Design of a Rural Hybrid pumping System

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Abstract

A hybrid powered pumping system capable of supplying 40 m³ of water per day at a head of around 25 m has been designed. Design criteria are based on requirement for drinking water supplies to small village in the Sudan. The system consists of three technologies: wind pump, solar pump and diesel pump. Simulations of the volume of water pumped during standard solar day of 4kWh/m² and average wind speed of 3.5 m/s, have shown that the combination delivers required 40 m³ per day. The unit costs were compared and showed that hybrid pumping wind/solar system is economically optimal compared to the diesel pump only.
2.5- Pumps & Pumping requirement ............................................. 11
2.5.1- Wind pump ............................................................... 11
2.5.1.1- Wind power .......................................................... 12
2.5.2- Solar Pump ............................................................... 12
  2.5.2.1- PV Arrays ........................................................... 12
  2.5.2.2- Array Sizing ......................................................... 14
  2.5.3- Diesel Pumps ......................................................... 15
  2.5.3.1- Description ......................................................... 15
  2.5.3.2 - Fuel Consumption ................................................ 15

III- Description of case study site .............................................. 16
  3.1- background ............................................................... 16
  3.2- Village water demand.................................................... 16
  3.3- Growth in demand ....................................................... 19
  3.4- The sources of data ...................................................... 21
  3.5 – The Well description .................................................... 21
  3.6- Storage tank ............................................................... 21

IV- Optimization of the Hybrid Pumping System ............................. 25
  4.1- Introduction ............................................................... 25
  4.2- Hybrid system components ............................................. 26
  4.3- Technical Analysis ....................................................... 26
    4.3.1- Equations Equipped ............................................... 29
    4.3.2- Scenario 1: Windy day and sunny day ......................... 30
    4.3.3- Scenario 2: Average windy speed and average radiation day... 32
    4.3.4- Scenario 3: Wind speed below the average and average radiation.32
    4.3.5- Scenario 4: Weak radiation & no or Low wind speed ........ 35
    4.3.6- The best months .................................................... 35
    4.3.7- The average month ............................................... 37
    4.3.8- The worst months ............................................... 37

V- Economical analysis .......................................................... 40
  5.1- Definition ............................................................... 40
    5.1.1- Present – Worth Analysis method ............................... 40
5.1.2- Costs component .................................................. 40
5.1.3- The Discount Rate ............................................... 41
5.1.4- The Inflation Rate ............................................... 41
5.2- Methodology .......................................................... 41
5.2.1- Investment ......................................................... 42
5.2.2- Cost of using the Hybrid pumping system (wind, solar and diesel) 43
5.2.3- Cost of using the Hybrid system (wind/solar) ......................... 45
5.2.4- Cost of using the diesel pump only ................................ 46
5.2.5- Comparison ........................................................ 48

VI- Computer program and design ............................................. 53
6.1- Introduction .......................................................... 53
6.2- The Algorithm of the program of a hybrid system ..................... 53
6.3- Inputs ................................................................ 53
6.4- Outputs ................................................................ 53
6.5 – The Step .............................................................. 53
6.6- Symbols and Units ...................................................... 57
6.7- Running of program .................................................... 57

VII- Conclusion ............................................................... 58
References ....................................................................... 59
Appendix ......................................................................... 61
Chapter I

Introduction

1.1- **Background:**

Generally speaking, Sudan is rich with renewable resources such as wind energy, solar energy, biomass. However, these energies have not yet been exploited. For example, the solar energy is found in all parts of Sudan except for few days in the South. The annual mean solar radiation sometimes exceeds 7kWh/m² per day.[1] Likewise the average wind speed may exceed 5m/s especially in Eastern and Northern parts of the country.[1]

This abundance of energy in Sudan has led researchers to think about exploiting them. This is because the global trend today is to use renewable energy resources to avoid the effect of using fossil fuel.

In a country such as Sudan, grid electricity is generally not available and supply sometimes is not certain. For this reason it is important to consider the potential of alternative renewable energy source to provide the power source to operate pumps.

The term hybrid system is used to describe any power system with more than one type of resource. Most of these systems combine wind turbine, solar Photovoltaic, diesel generator and battery. The use of renewable energy technology to meet demand has been steadily increasing over the years. Combining wind and solar energy into hybrid generation system could satisfy the needs.

1.2- **Objectives & Field of research:**

The field of this study is developing a remote village by introducing renewable energy, namely wind and solar pump. Traditionally, the diesel engine has been used to pump water. An access to a clean and reliable water supply can make a vital difference to the health and quality of life of a community.

In many areas of the Sudan ground water exists, and throughout the country the most widespread way of water lifting is still by bucket, hand pump or with assistance of animal. The principal mechanized power source is the diesel engine, but it is often
beyond the means or technical capability of small communities. Sudan has the annual mean daily global solar radiation that ranges from 3.05 to 7.62 kWh/m² per day.\textsuperscript{[1]} The annual average wind speed ranges from 1.53 to 5.07 m/s.\textsuperscript{[1]}

The adoption of one form of energy conversion or another depends on solar or wind availability, which is sometimes unsafe, because water is of vital importance. The use of diesel system alone raises numerous problems. This makes the designers think about the possibility of hybrid energy system.

The objective of this study is to optimize the energy production from the hybrid system (wind/solar/diesel) for pumping water.

The focus of this study was to identify the possibility of pumping water in small village by using the wind and solar energy. It examined the economic, environmental and technical issues involved in installing wind and solar energy.

1.3- **Methodology:**

The method followed depends on statistical data taken from both Khartoum Metreological Department and Soba Station and anlyse the possibility of the application of hybrid pumping system to a village.

This research studied a small rural village and a hybrid pumping system was designed to produce 40 m³/day. The hybrid system simulation was conducted combining wind, solar and diesel pump. The wind pump was chosen according to the site. The solar pump was chosen to give a limit sum of the needed water, because the Photovoltaic cells are very expensive. The diesel pump will operate when wind stops and on a cloudy day. This is for the purpose of just covering the shortage of water that occurs. A simplified economical approach based on system capital cost analysis is introduced to show the impact of wind pump integrated with a solar pump and diesel pump. The simulation was adapted for small-scale system. The complementation between solar and wind pump leads to a net decrease of the using of diesel pump.
1.4- **Research Structure:**

This study includes seven chapters. Chapter one, which is an introduction, includes background, objective, and methodology. Chapter two is theoretical background and it covers history of wind energy and Photovoltaic, hybrid system, and pumping. Chapter three is the case study of Iseali village. Chapter four is the optimization of the hybrid pumping system including technical analysis. Chapter five is the economical analysis including an economical analysis of the three technologies. Chapter six is a computer program. Chapter seven is the conclusion. The appendix includes tables of data, pumps, etc.
Chapter II

Theoretical Background

2.1 History of Wind Energy Use:

The history of wind power shows a general evolution from the use of simple, light devices driven by aerodynamic drag forces; to heavy, material-intensive drag devices. The earliest known use of wind power is the sailboat, and this technology had an important impact on the later development of sail-type windmills. The early form of wind machines had sails attached at right angles to vertical mounted shaft. This form is reported to be in use in China from 2000 B.C.\textsuperscript{[1]}

The earliest-known design was the vertical axis system developed in Persia about 500-900 A.D. This one with vertical sails made of bundles of reeds or wood, which were attached to the central vertical shaft by horizontal struts. The primary applications were apparently grain grinding and water pumping. By the 11\textsuperscript{th} century, people in the Middle East were using windmills extensively for food production; returning merchants and crusaders carried this idea back to Europe.

Vertical-axis windmills were also used in China. The earliest actual documentation of a Chinese windmill was in 1219 A.D. by the Chinese statesman Yehlu Chhu-Tshai. The first windmills to appear in Western Europe were of the horizontal-axis configuration. The first illustration in 1270 A.D. shows a four-bladed mill mounted on a central post, which was already fairly technologically advanced relative to the Persian mills.

As early as 1390, the Dutch set out to refine the tower mill design, which had appeared earlier along the Mediterranean Sea. The Dutch essentially affixed the standard post mill to the top of a multi-story tower, with separate floors devoted for grinding grain, removing chaff, storing grain, and living quarters for the wind smith and his family. In the late 19\textsuperscript{th} century, Americans succeeded in designing a multi-blade windmill that was used in the first large windmill to generate electricity.
Industrialization, first in Europe and later in America, led to a gradual decline in the use of windmills. The steam engine replaced European water-pumping windmills. In the 1930s, the Rural Electrification Administration's programs brought inexpensive electric power to most rural areas in the United States. In the 1940s the largest wind turbine of the time began operating on a Vermont hilltop known as Grandpa's Knob. This turbine rated at 1.25 MW in winds of about 30 mph, fed electric power to the local utility network for several months during World War II.

