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REVIEW OF PHOTOVOLTAIC ENERGY DEVELOPMENT IN KENYA FOR RURAL ELECTRIFICATION

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ABSTRACT

Energy demand is rapidly growing [1] throughout much of the developing world, where an estimated two billion people, mostly from sparsely populated areas, currently live without electricity. As electrical energy systems are selected to help meet these people's electricity need, the environmental ramifications of the generating systems become increasingly important. Photovoltaic systems generate electricity without emitting greenhouse gases, and result in global, regional and local air quality advantages. In this work we intend to carry out research and development of photovoltaic solar cells for rural electrification – especially solar powered water pumping.

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1. Introduction

Angrist S.W. [2] classified the actually known energy sources into two groups: energy capital and energy income. The former consists of fossil fuels while the latter refers to renewable resources such as wind, tides, rivers, solar, biomass etc. We, therefore, realise that the world's present energy is mostly provided by the capital resources. Power is mainly produced in the form of heat and electricity by burning fossil fuel or using potential energy of water or hydro-electric.

The 'energy problem' is as much a problem of distribution of resources between countries (or precisely between groups within countries) as a problem of absolute shortage of usable energy supplies, see Fig. 1. The unequal distribution of resources such as oil, or capital, is reflected in the distribution of resources for the energy – related research and development – over 95% of the world's research and development (R&D) takes place in developed countries. Therefore, a further dimension of rural energy problems is that, the vast majority of the technical options which are available to the rural Third World, will be produced outside the developing countries, and will often be primarily designed to meet the needs of rich countries. This must change if Third World is to realise its energy needs, and hence, development. For this to be realised, the R&D's facilities must be located within the developing countries, and close to the end-user in order for them to acquire the skills, mainly through local training with the aim to transfer the technology. The technology transfer should be designed to promote the development and use of local technological capabilities with the following aims in mind:

(i) To accumulate more systematic knowledge about the condition for successful innovation – particularly in the informal sector, about which knowledge and information are singularly lacking.

(ii) To start a programme of experimenting – with measures to get on with the practical business of drawing local resources (e.g., human resources – their knowledge, skills, and capabilities) more substantially into the process of implementing technical changes.

Currently, most of the developing countries are pursuing development policies geared towards reducing poverty, energy use will probably need to rise to support basic services like electric lighting, refrigeration etc. Technologies that could enable developing countries to grow economically while reducing or stabilising energy use are currently of limited availability. What's more, even when such technologies are economically competitive over the long-term, they tend to require more up-front capital than developing countries can afford, unless they receive support from aid agencies or other international funding sources. Even worse hit, are the rural areas of the developing countries.

The current world-wide use of energy per capita is about 2.2 kW/inhabitant, although wide differences exist between the richest (6 to 11 kW/inhabitant) and poorest (1 to 0.1 kW/inhabitant) nations. If this average of 2.2 kW can be maintained – the improvements and increased use in the South being offset by economies and better efficiency in the North – the total energy use of the world would still have to be multiplied by 2.5 by the year 2010 - 2050; this factor might be 4 if the North insisted on staying at its present high level of consumption [3-6].

Although high, these aims appear within reach from the resources point of view, if man turns to renewable energy sources. An increased effort on the development of all renewable forms of energy supply however exotic (geothermal, tidal, wind, temperature gradients of the oceans, biomass, solar, etc.) can lead to a greater reduction in the use of fossil fuels for our energy needs [7]. Of the above mentioned alternative forms of energy (renewable); wind, biomass and solar are the most appropriate ones for use in remote rural parts of developing countries, when one takes developmental cost into consideration. Wind energy for rural electrification and water pumping has been discussed in a paper by Rabah *et al* [8]. It has been in use in remote rural Europe for centuries [9], and recently in some parts of developing countries.

Biomass today accounts for over one-third of all energy used in developing countries, see Fig. 1, where it is used primarily for domestic cooking and heating [7,11]. Apart from their technologies being relatively inefficient, considerable time is spent by women and children in rural areas collecting daily fuel needs. Moreover, the use of rural children to fetch firewood has led to their poor performance in school, leading to higher dropouts, when compared to their urban counterparts. Biomass in the form of biogas have been in use for many years in rural Third World, especially in the Indian Sub-continent. An indication of the limitation of technology alone to effect changes, is given by the Indian household scale biogas (methane) programme [11-13]. Apart from their contribution to greenhouse gases, the use of biogas plants is even said to widened the gap between rich and poor, by removing a resource (dug) from the poorer groups – at almost no cost. Furthermore, the increase use of biogas may lead to reduced fertiliser availability (cow dug – has an alternative use as an organic manure), and consequently, to reduced crops yield and lowered nutritional levels for the rural poor.

Furthermore, when plants are burned as fuel (i.e., to produce biomass energy), without being allowed to grow back – as in the case of massive deforestation – the use of biomass fuels can yield a net increase in atmospheric CO_2, and hence, global warming [5]. Moreover, biomass fuels used today generate a number of indoor air pollutants, including particulates, carbon monoxide, and variety of volatile hydrocarbons, all which can produce adverse health effects [11,14]. The health impact of biomass cookers most likely exceeds that of all other air pollutants combined [11]. Other cook-stove fuels, such as coal generate some or all of these pollutants, as well as nitrogen and sulphur dioxides. Another factor which is going against large scale use of biomass energy in developing countries is – with the population growing – will there be sufficient land resources to both feed future population and sustain the magnitude of biomass energy development? Furthermore, it is believed that, if intensive biomass farming (to feed biomass fuel generators) were to be introduced in developing countries, the rural poor will abandon crop farming for biomass plantation, to generate some monetary income. This could lead to a drop in food crop production, resulting in lower nutritional levels with consequent increase in health problems.

