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SOLAR WATER PUMPING: CLEAN WATER FOR RURAL AREAS

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INTRODUCTION AND SUMMARY

There is a lot of interest in solar water pumping, for obvious reasons. Over the past ten years approximately 6,000 photovoltaic water pumps have been installed. Considerable progress has been made and the present generation of systems appear to be reliable and cost-effective under certain conditions. The current cost (1988) of PV modules is about $4.5 to $5 per peak watt ($/Wp). PV pumping system costs are typically in the range $7 to $15/Wp. A PV pumping system to pump 25 m^3/day through 20 m head requires a solar array of approximately 800 Wp in the Sahelian regions. Such a pump would cost approximately $6,000 FOB. A range of prices is to be expected, since the total system comprises the cost of modules, pump, motor, pipework, wiring, control system, array support structure and packaging. Systems with larger array sizes generally have a lower cost/Wp. The cost of the motor pumpsets varies according to application and duties; a low lift suction pump may cost less than $800 whereas a submersible borehole pumpset costs $1,500 or more.

This paper reviews experience gained and lessons learned over this period.

EARLY EXPERIENCE

Solar-thermodynamic

A significant part of the early development of solar technology was concerned with water pumping. Many practical experiments demonstrated the conversion of solar generated heat into shaft-power via a thermodynamic cycle. A solar steam engine pumped water at the Paris Exposition in 1878 (for more history see Butti and Perlin (1)). For the next hundred years (that is until about ten years ago) this was the generally accepted approach to solar pumping. The solar pioneer Tabor writing in 1967 on power for remote areas (2) summarised the prevailing view:

> "Solar cells and thermoelectrics may some day pump water for the African native, but for the moment, power generators with moving parts appear to be a more practical solution to his problem"

He added that photovoltaics would be ideal were it not for their extremely high price and low efficiency (and then went on to describe an organic Rankine turbine).

The development and commercialisation of a viable solar-thermodynamic pump was pioneered by the French company SOFRETES (3) following early work in Senegal. Many of these pumps were installed around the world, particularly in the Sahelian countries and Mexico, but they failed to operate reliably without continuous attendance by skilled technicians to undertake adjustment and repairs. SOFRETES went out of business in the early eighties.

There is potential for development of solar-thermodynamic systems into reliable cost-effective products, and development and commercialisation is underway, for example a joint German-Indian project (4). But it is the view of the authors that the significant further investment required to produce a product which competes with small PV pumps will not be forthcoming.

Photovoltaic

Development of photovoltaic pumps was also pioneered in France. Roger et al (5) designed a system to use a Pompes Guinard motor-pump comprising a surface-mounted permanent-magnet DC motor driving a submersed centrifugal pump via a vertical shaft. The motor was connected directly to the PV array. An experimental demonstration unit using a 500 W array to pump water from a depth of 23 m was installed in Corsica in April 1986. Detailed results of performance measurements as well as theoretical calculations were published in June 1977 (6). This type of PV pump was installed in significant numbers mainly in Africa.

In 1978 Smith and Allison (7) presented a compelling case for a programme to apply small PV pumps for irrigation ("micro-irrigation") on a huge scale. A goal of 10 million units installed by the year 2000 was presented as appropriate, as having a significant impact on world food production yet representing only 10 percent of potential farmer users. Economic analysis suggested that small PV pumps would be economic with array costs of around $5/Wp (1978 dollars) which was the US Government (the Energy Research and Development Administration, today the Department of Energy) projected price for 1981. This work was undertaken by the Massachusetts Institute of Technology Energy Laboratory, but is was significant that one of the authors (Allison) was an officer of the World Bank. The results of the work were widely circulated through the development assistance (donor) agencies. The regions thought to be most in need of this technology were Bangladesh, India and Pakistan.