The popularity of using the energy in the wind has always fluctuated with the price of fossil fuels. When fuel prices fell after World War II, interest in wind turbines waned. The wind turbine technology research and development (R&D) that followed the oil embargoes of the 1970s refined old ideas and introduced new ways of converting wind energy into useful power. Many approaches have been demonstrated in wind power plants-groups of turbines that feed electricity into the utility grid-in the United States and Europe.

Today, more than a decade of operating wind power plants, along with continuing R&D, have made wind-turbine for pumping water very close in cost to the power from conventional utility generation in some locations. [2]

2.2- History of Photovoltaic

The physical phenomenon that converts sunlight to electricity is called the Photovoltaic effect. Edmund Beequerel, a French physicist, first observed it in 1839; he noted that a voltage appeared when one of two identical electrodes in a weak conducting solution was illuminated. The Photovoltaic effect was first studied in solids, particularly in selenium during the 1870s by Adams and Day, in 1880s selenium Photovoltaic cells were built which exhibited from 1% to 2% efficiency in converting light to electricity. [3]

In the 1920s and 1930s solid-state researchers, including Lange, Groundahl, and Schottky, did pioneering work on selenium and cuprous oxide photovoltaic cells. Advance in quantum mechanics laid the theoretical foundation for our present understanding of photovoltaic. The Czochralaski method developed in the 1940s and
1950s marked a major advance in solar-cell technology. A single-crystal silicon photovoltaic device was made at Bell laboratories as early as 1941. However, it was not until the impurity diffusion method a p-n Junction formation was developed 12 year later that silicon solar cell become practical. Significant developments also occurred at this time with cadmium sulfide, cadmium telluride, and gallium arsenide solar cells. [3]

In 1954, Bell Laboratories researchers announced the development of a silicon solar cell with 4.5-percent energy efficiency, sparking Photovoltaic (PV) cell development that has progressed from space applications in the late 1950s to terrestrial applications today. Over this period, research and development have resulted in lower prices for solar cells and modules, and higher efficiency. Additionally, rising electricity prices and the increase in the cost of building new generation, transmission, and distribution capacity have had a positive impact on Photovoltaic system economics and sales. [4]

The advances in fabrication process as improved understanding of the theory of cell operation and better design led to even higher cell efficiency. In 1958 Hoffman Electronic Corporation produced terrestrial Photovoltaic cell with an energy conversion efficiency of nearly 14 %. Although PV cells were not yet cost-effective for terrestrial applications a practical use was found in U.S. space program. Also in 1958, the Vanguard became the first PV-powered satellite. The 0.1 watt (W), approximately 100 cm², silicon cell system powered a 5-milliwatt backup transmitter for 8 years. The success of solar cells on vanguard made outer space PV primary arena for the future.

Until recently, development of solar technology has depended mainly on the space program and the solid-state transistor industry, which uses similar and physical mechanisms. The “energy crisis” years of the 1970s brought renewed interest in photovoltaic terrestrial applications. Research to improve existing solar cell technologies and develop new solar cell material and designs has resulted. The world
of PV market for cells and modules has grown rapidly since 1994, due principally to
heavily subsidize programs for PV use in Japan and Germany.\[^4\]

2.3- **Hybrid systems**

The term hybrid system is used to describe any power with more than one type
of resources, usually a conventional generator or power by diesel or gas engine and
renewable energy sources such as a Photovoltaic unit, wind generator, batteries …etc.

The adoption of one form of energy conversion or another depends on solar or
wind potential. The use of diesel system raises numerous problems (fuel transport,
spare parts, repair shops) which bring the designers to think about the possibility of
combined renewable energy systems. To address this problem, hybrid systems that
use more than one power supply has been employed where the demand for water is
critical and outages cannot be tolerated. These systems are now an emerging
technology for generating alternative current electric power for remote communities.

To assist U.S industry in developing and demonstrating hybrid systems for
village power applications, National Renewable Energy Laboratory (NREL) manage
a program of collaborative technology development and technical assistance.\[^6\]

2.3.1 **The Simple Model**:

While there are several models in use for evaluating the performance of hybrid
systems, they suffer from either limited architecture, control strategy, availability, or
user-friendliness. Accurate models of Renewable Hybrid Power System (RHPS),
such as HYBRID1 (Manwell and McGowan, 1994), HYBRID2 (Green and Manwell,
1995), SOMES (Van Dijk and Alsema, 1992), and WDILOG (Lundsager, 1991)
include complexities such as: \[^5\]

1- Statistical treatment at load and resource fluctuation within a time
step, either analytically or by a Monte Carlo approach;

2- Battery models that account for internal resistance, voltage variations
and chemical reaction rate;

3- Power conversion losses, which depend on the AC/DC bus
configuration;
4- Strategy staging of multiple diesel;
5- One or several programmed dispatch strategies.

In 1991 Contaxis and Kabouris have used wind and load forecasts for wind/diesel system with no batteries. Millgan et al (1995) have shown the value of wind forecasting in utility systems where again energy storage was not used to absorb shorten fluctuation.


2.3.2 The Hybrid Optimization Model for Electric Renewable (HOMER)

HOMER is an optimization model for designing standalone electric power systems. HOMER has been in development at NREL since 1994. Assessing the least cost mix of supply technologies is a difficult analytical problem. This depends on the quality of the various resources, the costs of equipment, labor and fuel, and the site-specific description of the daily and seasonal variations in the loads, as well as the options for simple load management. The HOMER is a screening model that is useful for feasibility and sensitivity analysis.

HOMER can model any combination of:
- wind turbines
- photovoltaic panels
- diesel generation
- battery storage

Comparisons can also be made between the optimal hybrid system and grid extension.

HOMER provides hourly energy flows through each component, the impact of several simple load management strategies, and economic information such as the
cost of energy and net cost of the system. The NREL researchers have used HOMER in several analyses for Indonesia, China, Russia, Chile, Brazil, Argentina, Mexico, and South Africa and for market analyses for domestic renewable suppliers and technology developers. In 1997 HOMER was converted from specialized optimization software to visual C++. This conversion improved the model’s user friendliness and facilitated wider distribution. [6]

2.3.3- Hybrid2:

Hybrid2 is hybrid power system simulation software. In June 1996 the (NREL), in collaboration with the University of Massachusetts has developed the window-based Hybrid2 model that is versatile in its components/control strategy options and publicly available. Typical hourly wind and solar resource data are available to scale if site data are not available. Village load profile, system architecture, and control strategy, unit costs, and financial parameter are inputs. The key outputs are component and system performance, diesel-fuel use and economic parameters. This model is used regularly by analysts who want to compare the economics of hybrid system options to conventional diesel generator sets. The Hybrid2 code can model any combination power converters and battery storage. [6]

2.3.4- Hybrid Power Test Bed (HPTB)

NREL of the USA has a significant program addressing hybridization of diesel generator set with renewable energy. The recently developed Hybrid Power Test Bed (HPTB) is used to characterize the performance of emerging hybrid architectures, components, subsystems, and control strategies for simulating village power load profile. The initial hybrid system test combines a 50 kW induction wind turbine with 175 kWh battery bank and a 50 kW diesel generator set. Currently scheduled tests include a 50kW electric inverter developed under NREL’s PVMAT program and the control panel for Alaska, high penetration wind/diesel project. Smaller hybrid systems, in the 1.5 – 10 kW ranges are scheduled for testing in 1997. The model of HOMER and Hybrid2 are very expensive and unavailable for application in Sudan.
2.4- **Wind & Solar pumps in Sudan**

Work on those types of pumps has been proceeding in Sudan since the 1980s for the purpose of pumping water, for drinking. Earlier wind machine was of the Southern Cross type and suffered from several problems. [7] None of them is now working. Ten wind pump of the CWD type (Holland) were installed around the Khartoum area (five of them were working until 1991). [8] Addition of solar pump had been proceeding since the 1980s. A number of solar pumps was installed and are still working.

2.5- **Pumps & pumping requirements**

2.5.1- **Wind pump:** -

The Wind machines convert the energy in wind into mechanical or electrical energy. Wind machines are generally subdivided in two ways – horizontal-axis or vertical-axis machine. The horizontal axis type is the one, which has been built, in large numbers. The most common type is the horizontal-axis, which is usually referred to as steel-blades, farm- type, or simply, a farm wind machine.