2. Solar energy as an alternative

Unlike biomass, solar energy is the most abundant form of energy available, and it has been the source of the fossil fuel energy stored in the Earth's crust. The greatest amount of solar energy is found in two broad bands around the Earth: between the 15° and 35° north and south parallels, respectively, with the next favourable region for the purpose of solar energy application, being located in the equatorial belt between the 15° N and 15° S parallels. Most developing countries are located within these bands, with approximately one-third of the world's population living in those areas.

It has been estimated that the energy received over the total surface of the Earth amounts to 1.73×10^{14} kW, an enormous amount of energy, roughly 20,000 times larger than the current global energy consumption [3,4]. Hence, from a purely technological point of view, solar energy conversion systems are potentially capable of producing the bulk of the world's future energy demand. For example, the world's energy consumption of about 56×10^{12} kWh in 1972 equals the solar energy which is received every year by an area of 22000 km^2 in a desert region. Thus, a solar energy converting devices covering about a quarter of the area of Egypt, for example, could theoretically provide all energy consumed in the world [3,4].

At present, the most promising techniques for solar energy utilisation are based on photothermal and photovoltaic (PV) conversions. In the photothermal approach, the sunlight is absorbed by a surface to generate heat. Such a surface must fulfil certain optical criteria to achieve a good efficiency. In the second approach, the solar energy is directly converted to electricity by means of photovoltaic effect. The direct conversion of the sunlight into electrical energy involves electronhole pairs generation and separation. Once photocarriers are separated, electrons are collected at an external circuit to obtain an output electrical power. This conversion is achieved by semiconductor devices – solar cells – which are large area junction diodes, specifically designed to obtain the highest efficiency under fixed condition of illumination [15]. In this project, we will concentrate on the study of photovoltaic systems, its fabrication and application in rural electrification in small-scale water pumping for domestic consumption and agricultural irrigation, apart from in-house lighting and appliance use.

The possibility of using solar energy to produce electricity in photovoltaic cells, if the cost problem is solved – i.e., by developing easy and efficient cost-effective fabrication techniques, that can easily be employed in developing countries to produce cheaper photovoltaic cells – is enormous. The first photovoltaic effect was discovered by A. Edmond Becquerel, when he observed that certain materials produce a small current when exposed to light [16,17]. The possibility of utilising this discovery was not realised until a century later, and even then, the incident light-to-electricity conversion efficiencies were only 1%. However, by late 1950s and with the discovery of single crystals silicon, the technologies had advanced enough to be used in the U.S. Space Programs, the first solar powered space vehicle, Vanguard I, being launched in 1958 [18]. By mid 1970s, the prices for PV-generated power were just starting to approach the commercial - feasible range, and by early 1980s, PV market had been established world-wide. The current available PV modules can achieve between 10 to 18% efficiency depending on the material used, while those in the laboratories have shown efficiencies of over 28% [19]. One-third of the world PV modules used today are made from amorphous semiconductor materials.

Photovoltaics with their multiple advantages offer an attractive alternative for rural electrification when compared to traditional energy sources: it is decentralised, uses a locally generated resources (sun), frees from price fluctuation common with centralised grid systems, is easily transportable, and thus, can penetrate remote rural areas, is safer for the environment in many ways than traditional fuels. While the fabrication and disposal of photovoltaic system components will have some environmental impacts, careful manufacturing controls and recycling can keep these to a minimum [26,27]. Studies evaluating the overall environmental impacts of electricity supply options, typically rate photovoltaic systems amongst the most environmentally benign [26,28,29]. Furthermore, the building of solar generators is greatly simplified by the fact that they can be combined with other constructions, since solar energy collectors, because of their flat shape, can easily be installed over existing buildings. Thus, solar generators can be envisaged as a secondary users of occupied site, except of course, agricultural land.

Interest in PV systems centres on two broad areas: The first is the use of PV/battery or PV/battery/small-generator system in "stand alone" configurations to meet the power requirements of remote areas. The second is the connection of the PV systems to power grids to meet peak power demands when the sun is shining; for example, on hot, sunny afternoons when air conditioners are in high use. In such grid-connected applications, the electricity would be produced to meet demand, therefore, avoiding the issue of storing electricity for later use [20].

The economic viability of stand-alone PV systems (*typically* 10 – 100 kW per site) have been established – they are cost-effective and should be encouraged. Small-scale PV systems can pay for themselves within a couple of years. Often, PV systems represent the most appropriate and cost-effective technology for rural electrification. Traditionally, utilities have not become involved in serving remote power needs, having declined to serve in areas distant from the existing grid because of the high cost involved. PV systems (*typically* 10 – 1 MW per site) provide a new, low-cost-approach to rural electrification that has proven feasible and effective in the USA and some parts of Europe.

Decentralised (stand-alone) photovoltaic systems have also been found to be highly efficient than in rural villages connected to centralised electricity distribution networks. Solar-based rural electrification can provide a source of employment, and hence, increase in commercial activity and productivity (e.g., agricultural through – solar powered water pumps). In many developing countries, solar-based rural electrification activities can become self-sustaining after an initial period of external support through local training, financial assistance and community loan fund capitalisation. The system must be managed by the locals themselves through rural-based community groups, or non governmental organisations.

3. Photovoltaic energy use in Kenya

Kenya lies right at the equator, see Fig. 2, and this makes it a good candidate for solar energy applications. Kenya gets its electricity mainly from hydro 88%, with some small amount coming from geothermal and importation from Uganda, see Fig. 3 [21-24]. The bulk of these energy is mainly used to serve urban areas and industries, with the rural Kenya (with over 70% population), being left with only about 10% [21,25]. Hence, the need to develop a suitable cost-effective system for rural electrification [24,25].