UNDP/WORLD BANK GLOBAL PROJECT

As a result of the work mentioned immediately above, as well as other interests, the United Nations Development Programme (UNDP) launched its Global Solar Pumping Project (GLO/78/004), to be executed by the World Bank. In July 1979 consultants were appointed by the World Bank to evaluate, test and demonstrate commercially available small-scale solar powered irrigation pumping systems. At the time the technical feasibility of solar powered pumping had been demonstrated in a limited way, but the technology was clearly immature and expensive. The purpose of the project was to advise the UNDP and the World Bank on the way in which solar pumps should be developed and applied so as to provide an appropriate method for irrigation under the conditions that prevail on small farms in developing countries. The capacity required amounted for flows in the range one to five litres per second (1-5 l/s) and static heads up to 7 m. Pumps of this capacity have outputs in the range 150 to 500 W and can irrigate areas of between 0.5 and 1.0 hectares, depending on the crop and efficiency of water distribution. The target cost of water delivered was $0.05 per cubic metre (1979 prices).

The activities undertaken by the project included:

- a review of developments in solar pumping technology,
- the organisation of field trials of selected systems in collaboration wiht national energy research agencies in Mali, Philippines and Sudan,
- the organisation of laboratory tests on solar pumping sub-systems and components,
- a study of the design of solar pumping systems utilising mathematical modelling techniques to simulate performance and cost.

It is important to note that the project dealt with both solar-thermodynamic and photovoltaic systems. When the project was defined both technologies were considered to be of equal merit and potential.

Following the review a State-of-the-Art report was released in December 1979 (8). This was followed by the other activities. An international call for offers, together with 250 questionnaires sent to potential suppliers, resulted in only thirteen suppliers being able to realistically supply equipment. A total of twelve pumps were tested in the field, four in each country. One system was solar thermodynamic the remainder were photovoltaic. One photovoltaic system in Mali (similar to that the Koni, mentioned earlier) was already in operation while the other eleven were purchased by the World Bank. Most systems were installed ready for test by the end of July 1980 although some were not ready until September 1980. PV modules, pumps, and motors were also tested as components in the UK and USA.

Three systems performed better than their rated value, two systems were within 10% of rated performance, and five systems performed significantly below rating. Two systems (including the solar-thermodynamic pump) failed to operate.

The detailed results of this work were published in July 1981, (9) and four papers were presented at the Solar World Forum in Brighton in August the same year (10, 11, 12, 13) when a "late-news" Workshop was also held which attracted a very large audience. The work concluded that there was indeed considerable potential for the use of solar pumps for irrigation, but that none of the products then available on the market were yet suitable for widespread use. Extensive recommendations were made on improving performance, reliability and cost. The project also reported that meeting the target irrigation water cost of $0.05/m^3$ would not be easy but that a significantly higher cost would be acceptable for drinking water. It was recommended that any further work should include water supply applications as well as irrigation. A Technical and Economic Review which summarised all the findings and also presented preliminary economic comparisons between solar and other pumping systems, was published in September 1981 (14). The UNDP and World Bank decided to continue the work started to the point where really widespread demonstration (Phase II) could be contemplated (at the annual meeting of the UNDP scheduled for June 1983). The activities included:

- Continuation of field trials started in Phase 1 together with monitoring of a system in Egypt and analysis of additional data
- Study of the technical and economic factors which need to be satisfied if solar pumps are to be viable for agricultural and water supply purposes
- Assessment of prospective countries for participation in Phase II (countries short-listed were Bangladesh, Brazil, Egypt, Kenya, Mexico, Pakistan, Sri Lanka and Thailand)
- Procurement of improved commercial PV pumps systems and sub-systems and their testing in order to qualify them for use in Phase II
- Evaluation of further developments of thermal pumping systems and the prospects for their commercialisation
- Further developments of components in PV systems
- Study of the potential for assembly and/or manufacture of systems in selected developing countries.

The scope was presented in detail at the 4th European Photovoltaic Conference in Stresa in May 1982 (15).

Based on the experience gained in Phase 1, exacting specifications were developed to define the performance of improved pumping systems, and tenders were invited.