A typical farm wind machine has four main parts: [9]

1- A horizontal - axis wheel, which converts power into the wind into the rotary shaft power of the axis;

2- A wind machine ‘head’ which changes the rotary motion of the axis to a vertical reciprocating motions and makes any necessary gear reductions;

3- A tail attached to the head, which has two purposes:
   i) It allows the wind machine to follow the wind direction.
   ii) Along with a brake permits the wind machine to be furled during high winds or when desired;

4- A tower usually fabricated of steel on which the wind machine head is mounted.

This design is nearly always used with a reciprocating – pump. The typical wind machine is designed to provide the required high torque to start the pump at low wind speeds.
Two ways for pumping water: mechanical or electrical. Windmills work very well at low wind speeds, so they tend to give more reliable water supply than wind-electric systems. But, the wind-electric systems are more efficient over a wide range of wind speeds, they can pump higher volumes of water, and the wind turbine can be placed far from the well. Perhaps most important, wind-electric systems need much less maintenance.

2.5.1.1- **Wind Power:**

The power available in wind is given by the following formula: \[^{[10]}\]

\[
P_w = 0.5 \times \rho_A \times A \times V_A \tag{2.1}
\]

Where \(P_w\) = power available in the wind in watts  
\(\rho_A\) = air density in kg /m\(^3\)  
\(V_A\) = air velocity in (m/s)  
\(A\) = cross-sectional area of wind being intercepted

2.5.2- **Solar Pump:**

In most cases it is feasible to utilize off shelf, mass produced motors and pumps. However, some manufacturers have developed specialized pumps and motors to minimize overall system costs. The pump/motor subsystem operates in a different way to a conventional motor because the power supply varies as the incident solar energy changes. Most motors are designed for maximum efficiency at a certain voltage/current characteristics, and performance can drop off quickly away from this operating point. Fig. (2.1) shows the possible operation hours zone of the solar pump. \[^{[11]}\]

<table>
<thead>
<tr>
<th>Time in hour</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation in kWh/ m(^2)</td>
<td>0.00</td>
<td>0.11</td>
<td>0.21</td>
<td>0.45</td>
<td>0.66</td>
<td>0.81</td>
<td>0.89</td>
<td>0.89</td>
<td>0.82</td>
<td>0.66</td>
<td>0.41</td>
<td>0.18</td>
<td>0.04</td>
</tr>
</tbody>
</table>
The active area shows the operation hours of the solar pump.

The motor/pump requires a certain minimum power input to start working and different pump types respond in different ways. A centrifugal pump will begin to rotate at very low levels, but will not lift any water through the head until the pump reached a certain speed. This power threshold increases with required pumping head. A reciprocating positive displacement pump needs a very high torque to start, as the pump is pushing against the whole head. [11]

2.5.2.1 - PV Arrays:

The basic unit of Photovoltaic (PV) equipment as far as the buyer is concerned is the PV module. These are building blocks of the complete PV array and may be connected in series or parallel to give the required voltage and current characteristics for the load. Module and array are rated in terms of the total power they produce in Watts at the radiation level 1000 W/m² and at a temperature of 25°C. This unit is known as the peak-Watt ($W_p$). [11]

They are protected by encapsulation between glass and a tough resin back. This is all held together by steel or aluminum frame to form a module. The efficiency
of conversion sunlight to electrical power is typically 12 – 15 % for mono-crystalline cells and around 10 % for the poly-crystalline. At standard irradiance of 1000 W/m² a 100-mm diameter circular cell will produce about 1 Watt of electrical power. The trouble-free service can be expected for up to 20 or 30 years for a modern module. [11]

2.5.2.2- **Array sizing:**

The size of the array and pump depends on the daily solar insolation and hydraulic energy requirement, which we shall express as volume-head product (duty in m³/day).

The actual power required to pump water is

\[ P_{\text{req}} = \frac{9.81 \times H \times Q}{\eta} \]  \hspace{1cm} (2.2)

Where:

- \( P_{\text{req}} \) = power required in W
- \( H \) = total pumping head in m
- \( Q \) = flow rate in liter per second (liter / s)
- \( \eta \) = subsystem efficiency

A more accurate way of estimating the size of the solar array needed to pump given amount of water is to use the following formula: [12]

\[ \text{Array size} \ W_p = \frac{9.81 \times H \times Q}{H_t \times 3.6 \times F_m \times F_T \times \eta} \]  \hspace{1cm} (2.3)

Where:

- \( W_p \) = peak watts
- \( H_t \) = global solar irradiation in the array plane (kWh / m²/day)
- \( F_m \) = array/load matching factor, 0.9 for centrifugal pumps, 0.8 for the other pumps
- \( F_T \) = de-rating factor for operating temperature of array output cells (0.8 for warm climate and 0.9 for cool)

2.5.3- **Diesel Pumps:**

As the most common type of prime mover in much of the developing world, diesel engines are used to drive a wide variety of pumps. In many countries, there is a broad national network (formal or informal) of equipment distributors, local dealers mechanics, and transportation facilities that supports diesel engines used for pumping
and other purposes. In most cases, diesel pump sets are the standard against which all other types of pumping systems must be compared.

2.5.3.1 Description:

Through drive shafts or pulleys and belts, diesel engine can be used to drive almost any type of pump. They can also drive electric generators to run electric pump sets, which is a configuration that has advantages in cases where submersible pumps are favored and grid electricity is available. \(^{[12]}\)

2.5.3.2 Fuel Consumption:

The fuel and lubricant consumption of diesel engine account for a significant portion of its operating costs. Fuel consumption’s dependent on the engine’s full rated power and loading condition. Full-load fuel consumption (FLFC) is often given by the manufacturers in gram of fuel consumption per rated kWh (g /kWh). To convert in liter per hour (l / hr), the calculation is:

\[
FLFC = g /kWh * (0.001/SG) * kW
\]  \(\text{… (2.4)}\)

Where:
- FLFC = full load fuel consumption in l/hr
- g /kWh = fuel consumption in grams per kWh
- SG = specific gravity of diesel fuel (usually 0.87)
- kW = engine’s rated full-load power output for a specific rpm (not de-rated).

Actual fuel consumption is FLFC in l/hr multiplied by the loading.

Chapter III

DESCRIPTION OF THE CASE STUDY SITE

3.1 Background of the studied area:

The Village of Iseali is chosen as the case study of this work. It is a village in Khartoum State not far away from the White Nile, see Fig (3.1). The nearby town of Jebl Awlia 10 km to the North East and from Khartoum center by 25 km to the South. Its Latitude is 15° - 32' N and the Longitude 32° - 32' E, at 380 m above sea level. The climate of Khartoum State is semi-arid climate. The average annual rainfall is 200 mm. The maximum temperature is 43 °C in May and the minimum 20 °C in Jan \(^{[13]}\).
The population of Iseali village is about 1100. They live in small houses, see Fig. (3.2). Most of them are cattle owners. They usually provide the Khartoum town with milk. They are involved in small farming. The number of the cattle ranges between 150 to 200. The sheep’s number is about 400. Fig. (3.3 a) shows the coming sheep & goats from grazing. The area being near Souba agricultural scheme gives an advantage for the cattle owners to rear their cows, sheep and goats. Fig. (3.3 b) shows them in the grazing.

Generally speaking, villagers in the Sudan get their water supply, either from dug wells or by borehole wells. On the other hand, surface water may not be suitable for drinking purposes. The static water level differs according to the distance of the well from the White Nile. The geographical location for water under ground indicates that it is abundant in the West of Iseali village, and it decreases considerably when we go East. The minimum static head is estimated to be 12 m and the maximum is 25 m.\textsuperscript{14}

### 3.2- Village Water Demand:

Water demand is dependent on site-specific conditions. Although general guidelines have been established by many development agencies specifying the minimum daily consumption for people, animals, and crops, actual consumption can vary considerably.

Typical usage figures are given in table (3.1) for most common consumers.

<table>
<thead>
<tr>
<th>Item</th>
<th>People</th>
<th>Cattle</th>
<th>Goat/Sheep</th>
<th>Poultry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand in liter/day</td>
<td>20 - 30</td>
<td>20 - 40</td>
<td>5 - 15</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table (3.1) the daily consumption for people and animals

The water requirement for people assumes that people get their water from centrally located stand posts.

The village daily demand of water is estimated as 40 m\textsuperscript{3}/day.

The calculation of the demand is:

\[
\text{People} = 1100 \times \frac{30}{1000} = 33 \text{ m}^3 \\
\text{Cattle} = 200 \times \frac{25}{1000} = 5 \text{ m}^3
\]
Sheep/goat = \(400 \times \frac{5}{1000} = 2 \text{ m}^3\)
The total demand = \(40 \text{ m}^3\)

This amount is scheduled on two periods, morning period (6:00 a.m.–12:00 p.m. and evening period (3:00 – 6:00 p.m.). Fig. (3.4) shows the consumption of the water during the day. This had taken from practice of daily life for the villagers.