Kenya is currently estimated to have 20,000 to 40,000 solar systems installed in private homes and small businesses around the country and still growing at a considerable rate [22]. Currently, all the PV modules available in the country are all imported and managed by either a local agent or an imported technical elite. We hope to change this, through the establishment of local R&D, and finally, fabrication of PV cells that are suitable for the country and within the region. Furthermore, it is important to note that currently there are no PV production or R&D facilities within the Eastern and Central African region, see Fig. 4 [22].

4.0 Developing fabrication materials for Kenya

The current aim of the University of Nairobi, Department of Physics in conjunction with the *International Program in the Physical Science (IPPS) Sweden, concerns support for research* funding in the area of Renewable Energy Studies i.e., Research and Development of Renewable Energy Technology and related fields (e.g., Environmental studies) in the area of Solar Cells study (especially in the area of wet solar cells), so that it can contribute more effectively to the following National objectives:

(i) To enlarge the pool of Kenyans with the knowledge, skills and experience required to undertake original designs and implementation of renewable energy supply systems.

(ii) To promote the utilisation of renewable technology especially in the rural areas for the preservation of the environment, and improvement of rural population income capabilities.

(iii) The future plan and goal of the solar energy research group will be in pursuit of International support, for a Centre for energy Studies at the University of Nairobi, that will support co-ordination of researchers from the Eastern Africa region.

iv) To hold local and regional seminars, training workshops from time to time to report on research findings.

In this project, we will concentrate in the study of photovoltaic systems and carry out research and development, with intention for developing new techniques in fabrication and testing of wet solar cells. The ultimate aim is for the search for potentially lower cost methods and materials for efficient conversion of solar energy into electrical power, for rural electrification.

4.1 Types of solar cells: *Thin film versus solid state PV solar device*

Solid state solar cells i.e., *p-n*, Metal-Oxide-Semiconductor (MOS) and, metal-semiconductor (Schottky) junctions are currently fabricated using mainly crystalline silicon. The highest efficiency of over 28% have been reported. These are obtained through high quality materials and sophisticated techniques [17,30]. Such cells are too expensive for the market particularly in developing countries. It is also important to note that even with solid state junctions, cost-effective conversion efficiency still needs to be improved.

Amorphous PV solar devices uses thin (1μm) films of materials, such as amorphous (glassy) silicon (*a*-Si), copper indium diselenide [31] and cadmium telluride (CdTe) [32,33] instead of crystalline material. First discovered in 1974 and introduced as a commercial product in 1978, *a*-Si PVs have spanned an exceptionally wide range of applications, from initial powering of calculators and small appliances to portable electricity generators to installations for production of bulk power. Amorphous silicon has proven to be a versatile thin film semiconductor with numerous non-solar applications, which have contributed vigorously to rapidly expanding technology base. However, these materials have modest quality and are not very stable and hence thin film cells have low efficiency i.e., approximately 10% [34]. We will built our project from this *a*-Si technological base.

There are two primary reasons for believing that thin films can eventually achieve lower costs than crystalline devices. First, Amorphous semiconductor materials absorbs sunlight extremely well, so that only very thin active cell layer is required (about 1μm as compared to 100 μm or so for crystalline solar cells) [35]. As a consequence, far less PV material is needed, which greatly decreases costs [27]. And second, the techniques used to produce thin films are particularly well suited for mass production. The costly batch processes of single crystal production can be replaced by a continuous process in which active materials are sprayed or sputtered directly on to the glass or metal – and this makes the technique a good candidate for technological transfer to developing countries.

The third possibility, and which is of interest to us in this project, is the application of thin film technique coupled with a liquid media to form a solid-liquid (i.e., semiconductor-electrolyte) junction. At present, three types of solid-liquid junction are being studied, namely: photoelectrolytic, photogalvanic and photoelectrochemical (PEC) cells. In the former, solar energy is converted into chemical energy and then into electrical energy. The second and the third convert sunlight directly into electricity, but in photogalvanic cells, the light is absorbed in the solution, while in PEC cells it is absorbed at the semiconductor-electrolyte interface.

The overall task of developing stable high efficiency, low-cost thin-film solar cells can be expressed in terms of four objectives: 1) To control the physical, chemical, optical and electronic properties of amorphous semiconductors; 2) to optimise amorphous semiconductor film deposition by learning the details of film deformation; 3) to develop computer models for optimising the design of solar cells without having to build and test them; 4) to understand and overcome the light-induced instability that affects the most-efficient amorphous thin films.

4.2 Thin film based semiconductor –electrolyte (wet solar) devices

Heterostructure involving thin films of II-VI compounds, especially cadmium sulfide, occupy the central position among thin-film solar cells [36,37]. In the very first solar cells made from this semiconducting material [38], the separating barrier was produced by depositing semitransparent layers of silver, copper or platinum on the cadmium sulfide surface. However, the current solar cells are fabricated using copper sulfide–cadmium sulfide heterojunction, where the copper sulfide is produced by substituting copper for cadmium atoms in the course of the chemical reaction (at 90-95°C) between cadmium sulfide and coprous chloride in liquid form [39,40] and solid [41] phases.

The first is the so-called wet method. When it is used, the surface of the solar cell and the heterojunction itself has numerous pits and projecting grains, and the surface structure is enhanced by chemical etching. This reduces the reflection coefficient of the cell surface, but increases the reverse saturation current. In the latter case, coprous chloride was first deposited on the surface of cadmium sulfide films evaporated in a vacuum. This is the so-called dry method — results in an almost planar heterojunction, plane-parallel relative to the substrate, but the photosensitivity of the copper sulfide films produced in the course of the reaction in the solid phase is somewhat lower than that of the films produced by the wet method. In this project we will concentrate mainly with wet technique.

