erosion in the region. Small scale renewable energy technologies, like hand pumps and small scale solar systems provide their own control. With fossil fuel systems the control needs to be either economic or imposed by planning regulations.

In this zone there are still some isolated areas with small population groupings where renewable energy technologies can be appropriate. If the numbers are small (200-300 people) and the water table is not too deep (≤ 50 m), it is possible to install some of the newly developed hand pumps for deep wells, such as the India Mark II model. Finally, if solar pumping tests for deep well applications are successful, some solar units may serve isolated communities in this region in the near future.

If excessive water is available, cattle can multiply too fast and denude the scant grass cover

Southern Cassamance Region

In this region the wind regime does not favour wind pumping, and solar radiation is more limited, thus making solar pumping less effective, though still a possibility in some special cases.

The rainfall is abundant here so that RWCS systems could be very appropriate. Given that an average inhabitant has an impermeable roof area of 6 m^2 and the average RF is 1250 mm/yr, the amount of water that can be collected from rainfall is $\frac{1250}{1000} \times 6 = 7.5$ m^3 which represents about 50% of the domestic water requirements.

The area is also very favourable to the exploitation of sanitary open wells and hand pump installations. Most of the water table is within 20 m which favours the installation of small lightweight hand pumps which have the potential of being eventually manufactured within the country.

Finally the presence of the Cassemance river offers the possibility of irrigated farming within the dry season. The solar radiation range 1600-1800 $Kwh/m^2/yr = 4.4 - 4.9 Kwh/m^2/day = 15.8 - 17.6 MJ/m^2/day$ still falls within the range of economical solar pumping for irrigated farming, so that small scale solar pumping systems are feasible here as with the Senegal river in the north.

CONCLUSIONS

The development of small-scale renewable energy technologies in rural areas of developing countries requires careful planning. The renewable energy potential must be carefully measured and analyzed throughout the country. The limitations of the existing RE technologies must be understood as well as the comparative economics of their operation. When these factors are known, an overall plan for energy development of the countryside can be initiated.

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