---

**Fig.(3.4) the consumption of the water demand during the day**

3.3 - **Growth in demand:**

The demand is affected not only by population growth (people and animals) but also often by ease of access. Increased demand due to growth in population and per capita consumption can be calculated by using this formula: \(^{[12]}\)

\[
D_F = D_P \times (1 + F_{PG})^{(N-1)} \times (1 + F_{CG})^{(N-1)}
\]

Where: \(D_F = \text{future demand}\)
\[ D_p \] = present demand

\[ F_{PG} = \text{population growth factor} = 0.02, 0.03 \text{ or } 0.04 \ldots \] \[^{[12]}\]

\[ N = \text{design period in years} \]

\[ F_{CG} = \text{consumption growth factor} = 0.02 \ldots \] \[^{[12]}\]

For calculation of future demand, substituting in equation (2.1)

The population growth factor \( F_{PG} = 0.03 \), (this is taken from the Central of Statistics - Khartoum)

\[ F_{CG} = 0.02, \text{ } N = 20 \text{ year} \]

\[ D_F = 40*(1+0.03)^{(20-1)}*(1+0.02)^{(20-1)} = 102 \text{ m}^3 \]

3.4- The sources of data

The data were mainly obtained from the Sudan Meteorological Department Office in Khartoum. The annual average wind speed exceeds 4m/s along the main Nile from Khartoum down to Halfa and south of Khartoum covering the Gezira area. It exceeds 5m/s at the coastal of the Red Sea. The wind speed given by Meteorological Department Office is usually quoted at standard height of 10 m. Table (3.1) shows the data of wind speed of Khartoum. Solar radiation as obtained from Soba Station is shown in Table (3.2).

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</tr>
</tbody>
</table>

Table (3.3) the daily and average wind speed. In m/s Khartoum 1984
3.5- **The Well description**

The well is assumed to be as follows:

1. case diameter = 250mm
2. the depth of the well = 30m
3. the static water level = 15m
4. the draw down level = 18m
5. The yield of the well = 25m³/hr.

3.6- **Storage System:**

The storage system consists of the following three components:

1. Elevated tank: The elevated tank for drinking water should be positioned high enough to provide only enough head necessary to carry water effectively through the distribution system with capacity 25 m³ and 2 m height from its bottom. 25 m³ is represented about 62.5% of the required water and this stratifies for one-day of the people water demand. The capacity of the storage should be to supply 8 hours operation, when the production stops. This represent third of day operation. *(From Khartoum Water Corporation).*

   A higher tank level will mean increased cost. The energy used in lifting a certain amount of water is directly proportional to the pumping head, when fixed the daily flow rate. The increasing in power mean that increasing in the cost, especially in case of using solar pump increasing in number of modules. For this reason the tank should be wide and squat rather than tall and thin, or the static head may be significantly increased, as the tank becomes full. It should always be covered to ensure clean supply water and prevent entry of dirt, insects and animals.

2. Lower Storage is designed for animals. It takes a cylindrical shape with capacity of 16 m³. It is to be built from local material. (Brick and cement).
3- The water produced by the hybrid pumping system is expected to exceed sometimes the required demand of Iseali village, especially in wintertime. The surplus is to be stored in any ground storage (i.e. Hafeer) which may be dug by inhabitants of Iseali village. This is used for domestic activities.
Chapter IV

**Optimization of the Hybrid Pumping System**

4.1- **Introduction:**

Combining wind and solar energy into hybrid generation system could satisfy the energy needs. The two sources of energy, which are individually unreliable, could as a whole has a higher reliability. It has been found that a hybrid wind/PV system is better than an individual wind or PV power system.\(^{[15]}\)

The site data of wind speed and solar radiation in the case study area Iseali village shows that it is possible to use the two technologies. However, generally wind and solar options have unpredictable nature being dependent on weather and climatic changes.

The data are for Khartoum and include hourly average wind speed in m/s, global horizontal extraterrestrial insolation and the direct normal extraterrestrial irradiance (W/m\(^2\)). The data in table (3.1 & 3.2) is the average values for every hour of all the days for the year of 1980.

4.2- **Hybrid pumping System Components:**

The hybrid pumping system consists of four main systems and accessories:

The main systems are:

- wind pump
- solar pump
- diesel pump

storage systems which are:

- elevated tank
- lower reservoir for animals
- Ground storage (Hafeer) for surplus water.

In the local market of the Sudan, small size submersible pumps are available with an external diameter of 70 to 100 mm. The three pumping sets mentioned above can be entered in one borehole with a case of 250mm (10-inch) diameter. Each pump
will have a separate delivery pipe into the storage system. The hybrid pumping system components are illustrated in schematic diagram fig. (4.1)

4.3- **Technical Analysis:**

Transfer of technology should be taken with great care to suit the local climatic geographical and social conditions of the community concerned.

The design puts two small submersible pumps and piston pump in one borehole. Because the electric wind turbine is unfeasible in this case, the wind pump is chosen to drive mechanically direct coupling.

The available type of solar pump in local market is GRUNDFUS – submersible pump. It is dried through inverter, which converts the direct to alternative current (DC/AC). Second submersible pump is chosen as standby driven by AC single-phase diesel generator (220V). The motor of solar pump differs in voltage from the diesel generator (220 or 415V) (see Appendix B). A regulator needs to be connected, which increases the cost. For this reason two submersible pumps will be used in one borehole. Also there is an advantage which is the availability of submersible pump single phase in local market that is suitable for this case.

The analysis discusses the selection of four days taken from table (3.1) of average wind speed and solar radiation table (3.2) (see Appendix B1). Three days are illustrated in table (4.1) below. The four days are as follows:

- windy and sunny day
- average wind speed and average radiation
- wind speed below the average and average radiation
- Weak radiation and no/or low wind speed.

4.3.1- **Equations required**

Power required for pumping water by wind pump is

\[ P = 0.1A*V^3 \] \[ \text{[16]} \] … (4.1)

Hydraulic power \[ = \rho_w gQH \] \[ \text{[4.2]} \]

Equating equation (4.1) and (4.2) to get flow rate (Q) in m³/day

\[ Q = 0.69* d^2V^3 / H \] m³/day \[ \text{[4.3]} \]
All the following calculation of the flow rate \((Q)\) in the analyses based on equation (4.2)&(4.3)

**Sizing of solar pump:**

Referring to table (3.2) the annual average solar radiation is 6.24 kWh/m\(^2\) day. Using equation (2.3).

\[
W_p = \frac{9.81 * H Q}{H_t * 3.6 * F_m * F_T * \eta}
\]

\(W_p\) = No. of module * peak watts of module

Substituting \(F_T = 0.8, F_M = 0.9, \eta = 0.35\) in equation (2.3).

\[
W_p = 9.81 * 40 * 25 \times \frac{3.6 * 6.24 * 0.9 * 0.8 * 0.35}{31.5} = 1733W
\]

This calculation was based on annual average solar radiation of Khartoum in 1980. Module size is 55 \(W_p\) and output voltage is 15V.

The number of modules = 1733/55 = 31.5 = 32 module

The SOLARTRONIC inverter type SA 1500 converts the DC voltage supplied by PV system or by battery of accumulators into a three-phase AC voltage with a variable frequency. The inverter is specially designed to power submersible pumps installed in GRUNDFOS. The nominal input load voltage is 105 or 120 V (see the appendix C\(_2\)), this should be needed 8 modules to produce 120V. The 8 modules may be double or three times …etc to produce the required power for operation of submersible pump. Other type of modules for operating a solar pump takes regular form as follows: 16, - 24, - 32, … (see the table in appendix C\(_2\)).

Because of the relatively high cost of PV modules, solar pumping is most economical for small power demand application. The selection of the number modules is not taken into account for economical analysis. And the comparison between increasing in number of modules and diesel pump also is not taken into account, because the diesel pump is designed in the system as standby. The 16 modules were chosen here as assumption. These modules provide a power that would produce a half of the required water.
Again peak watt = 55*16

\[ = 880W_p \]

Using power 880W and the same assumption to calculate solar pump flow-rate (Q) in m³/day by pumping head and solar radiation.

\[ 880W_p = 9.81 * H Q \]

\[ H_t* 3.6 * 0.9* 0.8* 0.35 \]

\[ Q = 81.4* H_t / H \quad \text{m}^3/\text{day} \quad (4.4) \]

This equation was deduced from equation (3.4)

4.3.2 – **Scenario 1: windy day and sunny day:**

The windy day chosen is the 16th of April 1980 (table 4.1), with average wind speed 7.2 m/s, and it is the highest speed in this month. The solar radiation for that day is 5.99 kWh/m²/day. Data set of the wind speed and solar insolation showed no day having both highest wind speed and solar insolation. Thus, the highest wind speed is preferable to select this day rather than the highest inoslation.