The above techniques means that these types of devices (wet) solar cells can easily be fabricated and are well suited for technological transfer to developing countries, since there are no such elaborate and expensive processes like slicing, diffusion, surface passivation and texturing, antireflective coatings and metallization which are normally required for solid state devices fabrication. In this technique, the semiconductor is simply dipped in the electrolyte after forming an ohmic contact on one of its faces for carriers collection in an external circuit. This advantage combined with the use of thin film materials, can really lower the device cost. However, the biggest advantage of semiconductor–electrolyte devices, compared to solid state cells is their capacity to store energy. In fact PEC conversion can be combined with electrochemical storage if suitable redox couples are used in the electrolyte. Thus, an auxiliary storage system needed for solid state cells is not required. Fig. 6 show (a) the storage current, (b) the photocurrent and, (c) the output current on two days operation of and *n*-Cd(Se,Te)/aqueous Cs_2S_x/SnS cell [31-

33,42]. It can be observed, from Fig. 6. that the output current is near constant i.e., insensitive to light variation and the overall solar to electrical conversion efficiency is approximated to 11.3%.

4.3 Thin film PEC solar cells

Thin film PEC solar cells have been known for quite some time. However, early researchers were mainly concerned with solid state devices and dominated by the discovery of photovoltaic effects in *p-n* junctions in 1954 [16,17]. Nevertheless, the first solar cell was a photoelectrochemical device constructed by Becquerel in 1839 [2,16,17]. No significant work had been done on the subject up to 1955, whence a group of Japanese workers investigated the nature of the semiconductor-electrolyte junction [16,17]. PEC devices operating in sunlight have been investigated more recently under the stimulus of workers on photoelectrolysis [17,43,44].

From those early works, it was discovered that the major problem to overcome in PEC cells, is the control of the chemical phenomena at the interface, and particularly, the electrode stability. Various solutions have been proposed against photodecomposition of electrodes. One solution which has been attempted, is to coat on the anode a thin film of a more stable oxide semiconductor e.g., TiO_2, Au_2O_3, Ag_2O etc. [17,45,46]. Since such oxides have low-band gap they, therefore, give low conversion efficiency with sunlight [17]. The most promising solution is stabilization using the electrolyte as redox reaction, which is thermodynamically and kinetically favoured compared to the oxide-reduction of the semiconductor [17,46]. This method has been used to stabilise CdS, CdSe, CdTe, ZnSe, SnS and Bi_2S_3 anodes [17,26,46,47]. The highest efficiency of 12.7% reported for PEC cells was obtained by *n*-type Cd(Se,Te) in polysulfide solutions [31-33]. Polyiodide solutions and iodine in alkaline solution have appeared promising, with regard to stabilization and high conversion efficiency [47,48].

5.0 Photoelectrical studies of iron disulfide (FeS_2) thin film in iodine – polyiodide electrolyte PEC solar cells

Iron disulfide FeS_2 thin films will be studied for application as a photoanode in a PEC cell. The anode will consist of *n*- type FeS_2 coated on Titanium or glass-ITO (Tin doped Indium oxide) substrates. Platinum will be used as counter electrode. Coatings will be done by spray pyrolysis. A KI/KI_3 aqueous solution will be used as electrolyte. Thus the redox couple against the photodecomposition of the anode will be I^-/I^-_3.

Iron disulfide FeS_2 is one of the most promising stable photoelectrode material [47]. Different techniques have been used to prepare FeS_2 thin film i.e., CVD, spray pyrolysis, sputtering and reaction of Fe_2O_3 or Fe_3O_4 with sulfur [46,48]. In each case, the film show a sufficiently long majority carrier lifetimes. Ennaomi *et al* [31]. reported an absorption length $1/\alpha$ of 10^{-5} cm for $h\nu > 1.2$ eV and a depletion region width $W = 3.5 \times 10^{-6}$ cm. Therefore, most of minority carriers are created within the depletion region where they are separated from the majority carriers by the built-in-field. Recombination of created carriers in the bulk is therefore minimised. Thus, only a thin layer is required in the fabrication of FeS_2 based PEC cells. Moreover, iron disulfide FeS_2 can easily be obtained, since the iron is the second most abundant metal after Aluminium and fourth most abundant element in the earth's crust [49]. Despite these advantages, the material shows a poor photoresponse in current PEC configuration and need to be further investigated.

5.1 Fabrication of FeS_2 PEC solar cells

One of the major advantage of PEC solar cells compared to solid states cells is the ease with which the junction is established. No elaborate procedures are required to ensure good junction; thus the manufacturing cost is lowered. In a semiconductor-electrolyte junction, the physical contact is more uniform and intimate compared to solid state junctions. Therefore, polycrystalline as well as single crystalline semiconductor can be used as electrodes without significant change in cell performance. In case of solid state devices, the use of polycrystalline materials result in about 3 to ten fold decrease in cell efficiency compared to single crystals [17,50,51]. A chemical deposition technique, namely spray pyrolysis will be used for thin films deposition. As was earlier stated, chemical techniques are low cost compared to physical methods, where a vacuum is needed i.e., expensive equipment involved.

The fabrication process will proceed via three main basic steps: (i) photoanode preparation, (ii) its characterisation and, (iii) its photoelectrochemical behaviour studies. FeS_2 films and In_2O_3:Sn films will be deposited by spray pyrolysis or thermal decomposition. Temperature on the substrate surface will be recorded using a thermocouple. The primary solution for FeS_2 and ITO will be mixed solution of $FeCl_3$ with thiourea and $InCl_3$ with $SnCl_4$, respectively. Fig. 7 shows the schematic structure of photoanode.