Three broad bands of hydraulic duty were defined to represent categories of pumping system which are believed to have significant market potential:

<u>Category A</u> - to pump 60 m^3/day output through a static design head of 2 m, intended mainly for irrigation applications,

<u>Category B</u> - to pump 60 m^3/day output through a static design head of 7 m, intended for water supply and/or irrigation applications,

<u>Category C</u> - to pump 20 m^3/day output through a static design head of 20 m, intended mainly for water supply applications.

The environmental conditions under which the pumps were to provide these outputs were defined in detailed performance specifications. One of the most important innovations was the introduction of a 'Standard Solar Day', the profile of which provided a daily irradiation of 5 kWh/m^2 on the horizontal plane. The specification also incorporated minimum system performance requirements for when either the static head or irradiation varied from design values.

Following an evaluation of the 64 systems tendered, two complete systems and two subsystems (system less array) for each category were procured for testing. All testing took place in the period September 1982 to January 1983 at a specially developed test facility. To obtain consistent and comparable results, each of the twelve subsystems was tested using a photovoltaic array output simulator. Using the simulator, the daily pumped volume and overall efficiency of each system were measured under the conditions of static head and solar input specified. Complete systems were also tested in sunshine. Simulator test results were compared with sunshine results and gave close agreement, thus validating the simulator's performance.

The final report on the testing and all the other activities was published in June 1983 (16) and papers summarising the main findings were presented at the Solar World Congress in Perth in August 1983 (17, 18, 19). It was concluded that the general standard of system design had improved significantly compared with the systems tested in Phase I. The best daily system efficiency increased from 2.3% recorded for a Phase I system to 3.8%, and systems were available where efficiency changes little with static head. There was still the need and scope for improvements in performance and reliability.

From the economic studies it was concluded that PV pumps were broadly competitive with the primary alternatives. PV pumps could be justified in sunny regions where diesel costs are high, wind speeds low and a steady year round demand for water. It was shown that drinking water supply would in general become economic before irrigation.

It was recommended that a second Phase of work should be undertaken, which would include demonstrations by field trial and pilot use, that selected photovoltaic pumps do provide a cost-effective, reliable and appropriate means of pumping water. It was not however concluded that immediate efforts to promote the use of solar irrigation on a wide scale (the premise which had led to the project) could be justified.

The UNDP decided that it was unable to finance a second phase of work. However, a Handbook was prepared which condensed all the lessons learned between 1979 and 1983 in a form which other agencies could use to design projects, select equipment and make economic comparisons (20). This was released by the World Bank in February 1984 and was later published by an international publishing house and is currently in its second printing.

The World Bank commissioned an up-date on PV pumps available commercially, and on the current economics in 1986 (21), and the results of this were summarised at the Sevilla photovoltaic conference in October 1976 (22).

PV PUMP TECHNOLOGY

Products Available

The five principal configurations of commercial PV pumps are as follows:

i. Submerged motor/pump unit, with centrifugal pump, often consisting of several impellers and then termed 'multi-stage'. The number of stages is a function of the lift required.

ii. Submerged centrifugal pump (alternatively a rotating positive displacement pump of the progressive cavity type) driven by the shaft from a motor mounted at ground level.

iii. Submerged reciprocating positive displacement pump (also known as a jack pump), driven by a shaft from a motor driven crank or beam ('nodding donkey') at ground level.

iv. Floating motor/pump unit with centrifugal pump.

v. Surface mounted motor/pump unit, with a self priming tank. The pump may be centrifugal or positive displacement. Positive displacement pumps have better self-priming properties but are generally less efficient for low head duties.

There are many ways of defining the size or rating of a PV pump. These include the peak photovoltaic array power and peak hydraulic power. Performance varies with solar input and it is the average volume of water delivered per day that is of most interest to potential users. The preferred method of referring to the capacity of a pump is therefore the daily volume of water delivered at the design head and design daily solar irradiation.