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<th>18th February</th>
<th>28th of April</th>
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<td>Radiation kWh/m²</td>
<td>Va. m/s</td>
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Table (4.1) the average wind speed and solar radiation

As far as the output of the wind pump is concerned, we notice (table 4.2, fig 4.1) that the wind speed-readings are not only high but also give us more output than that of the solar pump. From table (4.2) the fourth and the fifth columns show the wind and solar pump water supply per day. The total water supply of them is 283 m³/day. The surplus of water is (283 – 40) = 243 m³/day. This surplus of water can be changed directly to the ground storage (Hafeer), and manually controlled by a valve. This modified the pumping head from 25 to 20 meters. Since the calculation of water supply is based on elevated tank, the actual volume of water collected in the Hafeer is 243*25/20 = 304 m³/day

<table>
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<tr>
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<th>Q_s</th>
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Table (4.2) Scenario 1: Windy & sunny day

Fig. (4.1) Scenario 1: the (cumulative wind & solar flow rate and Demand) Vs Time

4.3.3 – **Scenario 2: Average wind speed and average radiation day:**

In the second scenario the day chosen is the 18th of Feb. 1980 (table 2.1), with wind speed 5.6 m/s. The average insolation in this month is 6.12 kWh/m²/day which almost matches the amount of solar insolation of the above-mentioned date (6.13 kWh/m²/day table 4.2). Again from table (4.3), the fourth & fifth columns show the wind and solar pump supply flow rate per day respectively. The eighth column shows the cumulative water supply of the two pumps.

The total water supply is 156 m³/day. The excess of the water supply is (156 – 40 = 116 m³/day). Assuming that the elevated tank (of size 25 m³) is empty at 12:00 a.m., which is the beginning of the day, the tank will be filled at 5:00 a.m. Water could be diverted directly to the lower storage (of size 16 m³) for two hours. These two hours are quite enough to fill the lower storage. At 6 a.m. when villagers arrive to
obtain water, the wind pump is still operating to supply both the storage tanks simultaneously. The storage tanks will be filled up approximately (38.9 m³) at 9:00 a.m. see table (4.3). At this very moment the solar pump will be in operation, and this will add a new amount to the total. Eventually, this could be drained directly to the ground storage i.e. (Hafeer).

<table>
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<th>Time</th>
<th>Va</th>
<th>Radiation</th>
<th>Q_w</th>
<th>Q_s</th>
<th>Q_w+Q_s</th>
<th>Demand</th>
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Table (4.3) Scenario 2: Windy & sunny day

![Graph showing cumulative flow rate and demand over time](chart.png)
4.3.4 – **Scenario 3: Wind speed below the average & average radiation:**

In this scenario the chosen day should be matched below monthly average wind speed, and monthly average solar radiation. The 28th of April 1980 table (4.1) is found to be that day. The 3 m/s wind speed is less than the monthly average wind speed (3.5 m/s). The start up wind speed is 3.5 m/s. The insolation in this day is 5.84 kWh/m²/day.

In table (4.4) the wind speed between (1:00 – 7:00 a.m.) is found to be below the 3.5 m/s. During this time mentioned above solar radiation is nil. The radiation will increase eventually in the course of the day light. This situation makes the diesel pump look justifiable.

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<th>Time</th>
<th>Va</th>
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<th>Q_s</th>
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Table (4.4) Scenario 3 wind speed below the average and average radiation

Fig. (4.3) Scenario 3: the (cumulative wind & solar flow rate and Demand) Vs Time

Table (4.5) shows the entering of the diesel pump to supply the system (see fig 4.4). The cumulative supply is 55.5 m$^3$; 45.5 m$^3$ of it is from both wind and solar and 15 m$^3$ is from the diesel pump.

Thus the total of water excess = (55.5 - 40) = 10.5 m$^3$

This excess water could be stored in the storage tank for the next day.

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4.3.5 – **Scenario 4: weak radiation & no or low wind speed:**

The global irradiance varies throughout the course of the day due to changes in sun angle and thus bath length through the atmosphere. For the same reason there are variations with season and Latitude, with changing length of day and additional factor. With exception of Southern States the insolation in the whole Sudan is above 5.44 kWh/m²/day. [⁶] In spite of this high insolation there are periods which are classified as low insolation that is due to clouds, dust, …etc. For wind speed there are also periods which are classified as not windy and /or very low speed. If the situation mentioned above occurred the substitute would be the diesel pump to produce a total volume of 40 m³ at rate of 7.5 m³/hr, this is to secure the water for the citizen of Iseali village all day.
4.3.6- **The best months:**

The best months in water supply (by wind/solar pumps) are defined as the months, which have greater supply than the monthly water demand. The best months are Dec, Jan, Feb, Mar and Jul according to the table (4.6). Feb is the best one, which is given a reading of 2283 m³. And it gives surplus of 1123 m³ exceeding all other best months. The total surplus of water (3074 m³) of the best four months (Dec, Jan, Feb, Apr and May) can be diverted to the nearby (Hafeer). The benefit from this Hafeer water is for the villagers of (Iseali) to decide about. This changing direction of water from elevated tank to the (Hafeer) modified the total pumping head from 25 m to 20 m.

Then the actual volume of water is \( = 3074 \times \frac{25}{20} = 3843 \text{ m}^3 \)

4.3.7- **The average month:**

November is found to be the average month in water supply which has 1201 m³. This volume of water is exactly covering the demand of the month. Also June is classified an average month which, has water supply 1277 m³. The surplus of June can cover the need of two days of the village.

4.3.8- **The worst months:**

The worst months in water supply (by wind/solar pumps) is defined as the months, which have less supply than the average monthly water demand. The worst months in this year are May, Aug, Sep, and Oct. However, Aug is the worst and during which the greatest shortage in production occurs. The total deficit is 335 m³ (see table 4.6). The diesel pump can cover this deficit at rate 7.5 m³/h.

The total working hours = 338/7.5 = 45 hrs/month

Summary:

The total shortage of 4 months is = 686 m³/year

The total working hours = 686/7.5 = 92 hrs/year

Assuming the excepted hours by wind stops or cloudy day = 108 hrs/year

The total working hours in a year are = 200 hrs/year
Table (4.6) the calculation of total water flow rate, water surplus and water deficit

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<th>Mar</th>
<th>Apr</th>
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<th>Jun</th>
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Symbol

- $Q_w =$ Wind pump flow rate in m³
- $Q_s =$ Solar pump flow rate in m³
- $Q_T =$ Total flow rate in m³
- D = Demand in m³

Summary

- total water flow rate = 17791 m³/year
- total water surplus = 3847 m³/year
- total water deficit = 686 m³/year

1-The best months of water supply

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<tr>
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<th>Jul</th>
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2- The worst months of water supply are

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<th>Sep</th>
<th>Oct</th>
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3- The average months of water supply are Jun and Nov.

Fig. (4.5) the monthly flow rate of the wind & solar pump ($Q_T$) and monthly demand (D)
Chapter V

Economical Analysis:

5.1- **Definition**: -

5.1.1- **Present Worth Analysis method**: 

While there are many kinds of comparative economic methods, the present-worth analysis is a convenient method for assessing the relative costs of different pumping systems. This method analyzed all costs associated with installation and the use of the pumping system by reducing them to a single number called the present worth or value. Dividing the present value by the total volume of water pumped over the system’s lifetime, gives a unit cost for water referred to. To make direct financial and economic comparison between the two or more pumping system, the unit costs must be calculated. The
different pumping systems are designed to deliver the same volume of water from the same head.

5.1.2- **Cost components:**

Present-worth analysis divides the system cost into two basic groups, installed capital and recurrent costs. Installed capital costs all assumed to occur at the start of the system’s lifetime (i.e., time zero). All later costs (e.g., for operation, maintenance, and spare parts) are recurrent costs. A system’s installed capital cost is the total figure for all equipment, materials, labor, and transportation needed for complete installation of a functioning system.

Recurrent costs generally include:

- an operator’s salary;
- wages for the mechanic to handle regular service and breakdowns;
- spare parts and replacement component;
- transportation, including a driver; and
- Overhauls, when necessary.

Recurrent costs can be subdivided into fixed annual, variable annual and non-annual costs.

5.1.3- **The Discount Rate**

The present worth of recurrent costs is determined by making assumptions about the discount rate and useful life of the system, also called the term of the analysis. The discount rate is used to calculate the present worth of future costs.