The project will proceed with the following five objectives in mind:

1. To grow iron disulfide FeS_2 thin films on glass-ITO substrate and on Ti substrate using spray pyrolysis.

2. To optimise deposition parameters for high photoresponse and stability in presence of a polyiodide solution namely; KI/KI_3.

3. To determine structural, electrical and optical characteristics of FeS_2 thin films prepared as

described above.

4. To study photoelectrochemical behaviour of these films in KI/KI_3 solution (alkali-polyiodide solution) using platinum as counter electrode.

5. To determine the optimum condition for high efficiency of a Fe_2 –I/I_3 PEC cell.

At Nairobi, the equipment's have already been set up for the test-run production, although initially, only for research purpose. The trial spraying has been done on a glass substrate in order to identify with a view to optimize FeS_2 thin film deposition parameters. These parameters are:

– the substrate temperature,
– the spray rate and,
– the spray height.

The spraying mixture consisted of 0.01M solution of thiourea [$CS(NH_2)_2$] and iron chloride ($FeCl_3$) in a volume ratio of 2:1. The optimum spray height and rate were estimated to be 35 cm and 24 cm^3/min, respectively, for temperature less 370°C. For higher for spray rate, the droplets on reaching the substrate could not decompose immediately. Thus, white precipitates are formed due to slow decomposition and the obtained film is not uniform. For low spray height and high rate, the substrate cracked due to rapid cooling. For high spray height a lot of solution is wasted. Further, it has been observed that FeS_2 film is opaque in visible but transparent in infrared.

PEC cells can be used both for direct photocurrent production and for hydrogen production by water electrolysis. But the investigation on electrodes stabilization and conversion efficiency improvement are still not conclusive. Further work is necessary. Production processes that couple such material economy with the speed and uniform quality of automation more than compensate for amorphous semiconductor's low energy conversion efficiency, so far found to be less than that of some other PV materials.

Moreover, some production capability exist – automated glass-in, PV-out normally used for the manufacturing of amorphous silicon modules including computer controlled laser scribing to form internal electrical connections are easily accessible and will be adapted here. In practice, an allowance must be made for the efficiency of solar energy conversion devices, as well as the efficiency of the associated energy storage systems which are generally required. This is very important if the solar system is in addition for home use – i.e., for lighting and home appliances.

5.2 Expected Results and Potential Beneficiaries

We are satisfied that the prospect for a successful outcome of project are very good. The basis for this is that substantial research work on photovoltaic conversion has been going on in the Department in the field of solid state electronics. However, the area of wet solar cells have been all along neglected, but we hope that this will now be a thing of the past. From our past experience, we believe that the ultimate product will be of high scientific standard and with publications that will compete competitively with those from developed countries.

5.3 Future plans

Future plans will involve developing others wet solar cells technology. This will centre on the development of a new type of solar cells based on sensitised, nanocrystalline, semiconducting films e.g., the development of TiO_2 [52-55] wet solar cells. These have been found to be more economical than the conventional solar cells that convert electricity by exploiting the photovoltaic effect that exist at the semiconductor junctions. Moreover, Titanium dioxide, the world-wide annual production of which is in the region of a million of tons costs 1$/kg. A nanocrystalline film requires $18 g/m^2$ for a thickness of 10 micron. Ruthenium the other material that is used is more costly but the quantity required are minimal and corresponds to a cost of $0.07\$/m^2$. One ton of this metal could furnish 1 gigawatt of electricity, that is to say, double the world's existing photovoltaic power. These two factors allow one to envisage production in Third-world countries. Further, our group will endeavour to solicit for more funds from other sources to help expand into other areas of renewable energy and its environmental implications. In short our aim is to make Nairobi a Centre of excellence in renewable energy study within this region.

Another research work which has been going on in Nairobi, is in the area of electronics hardware development of conditioners for electric water pumps, and this is explained below.

6.0 Small-scale solar-powered water pumping system

At the university of Nairobi, Department of Physics, we are developing cost-effective power electronic systems to increase the efficiency of electric solar and wind powered water pumps [56]. The technology behind this electronic systems will be expounded later in the text. These are intended for use in remote rural Kenya, where access to clean drinking water is next to impossible. This technology could then be extended to other developing countries in the near future, with the help of the academic institutions and non-governmental organisations working within the region.

The unavailability of water for domestic use in rural Kenya has been well documented in paper by Rabah *et al.* [8]. The UN normally designate water as "water for life" and without adequate water supply in any community is great disaster with even greater health consequences [8]. The use of renewable energy for water pumping, especially wind mill, have been going for many centuries. Windmills for water pumping were first recorded to have been used in Scottish Isle c. 1182 [9]. However, in the past decade, small-scale solar-powered water pumping has become increasingly practical alternative to diesel-powered pumps in tropical countries with large numbers of clear days [51]. In the design of solar powered water pump, it is important to first examine the basic components individually.

Fig. 8 shows a block diagram of a typical type of small-scale solar powered system. The power is generated by the arrays of solar cells which are grouped together into solar panels of a set output voltage. A typical solar panel produces approximately 45 watts in full sunlight, generating 3A at 15V. These values vary non linearly according to the insolation upon the panel and the load across it. Voltages can rise as high as 18 or 19 volts under open-circuit conditions, and fall to nearly zero volts under condition of poor sunlight or when subjected to a heavy load.

The arrangement of solar panel in array can be either in series, parallel or in series-parallel depending upon the most suitable output characteristics of the array for the application at hand. Although such combinations of several different types of solar panels yields a greater diversity of outputs to select from, in the end, continuously variable output are not an option with any sort of array.