It is convenient to consider a daily hydraulic energy equivalent as the product of daily output and head, ie m^3/day x m head = m^4/day. Figure 1 presents the capacity range of a selection of PV pumps considered to be "off-the-shelf" systems based on a solar irradiation of 5 kWh/m^2/day. Data is based on data supplied by more than 40 of the principal suppliers who were contacted on behalf of the World Bank in 1986. Of course it is possible to design a PV pump to meet any output and head requirements outside this range, but these become special designs, and, as discussed briefly later, high-capacity,, high-power systems are mostly not economic. Commercially available systems range from systems with a daily output of as little as 10 m^3/day at 3 metres head (85 Wp array) to 100 m^3/day at 80 metres head (15 kWp PV array).

The presentation used in Figure 1 includes the presentation of hydraulic energy equivalent lines (m^4/day) and also approximate array peak watts (Wp). A further update on commercially available solar pumping systems was recently completed for the Beijer Institute and the Swedish Missionary Council (23).

Field Experience

Although a large number of PV systems have been installed worldwide, measured performance on systems in the field is still limited. In Mali around 200 PV pumps have been installed, much experience has been gained and a standard evaluation methodology has been developed (24, 25,) but has been little used. Initially problems were experienced with early installations but systems installed since 1982 have been found to be reliable. One significant factor given to the improved reliability has been the change from systems with surface mounted motors and submersed pumps to that of DC and AC submersible motor pumpsets. Shaft and head bearing maintenance was often a problem. Failures of components have almost always been pump, motor or power conditioning failures. Problems with the PV array have been few.

Statistical data on reliability (such as mean time between failures and percentage time operating) are almost non-existent, but the experience of established users has been that recent installations of equipment supplied by the more experienced manufacturers have been very reliable. Problems experienced with early electronics for brushless DC motors and AC motors are no longer present. Often the problems that have arisen could easily have been put right if someone with a little technical training had been available. Typical failures are not a problem of PV pumps as such, but they do illustrate the problems of introducing technical equipment into rural areas.

One problem still not entirely overcome is that of pumps running dry. Some installations have been made where the peak pump output at noon can be greater than the borehole yield or recovery rate such that dry running occurs. Recent problems have also been experienced with very early installations in places where the water table has since dropped. Many systems are fitted with float switches or motor overspeed protection but these have not always proved effective and burning out of motors has then occurred. With proper consideration of the borehole or well characteristics such problems can easily be avoided.

Three new projects should provide some very useful field data, although their main emphasis is in Africa.

In the South Darfur province of Sudan the British Overseas Development Administration (ODA) is supporting a project to improve village water supply and the productivity of livestock and cropping through the provision of solar pumping systems. The conventional method of pumping water in this semi-arid region has been with diesel engine driven jack pumps raising water from up to 100 m below ground. The operation and maintenance of these pumping systems has been difficult with the regular supply of fuel a major undertaking in itself.

In view of these difficulties and the high recurrent costs associated with the diesel pumps, ODA awarded I T Power a contract to investigate alternative forms of pumping. It was decided to proceed with a demonstration project (26) with the Sudanese National Water Corporation consisting of eight solar pumping systems. The importance of determining the most appropriate type of solar pump for future, more widespread, deployment of solar pumps in the region led to selecting three pump types:

submersible alternating current multistage centrifugal; rotary positive displacement (progressing cavity); and reciprocating positive displacement (piston or jack pump). Each of these pumps is being fully instrumented and performance and running costs collected for one year after installation. The performance of eight diesel pumps under similar conditions will also be monitored. The installation phase currently underway is expected to be completed in May 1989. This project probably represents the most rigourous assessment of solar and diesel pumps under the most arduous field conditions.

An important solar pumping programme is being undertaken by the German Appropriate Technology Exchange (GATE) which is a division of the German Agency for Technical Cooperation (GTZ). This is financed by the Ministry of Research and Technology (BMFT) and the Ministry of Cooperation (BMZ) (27).