5.1.4- **Inflation rate:**

This is the expected rise of general price levels in the state concerned. From recent statistic, one can determine the inflation rate in the recent past.

5.2 - **Methodology:**

Generally speaking, there is a general practice of adopting a 20 year life for both wind and solar pumps. Diesel pumps, on the other hand, may generally be assumed to operate properly for first 5000 operation hours. Following that a costly overhaul would be necessary, and that does not usually restore it fully to the new engine
condition. Accordingly, the 5000-hour period is adopted here as the engine’s life and that the purpose of this research. The number of engines to be used is determined accordingly. Following each engine’s life a scrap-value of half the contemporary new engine price is assumed. The option here is for discount rate of 10%.

All costs were based on current local prices in Sudanese Denar (SD).

Fuel price, in SD is assumed to follow the 16% escalation rate (e) adopted for inflation rate during the 20-year period.

The formulae of economical analysis are follows: 

Present worth (P) \[= \frac{A \times (1+r)^N - 1}{r \times (1+r)^N} \tag{5.1} \]

Where: N is the design period in years & r is the discount rate

Annuity (A) \[= \frac{P \times r x (1+r)^N}{(1+r)^N - 1} \tag{5.2} \]

If the inflation is to be included, then equation (1) changes into

Present worth (P) \[= I + \frac{C_{omr} \times (1+i) \times 1 - \left\{ \frac{1+i}{1+r} \left( \begin{array}{c} L \\text{L} \end{array} \right) \right\}}{(r-i)} \tag{5.3} \]

Present worth of fuel cost \[= C_f \times (1+e) \times 1 - \left\{ \frac{1+e}{1+r} \left( \begin{array}{c} L \\text{L} \end{array} \right) \right\} \tag{5.4} \]

Where: L = Lifetime cycle

Annuity factor (F₁) \[= \frac{r (1+r)^N}{(r+1)^N - 1} \tag{5.5} \]

Where: N is lifetime in years

The present worth factor (F₂) \[= 1 - \frac{(1+r)^N}{r} \quad \text{or} \quad \frac{(1+r)^N - 1}{r (r+1)^N} \tag{5.6} \]

If inflation has to be included this changes into: 

\[F_1 = \left[ \frac{(1+i)}{(1+r)} \right]^N \tag{5.7} \]

\[F_2 = \frac{1+i}{1+r} \left\{ \frac{1-(1+i)^{-L}}{1-1} \right\} \tag{5.8} \]
5.2.1- **Investment:**

This is the price of engine pump or wind pump or solar pump including tank, installation and so on. The investment occurs at the end of year (0). The present value, if a capital (I) grows in N year to I * (1+r)^N we reverse this statement by saying that the value of sum I * (1+r)^N in the year N is equal to I at present. Or denoted a capital in the year N by I(N), we can define the present value of I(N) as

\[
\text{Present value of } I(N) = \frac{I(N)}{(1+r)^N} \quad \text{...(5.9)}
\]

If inflation has to be included this changes into:

\[
\text{Present value of } I(N) = I(N) \times \frac{1+i}{1+r}^N \quad \text{...(5.10)}
\]

In the case of wind machine there is usually a scrap value after the lifetime of wind machine. If it is estimated to be (s) in year (0), then it will be inflated to s*(1+r)^L, its present value, i.e. s*((1+i)/(1+r))^L has to be added to the benefits of investment.

\[
\text{Present value of a scrap is: } s \times \frac{1+i}{1+r}^L \quad \text{...(5.11)}
\]

The total Present worth = the sum of equations (5.3+5.4) – (5.11) … (5.12)

5.2.2- **The cost of using the Hybrid pumping system:** (wind, solar and diesel)

The hybrid pumping system depends mainly on the wind and solar pump. The reason for introducing diesel pump to the system is to cover the shortage in water if any. As already we know there are some months weak in both wind speed and solar insolation. In other wards, the diesel pump is stand-by for emergency. For this reason the life cycle of diesel engine in the hybrid system is estimated 20 year as the same as wind/solar pumps. As mentioned previously the life of diesel pump depend on working hours.

From table (4.6) the total shortage of water is 686 m^3/ year. The working hours is (686/7.5) = 92 hrs. The excepted wind stops and cloudy days during the year are about 108 hrs.
Then the total working hours is 200 hrs/year.

Assumptions:
- Discount rate \((r)\) = 0.10
- Inflation rate \((i)\) = 0.15
- Escalation rate \((e)\) = 0.16
- Life cycle period \((L)\) = 20 year
- Diesel working hours = 200 hrs/year
- Fuel consumption = 0.056 liter/m³ (this calculated from equation (2.4))
- Fuel cost \((C_f)\) = 87.5 SD/liter
- Scrap value (s) diesel engine = 60000 SD
- Scrap value (s) of hybrid (wind & solar pump) = 50000 SD

<table>
<thead>
<tr>
<th>Items</th>
<th>Install capital cost (SD)</th>
<th>Recurrent cost (SD)</th>
<th>Variable</th>
<th>Non-annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind pump</td>
<td>1200000</td>
<td>30000</td>
<td>26000</td>
<td></td>
</tr>
<tr>
<td>Solar pump</td>
<td>2098000</td>
<td>10000</td>
<td>400000</td>
<td></td>
</tr>
<tr>
<td>Diesel pump</td>
<td>380000</td>
<td>10000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage Tank</td>
<td>1200000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fencing + house</td>
<td>320000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>manpower</td>
<td>180000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel cost ((C_f))</td>
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<td></td>
<td>7350</td>
<td></td>
</tr>
<tr>
<td>Total cost</td>
<td>5198000</td>
<td>230000</td>
<td>7350</td>
<td>660000</td>
</tr>
</tbody>
</table>

Table (5.1) the expected costs of hybrid pumping system (wind, solar and diesel)

Substituting in equations (5.3), (5.4), (5.10) & (5.11)

\[ I = 5198000, \ C_{omr} = 230000, \ C_f = 71540 \ SD \]

Present worth \((P)\) = \( I + C_{omr} \times (1.15/\ (-0.05)) \times [1-(1.15/1.1)^{20}] \)

Present worth \((P)\) = 5198000 + 230000 * 32.95 = 12776500 SD

Present worth \((P)\) of fuel cost = 7350*36.6 = 269010 SD

The non-annual recurrent cost listed (660000 SD) occurs at year 10.

The present worth of the non-annual costs must be calculated separately: substituting in equation (5.10)

The present worth at year 10: \( P = 660000 \times (1.15/1.1)^{10} = 1029427 \ SD \)
The present worth of scrap = 110000*(1.15/1.1)^20 = 267606 SD  
Net present worth = 12776500+269010+1029427-267606  
= 13807331 SD

Substituting in equation (5.1)

Annuity (A) = 13807331*0.1174 = 1620980 SD

The actual volume of water produced by the hybrid system = 17791 m³ by wind & solar pump (from table 4.6) and 1500 m³ by diesel pump; then the total annual volume of water = 17791+1500 = 19291 m³/year

Unit Cost of Water: The economic unit cost is determined by annualizing the system’s life-cycle cost (ALCC) and dividing that number by the annual water output. Dividing by actual product

Unit cost = ALCC/19291 = 16209807/19291 = 84 SD/ m³

5.2.3- **The cost of using the Hybrid pumping system (wind & solar):**

<table>
<thead>
<tr>
<th>Items</th>
<th>Install capital cost (SD)</th>
<th>Recurrent cost (SD)</th>
<th>Variable</th>
<th>Non-annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind pump</td>
<td>1200000</td>
<td>30000</td>
<td>260000</td>
<td></td>
</tr>
<tr>
<td>Solar pump</td>
<td>2098000</td>
<td>10000</td>
<td>400000</td>
<td></td>
</tr>
<tr>
<td>Storage Tank</td>
<td>1200000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fencing + others</td>
<td>175000</td>
<td>40000</td>
<td>660000</td>
<td></td>
</tr>
<tr>
<td>Total cost</td>
<td>4673000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table (5.2) the expected costs of hybrid pumping system (wind, solar)

Substituting in equations (5.3), (5.4), (5.10) & (5.11)

I = 4673000, C_{omr} = 40000 SD

Present worth (P) = I+ C_{omr} x (1.15/(-0.05)) * [1-(1.15/1.1)^20] = 5991000 SD

The non-annual recurrent cost listed (660000 SD) occurs at year 10.