The above problem can be eliminated either by the use of energy storage systems or the power conditioners shown in Fig. 8. Energy storage systems are useful in providing energy to the pumping systems at night or on cloudy days. They can also be used to supply large bursts of energy for a short period of time, such as when starting the pump motor from rest, which requires a large surge, or when the pump encounters water pressure fluctuations due to the presence of air bubbles in the pumping systems. In this sense power storage systems can act as power conditioners, but only in the most primitive form. Power conditioners must handle two problems: short term power demand fluctuations and surges, and the more complex problem of impedance matching. A power storage system can only meet the first of these, and then only if it has components capable of high energy-discharge rates i.e., high current batteries or some easily dischargeable form of mechanical energy storage systems such as a flywheel. By far, the most common method of power storage for photovoltaic applications is chemical, utilising lead-acid batteries or gelcels.

However, in rural small-scale water pumping applications, in contrast to domestic uses, power storage is usually less crucial than power conditioning of a sort that can satisfy both requirements mentioned above. Power conditioning helps to provide load impedance matching between solar array and its load, the pump motor. In this type of application, there are two types of systems: linear and non linear systems. In the case of linear system i.e., a linear power source and a linear load, impedance matching is simply done by ensuring that both the input and output impedance are equal and are imaginary conjugates of each other. While in the latter case (and which is of interest to us), one must ensure that there is greatest possible power flow into the pump motor from the solar array given the instantaneous solar insolation, temperature, pumping conditions etc. At Nairobi University we have developed and currently testing the power conditioner for rural water pumping. This is described in the next section.

6.1 Designing of power conditioning system

Efficient power conditioning requires that the array must encounters an apparent load resistant *that, causes it to supply power at the voltage* and corresponding current along its I-V curve that, generates the maximum output power produced under the given conditions of solar insolation, panel temperature, etc. This point along the power curve is called the Maximum Power Point (MPP), and the conditioner that can transform the load impedance into an apparent impedance and keeps the array operating at its MPP is called a Maximum Power Point Tracker (MPPT).

The MPP of a curve which resembles a typical solar panel power curve is shown in Fig. 9. The top line shows a typical I-V curve encountered with solar panels, and the bottom curve an approximate power curve for the I-V curve above it. The MPP is the highest point on the curve, which corresponds to the "knee" of the I-V curve. With both the current I, and the voltage V, specified for the arrays output, then resistance that must be connected across it to induce this condition is known: the apparent resistance must be V/I ohms. MPPT ensures that regardless of what conditions exists at the pump motor and what its actual resistance might be, the motor will constantly appear as this same V/I ohm load to the solar panel.

As a typical example, if an array had its MPP at the location on the I-V curve where I = 3A and V = 15VDC, then the apparent load connected to it should be 5 ohms. If the motor to be connected to it had a constant resistance of 10 ohms, then connecting it directly to the motor would result in current saturation, i.e., the array would be capable of producing far more current than the motor could demand at that voltage. Current saturation would cause the array output to rise at the expense of its current output capability. This would continue until the array reached the location on the I-V curve at which V/I = 10 ohms. This would probably be somewhere in the region of I = 1.6A and V = 16VDC.

From the above simple analysis it is important to note that under this conditions, the panel would no longer be operating at its MPP. In fact, it would only be generating 25.6 watts, whereas at its MPP it could generate 45 watts. However, an MPPT could transform the power from the array to higher voltage, thereby lowering the current saturation of the array, while keeping its voltage closer to its MPP. Ideally, a perfectly efficient MPPT would keep the array operating continuously at its MPP voltage, and would transform the array's output voltage to the necessary voltage required by the motor, in order to operate it at the same power level under the given conditions. In other words, if the motor under the given pumping conditions would consume 45 watts only when the voltage applied to it was 26 volts, then the MPPT should transform the voltage from the array from 15 volts to 26 volts for the motor.

Obviously then, an ideal MPPT would have to be able to provide a continuously variable output voltage, and be capable of this for any input voltage, since the input voltage may fluctuate due to varying conditions acting upon the solar array. Furthermore, while undertaking this transformation, one should take care not to loose any power in the process i.e., it may not dissipate any heat. Practical attempts at this are doomed to a high degree of difficulties in implementation owing to the huge amounts of power that must be converted. High amperage at low voltages requires low resistance wiring and high amperage devices, and losses are bound to be significant.

With this objective in mind, we decided to develop a less expensive power conditioner. It is the lowest technology part of the overall solar systems, and is therefore the most easily redesignable in the entire solar electricity - water pumping systems, see Fig. 10. The developed conditioner, Fig. 11, although lower in efficiency when compared to the commercially available ones, it is inexpensive enough to compensate for the expense incurred in the lost photovoltaic energy presented to pump motor. However, further research is still needed to improve the efficiency of these conditioners. For further information, contact Dr. Rabah using permanent address.

7.0 Acknowledgement

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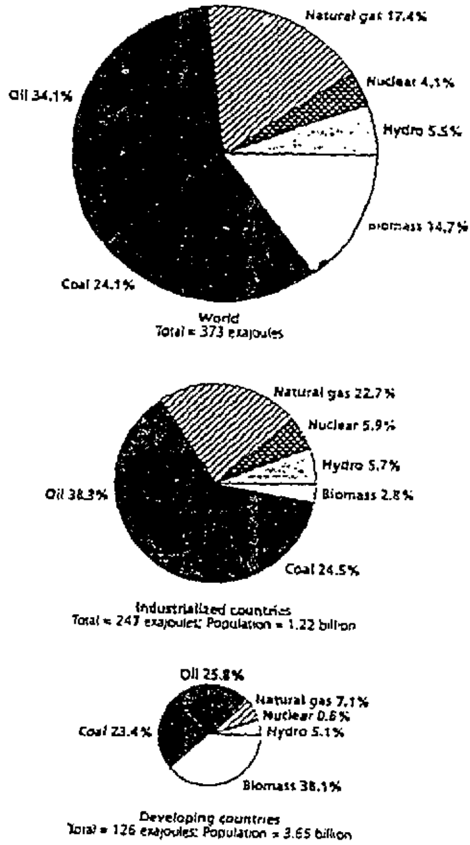

Fig. 1. Estimated energy use distribution in 1987 in industrialised countries, developing countries, and the world (Hall *et al.* [9]).