The present worth of the non-annual costs must be calculated separately: substituting in equation (5.10)

The present worth at year 10: P = 660000*(1.15/1.1)^10 = 1029427 SD
The present worth of scrap = 50000*(1.15/1.1)^20 = 121639 SD
Net present worth = 5991000+1029427-121639 = 6898788 SD
Substituting in equation (5.1)
Annuity (A) = 6898788 * 0.1174 = 809918 SD

Unit Cost of Water
The economic unit cost is determined by annualizing the system’s life cycle cost (ALCC) and dividing that number by the annual water output.
But the actual volume of water producing by the wind & solar pump is 17791 m³/year (from table 4.6), then
The Unit cost = 809918/17791 = 45.5 SD/m³

5.2.4- **Cost of using diesel pump only:** -

The necessary data about unit price, fuel consumption, convenient number of working hours and the expected returns of scrapped diesel engines were based on manufacture’s information, engineering norms and experience of local users.

To span the 20-year life of a wind-pump and solar pump a number of diesel-pump generations are needed. The analysis was detailed enough to account for the increase in fuel consumption as each engine ages during its prescribed lifetime. The present value cost of fuel is a summation of the consumption of all generations with fuel price discounted for the period of time in which it is used.

The cost of the diesel units involves the cost of the first generation of the engine series, the present-value cost of the later generations is less than the present-value returns from the scrapped engines.

The operation cost involves the present-value of fuel consumption in 20-years and that of maintenance. The diesel engine must be replaced after every 3 years.

The following table shows expected costs over the life of the diesel pumping system.

<table>
<thead>
<tr>
<th>Item</th>
<th>Install capital cost (SD)</th>
<th>Recurrent cost (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Variable</td>
</tr>
<tr>
<td>Diesel engine (6HP)</td>
<td>120000</td>
<td>35000</td>
</tr>
<tr>
<td>Generator</td>
<td>35000</td>
<td></td>
</tr>
</tbody>
</table>
Table (5.3) the expected costs of diesel pumping system.

The non-annual recurrent cost listed (60000 SD) occurs every 3 years. First occurs at year 4, 7, 10, 13, 16, and at year 19 (six times).

The present worth of variable annual cost is given by equation (5.3)

\[
\text{Present worth (P)} = 1650000 + 215000 \times \frac{1.15}{1.1} \times \left[1 - \left(\frac{1.15}{1.1}\right)^{20}\right]
\]

\[
= 1650000 + 215000 \times 32.95
\]

\[
= 8734250 \text{ SD}
\]

The present worth of the six non-annual costs must be calculated separately:

substituting in equation (5.6)

At year 4: \[ P = 60000 \times \left(\frac{1.15}{1.1}\right)^4 \]

\[ = 71676 \text{ SD} \]

At year 7: \[ P = 60000 \times \left(\frac{1.15}{1.1}\right)^7 \]

\[ = 81900 \]

At year 10: \[ P = 140000 \times \left(\frac{1.15}{1.1}\right)^{10} \]

\[ = 218363 \]

At year 13: \[ P = 60000 \times \left(\frac{1.15}{1.1}\right)^{13} \]

\[ = 106934 \]

At year 16: \[ P = 60000 \times \left(\frac{1.15}{1.1}\right)^{16} \]

\[ = 122189 \]

At year 19: \[ P = 60000 \times \left(\frac{1.15}{1.1}\right)^{19} \]

\[ = 139620 \]

Total present worth of non-annual \[ = 740682 \text{ SD} \]

Fuel cost (Cf) substituting in equation (5.4)

Present worth of (Cf) \[ = 71540 \times \left(\frac{1.16}{-0.06}\right) \times \left[1 - \left(\frac{1.16}{1.1}\right)^{20}\right] \]

\[ = 71540 \times 36.6 \]

\[ = 2618364 \text{ SD} \]

The present worth of scrap \[ = 60000 \times \left(\frac{1.15}{1.1}\right)^{20} \]

\[ = 145967 \text{ SD} \]

Net present worth cost \[ = 8734250 + 740682 + 2618364 - 145967 \]

\[ = 11947329 \text{ SD} \]

Annuity (A) by substituting in equation (5.1)

Annuity (A) \[ = 11947329 \times 0.1174 \]

\[ = 1402616 \text{ SD} \]

Unit cost \[ = \text{Annual Life Cycle Cost} / \text{annual products} \]

\[ = 96.1 \text{ SD/m}^3 \]
5.2.5 **Comparison:**

<table>
<thead>
<tr>
<th>Option</th>
<th>System</th>
<th>Unit cost SD/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hybrid wind, solar &amp; diesel pump</td>
<td>84</td>
</tr>
<tr>
<td>2</td>
<td>Hybrid wind &amp; solar pump</td>
<td>45.5</td>
</tr>
<tr>
<td>3</td>
<td>Diesel pump only</td>
<td>96.1</td>
</tr>
</tbody>
</table>

**Notes:**

The comparison was showed that the option (1) is economically optimal than the option (3). Because the option (1) was produced more water than the required.

The cost analyses for the three options at a duty 1000 m³/day are illustrated in fig. (4.1, 4.2, 4.3 and 4.4) below.
Table (5.4) the time cost analysis for hybrid wind/solar & diesel pumps

<table>
<thead>
<tr>
<th>Year</th>
<th>F2</th>
<th>A cost</th>
<th>Maint. cost</th>
<th>Non-annual cost</th>
<th>Total PV</th>
<th>Cum. PV in SD</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>3473000</td>
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</table>

Fig (5.1) time cost analysis for wind/solar & diesel hybrid pumping system at a duty of 1000m4/day
<table>
<thead>
<tr>
<th>Life time</th>
<th>Capital cost (SD)</th>
<th>Fuel fuel cost (SD)</th>
<th>O &amp; M cost (SD)</th>
<th>Non-annual cost (SD)</th>
<th>Total PV (SD)</th>
<th>Cum. PV (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>year</td>
<td>5E+05</td>
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<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>450000</td>
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<td>818</td>
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<td>300215</td>
<td>750215</td>
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</tr>
</tbody>
</table>
Table (5.6) the time-cost analysis of diesel pump

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<td>818</td>
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Fig. (5.3) the time - cost analysis of diesel pump at a duty of 1000 m³/day

Fig. (5.6) the time - cost analysis of diesel pump

Legend:
- Diesel pump only
- Diesel only
- wind/solar
- wind/solar & diesel

Time-Cost Analysis Chart

Livetime in years
Cumulative PV in SD

Diesel pump only

Livetime in years
Cum. PV in SD

Legend:
- Diesel only
- wind/solar
- wind/solar & diesel

Cum. PV in SD

Lifetime in years
A C++ program has been designed for the simulation of a hybrid wind, solar and diesel pump, working together. The computer program is designed for the three pumps to give the demand of water (i.e. equal to or greater than 40 m³/day). This program was used first wind pump and second solar pump. The diesel pump is operated when the two pumps can not cover the demand. Fig. (6.1) shows the decision chart for water supply.
6.2- **The Algorithm of the program of a hybrid pumping system:**

To calculate the volume of the water produced by the wind, solar and diesel pump per day.

6.3- **Inputs:**
- wind speed
- solar radiation
- Total pumping head
- Rotor diameter
- No. of modules

6.4- **Outputs:**
- Wind pump flow rate in m$^3$/day
- Solar pump flow rate in m$^3$/day
- Diesel pump flow rate in m$^3$/day
- Diesel fuel consumption in liter/day
- Cost of fuel in SD
- Diesel pump working hours

6.5- **The Steps:**

Simplifying the equations and choosing symbols to suit the applications of computer program.

Step –[1] Calculate the wind pump flow rate using equation

\[ Q_w = 0.69 \times V^3 \times d^2 / H \] …(6.1)

Where: \( Q_w \) = wind pump flow rate in m$^3$/day
\( V \) = the mean wind speed in m/s
\( d \) = rotor diameter in m
\( H \) = total pumping head in m.

Step –[2]

Calculate the solar pump flow rate, by using equation (2.3)

\[
\text{Array size} \ W_p = \frac{9.81 \times Q_s \times H}{3.6 \times F_T \times F_M \times \eta} 
\]

Array size \( W_p \) = N* Watts peak

Assumption:

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\[ N \times 55 = 9.81 \times Q_s \times H / (3.6 \times 0.8 \times 0.9 \times 0.35) \times R \]
\[ Q_s = 5.09 \text{ N}\times R/H \] …(6.2)

Where: \( Q_s \) = solar pump flow rate in m\(^3\)/day
\( N \) = No. of modules
\( R \) = radiation in kWh/m\(^2\)/day
\( H \) = total pumping head in m.

The water demand \( D = Q_w + Q_s + Q_d = 40 \) …(6.3)

Where: \( Q_d \) = diesel pump flow rate in m\(^3\)/day

Step- [3]

i- Calculate the diesel pump flow rate by subtracting the sum of \((Q_w + Q_s)\) from the demand \((40 \text{ m}^3)\). The remaining is covered by diesel pump,

\[ Q_d = 40 - (Q_w + Q_s); \quad \text{or} \quad Q_d = D - (Q_w + Q_s); \quad \ldots (6.4) \]

ii- Multiply this amount of diesel fuel consumption by fuel price (87.5 SD/liter);

iii- Divide the \((Q_d)\) by the pump capacity per hour to determine the working hours.

Assumption:

The diesel flow rate \( = 7.5 \text{ m}^3/h \)

Motor/Pump efficiency \( = 58\% \)
Transmission efficiency \( = 95\% \)
Generator efficiency \( = 80\% \)
Overall efficiency \( = 0.44\% \)
Total de-rating \( = 15\% \)
Total pumping head \( = 25 \text{ m} \)

Diesel engine power \((6\text{HP})\) \( = 4.5\text{kW} \)

\[ E_h = 0.00273 \times Q \times H = 0.00273 \times 7.5 \times 25 = 0.512 \text{kW} \]

Power input to the pump \( = 0.512/0.44 = 1.164 \text{kW} \)
De-rating power \( = 4.5 \times (1 - 0.15) = 3.83 \text{kW} \)
Loading \( = 1.164/3.83 = 0.30 \)

Substituting in the equation of full load fuel consumption (FLFC) below:

\[ \text{FLFC} = \frac{kW}{g} \times (0.001/SG) \times kW \]

From manufacturer information \((6\text{HP})\) Lister diesel engine,

\( kW/g \) \( =268, \quad \text{----} \ SG = 0.87, \)

\[ \text{FLFC} = 268 \times (0.001/0.87) \times 4.5 = 1.4 \text{ liter/h} \]
Actual fuel consumption = loading* FLFC = 0.3*1.4 = 0.42 liter/h

The amount of diesel fuel consumption = 0.42*\(Q_d/7.5\)

\[= 0.056Q_d \text{ liter} \quad \ldots(5.5)\]

The price of diesel fuel = 87.5 SD/liter

The cost of diesel fuel consumption = 87.5*0.056Q = 4.9*Q_d SD \ldots(6.6)

The diesel pump working hours = \(Q_d/7.5\) hrs \ldots(6.7)

**Step - [4]**

i- Substituting the diesel pump supply flow rate (\(Q_d\)) in the equation (6.5) to determine the amount of diesel fuel consumption;

ii- Substituting \(Q_d\) in the equation (6.6) to determine the fuel cost;

iii- Substituting \(Q_d\) in the equation (6.7) to determine the working hours.

**6.6- Symbols and Units:**

Symbols is assumed for computer program are as follows:

- A = amount of diesel fuel consumption liter
- C = cost of diesel fuel consumption SD
- d = rotor diameter m
- H = total pumping head m
- N = No. of modules
- Q = diesel flow rate \(m^3/\text{day}\)
- R = solar radiation kWh/m²day
- S = solar pump flow rate \(m^3/\text{day}\)
- W = wind pump flow rate \(m^3/\text{day}\)
- V = mean wind speed m/s
- h = working hours hrs

**6.7- Running of program:**

The program inputs of hybrid system power produced water for small rural community consist of water demand 40 \(m^3/\text{day}\), was supplied by hybrid pumping system (wind, solar and diesel pumps).

The program can be run easily in a personal computer to determine the flow rate of the three pumps individual of the hybrid pumping system, the amount, cost of fuel consumption per day, and working hours of diesel pump. For the demand = 40 \(m^3/\text{day}\), the system will cover this demand at minimum wind speed is 3.5 m/s and solar radiation is 4 kWh/ m²/day. Otherwise, the diesel pump will enter the system so as to cover the deficit occurred.
Chapter VII

Conclusions

The researcher collected statistical data taken from Khartoum Metreological Department and Soba Station. The wind speed and solar radiation data was analysed investigate the possibility of the application of hybrid pumping system in location of Iseali village. The simulation is adapted for small-scale system.

The following are the conclusions reached:

1- The minimum wind speed and solar radiation to cover the demand is 3.5 m/s and 4kWh/m² per day respectively.

2- The months of Dec, Jan, Feb, Mar, Apr and Jul are the best months and have a surplus about 3847 m³.

3- The months of May, Aug, Sep, And Oct are the worst months and have a deficit about 686 m³.

4- The economical analysis has revealed that the hybrid wind/solar option is the most feasible.

5- The wind/solar/diesel hybrid pumping system is less costly than the diesel system only.

Comparing the unit cost of the three alternatives of hybrid pumping systems, it has been found that the (wind/solar/ diesel pumps) is more costly than the (wind/solar) system. But this system can saves water supply throughout the year. This comparison is based on all systems designed to deliver the same volume of water from the same head.

This research studied the data of wind speed and solar radiation for one year, because we were not able to obtain the data for several years in details, hourly and daily.

The recommendation is that to study the data of speed and solar radiation for several years in the future for hybrid pumping system may be get best results than for one year.

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[16]- Dr. Mohammed. H. Siddig, the Feasibility of using Wind pumps in Zimbabwe (1998)

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A guideline on economic and financial analyses for feasibility studies
(CWD 84-1 January 1984)

[18]- National Water Equipment’s Manufacturing Co. LTD (Khartoum)

Semen’s Solar Products Catalogue

[20]- Http//www.rsvp.nrel.gov - Renewable of Sustainable Village Power (RSVP)
[21]- Http//www.solarelectric.com – Water pump

Appendix C1

Type of using Pump: -

In this case study using locally manufacturing pump type CWD 5000 (Holland) by National Water Equipment Manufacturing Co. LTD Khartoum. Work on this type of pumps has been proceeding in Sudan since the 1980 s for purposes of pumping water, for drinking.

Specifications of CWD5000 pump :-

Pump diameter \((d_p)\) = 4 inch = 100 mm
Stroke \((s)\) = 200 mm
Efficiency = 70%
Rotor diameter = 5 m
Tower = 9 m
Minimum wind speed = 3.5 m/s

Sizing:
The fig (c1) shows how to determine the size of the wind pump

Appendix C2

1- Solar pump:

PV arrays: modules from Solarman co. (Khartoum)
Type solar module SM 55/SM50 (SIEMENS)
The unit price of module = $ 337

2- Electrical parameters

Rated power = 55w, configuration = 12V, rated current = 3.15 A
Rated voltage = 17.4V, short circuit current = 3.45 A
Open circuit voltage = 21.7V
Solar pump/motor manufacturing by GRUNDFOS, the solar motor has specifications:
- Nominal data at 50 Hz; Cos. φ : 0.87
- Voltage = 65 V x 3, Current = 8.8 A;
- Power = 0.75 Hp = 550 W
Maximum Rating power = 1200 W

3- **Sizing:**
The fig (c 2) shows how to determine the size of the solar pump

4- **Section of pump**
The pump is a multistage centrifugal pump with radial impellers direct coupled with a GRUNDFOS submersible motor.

5- **Subsystem configuration:**
There are several different system configurations that are suitable with solar power, and it is important to choose the right one for each application. The five main types are shown schematically in fig. (c 3) below.

**Appendix C3**

**Diesel pump:**
Diesel engine from local market (India) 6HP = (4.5kW) = 120000 SD
Generator (3kW) single phase (China) = 35000 SD
Submersible pump = 80000 SD
Engine house from zinc + installation = 145000 SD
The total cost = 380000 SD

Submersible pump made in Italy single phase,
From Abu Hasanain co. (Khartoum)
Specifications:
Q = 1.6 --- 3 l/s,
H = 55 --- 10 m
Voltage = 230 V, -- single phase
Ampere = 5.6A, Hz = 50,
Speed = 2800 rpm
* The diesel engine is 6 HP = 4.5 kW
Power = HP = 4.5 kW
Kg/ = 268

Assume the total factor of de-rate 15%. [2]
The power de-rating = 4.5*(100 - 15)/100 = 3.83 kW

Examples of typical diesel-engine performance curves for torque, power, and fuel consumption are shown in fig. (c 4). While fuel consumption (grams of fuel consumed per hour of operation) increases with engine speed, specific fuel consumption (in grams of fuel consumed per kilowatt power output) varies with operating speed. In figure (c 5), the Kubota ER 1200 is designed to operate most efficiently (i.e., lowest specific fuel consumption) around 1900 rpm.
Appendix B2

Soba Meteorological Station
Solar radiation

Unit - mJ/m2

Data
Khartoum - February 1980

Fig. (4.1) the schematic diagram of the hybrid pumping system
Appendix B2

Soba Meteorological Station
Solar radiation

Date

Unit - mJ/m2

Data
Khartoum - April 1980

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