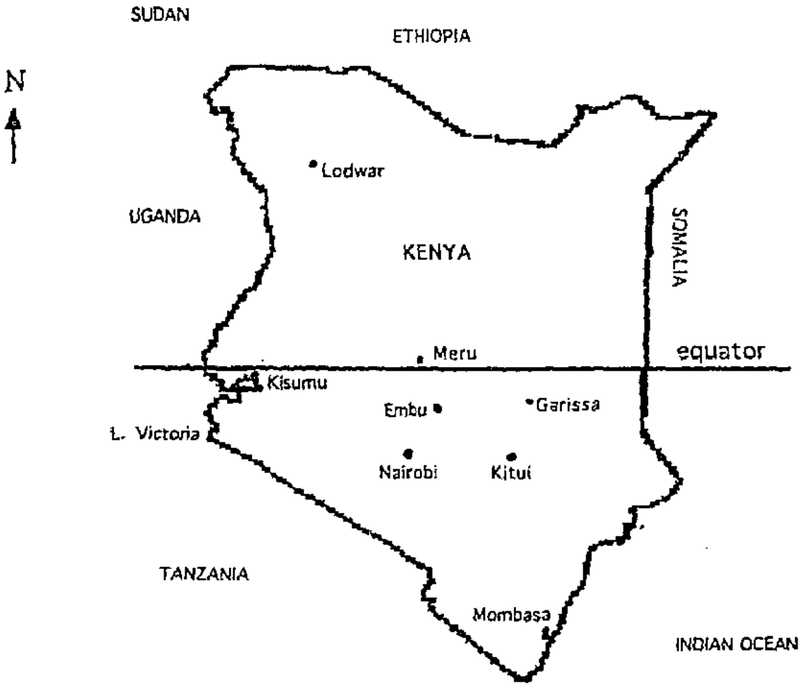

Fig. 2 Map of Kenya.

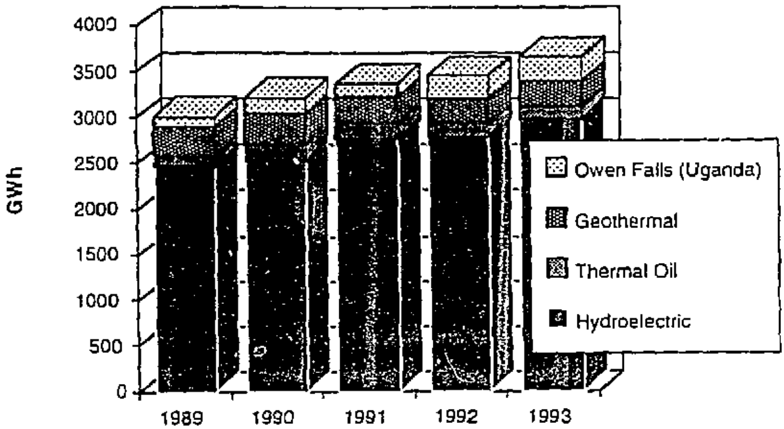

Fig. 3 Sources for Kenya electric supply (Acker *et al.* [22]).

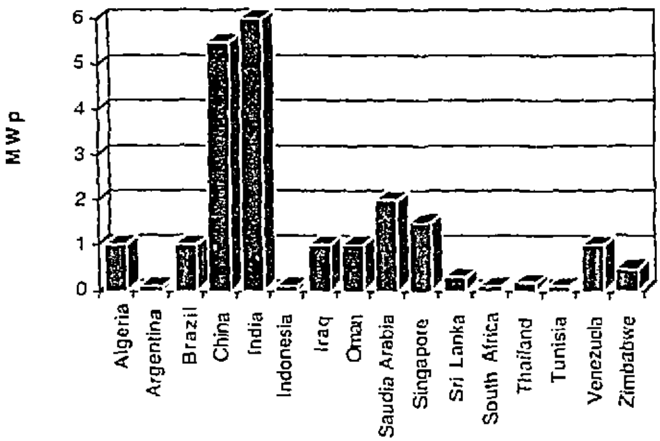

Fig. 4 PV-production capacity in developing countries (Acker *et al.* [22])

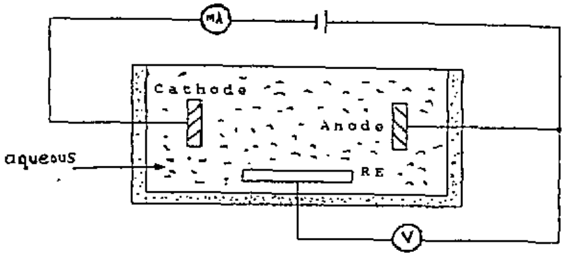

Fig. 5 Experimental set-up.

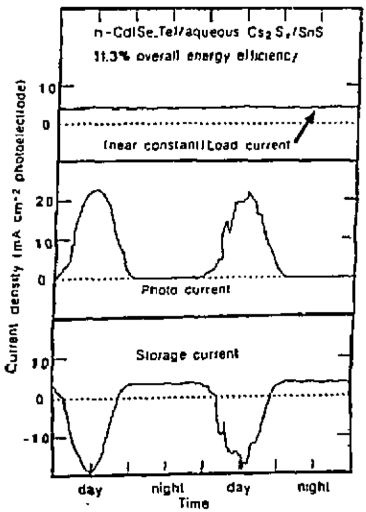

Fig. 6. Two days operation of an n-Cd(Se,Te)/aqueous Cs_2S_x/SnS PEC cell with in-situ storage.

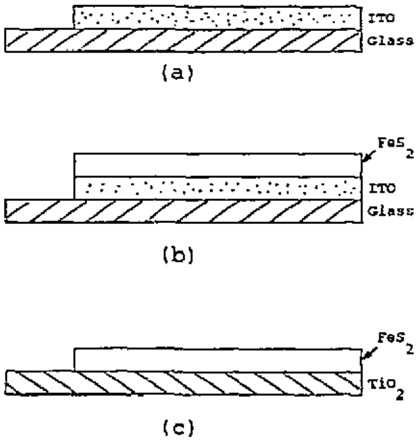

Fig. 7 Show the schematic structure of photoanode.

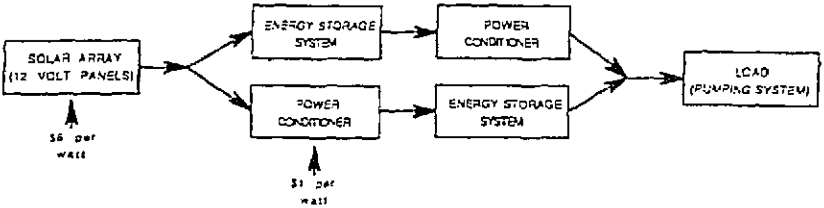

Fig. 8 Shows a block diagram of typical type of small-scale solar powered water pumping system.

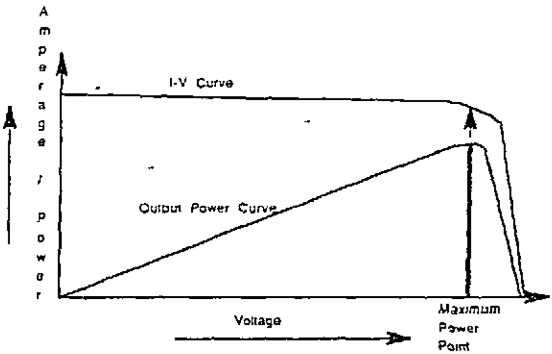

Fig. 9 Solar cell I-V and power characteristics showing MPP.

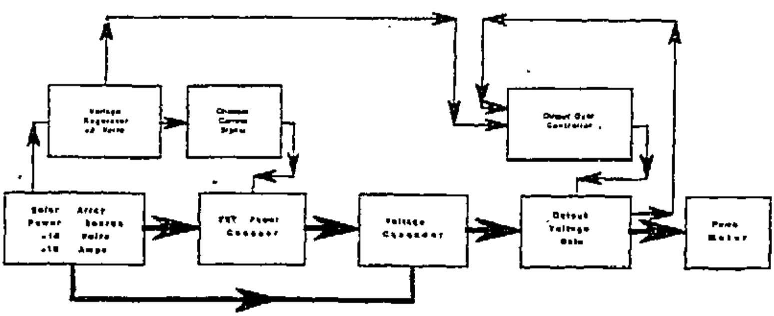

Fig. 10 Block diagram of a conditioner for solar powered water pumping system.

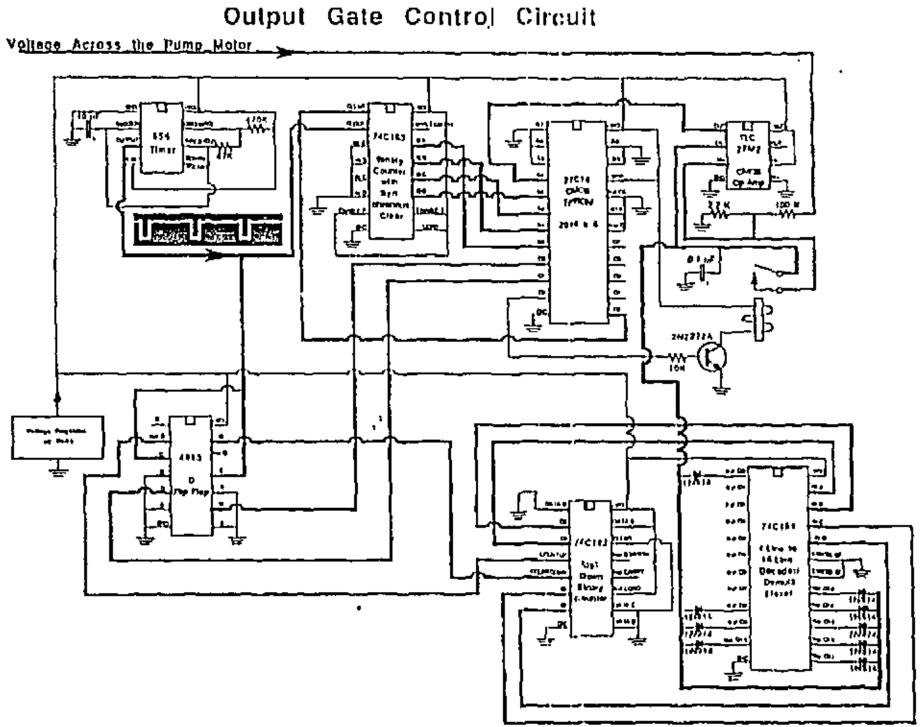

Fig. 11 Circuit diagram of a conditioner for solar powered water pumping system.