Four participating countries, Argentina, Brazil, Jordan and Indonesia, have been selected, and up to four are yet to be identified, one of which is almost certainly the Philippines. Detailed planning is underway in the four countries and it is expected that a total of up to 120 systems will be installed commencing in 1989. The pumping capacity of each system is around 25 m^3/day through a head of 30 m to 60 m.

Recently, the European Commission began planning the world's largest developing countries photovoltaic project, as a component of the 6th EDF regional programme to combat desertification in the Sahel and West Africa. Serious interest in using solar pumps in the Sahel (both solar-thermodynamic and photovoltaic) was expressed in 1977 (28). Approximately $35 million has been allocated to the regional agency CILSS (Comite Inter-Etats pour la Lutte Centre la secheresse dans le Sahel) for the procurement of photovoltaic pumping systems and related equipment for water and electricity supply in Burkina Faso, Cape Verde, Chad, Gambia, Guinea Bissau, Mali, Mauritania, Niger and Senegal.

An invitation to prequalify for a forthcoming restricted tender was published in March 1988 (29) and as a result of this a number of European suppliers (both individual companies and consortia) will be invited to tender in the near future.

The project anticipates the supply of approximately 1,350 PV pumping systems together with around 500 other PV systems (for lighting, battery charging and refrigeration). The total installed capacity will be approximately 1.3 MWp.

APPLICATIONS AND ECONOMICS

Irrigation

In the early stages of utilizing solar pumping systems, irrigation was considered to be the most promising application principally because of the several million internal combustion engine driven pumpsets in use for irrigation in developing countries, indicating a potentially large market, and also the desire to make an impact on food production in the developing world. Indeed, as noted earlier, the first phase of the UNDP/World Bank Project was targeted specifically at irrigation pumping.

The widespread use of solar irrigation pumps has not yet happened. The principal reasons for this are:

- the varying demand from month to month of irrigation water requirements result in solar irrigation pumps being under utilised in some months
- the necessary financing packages required to assist the poor rural farmer procure solar pumps have not been forthcoming
- the anticipated rise in fuel prices has not happened such that the cost of operating conventional diesel pumps has not risen to the extent expected
- there has been a proliferation of low cost diesel and petrol driven pumpsets on the market which has maintained the large capital cost disparity between solar pumps and engine driven pumps, even with falling PV prices
- in order to utilise solar irrigation pumping systems effectively it is necessary to adapt farming practices and upgrade water distribution and application systems to reduce water losses. (A PV pump applies water over a whole day whilst a diesel pump is used only for short periods each day)
- there remains a lack of awareness with some agricultural sector decision makers on the benefits of solar pumping

An example of the barriers facing the introduction of solar pumping systems can be found in Pakistan. In terms of employment and share of Gross Domestic Product, agriculture is the largest single sector activity in Pakistan. Irrigation pumping is vital to this activity and the population of engine driven and electric pumpsets has risen from around 2000 in 1960 to a current population in excess of a quarter of a million. It has therefore been believed by many that there are good prospects for solar irrigation pumping in Pakistan. Indeed one study (30) reported a potential demand approaching one million units. For this reason solar pumps have been under evaluation in Pakistan, principally by the Agricultural Development Bank of Pakistan - ADBP, who have field tested some 37 units from 10 different suppliers since 1981.

The majority of the diesel pumpsets in Pakistan are of chinese design or manufacture, the smallest of those in common use being 7.5 hp and priced at only 14,000 Rupees (around 900 ecu). The diesel pumpsets are used inefficiently often being oversized for the application and poorly maintained (improper lubrication, faulty injectors and worn out pistons). A study (31) reports typical efficiencies for diesel pumps in use of between 2.6 and 5.4% compared to 10% for an overhauled and well maintained pumpset.

Despite the poor performance of the diesel pumpsets a study undertaken by I T Power for the World Bank (32) concluded that with PV module costs at $3 per Watt, solar pumps would only be competitive with diesel pumpsets where the average daily water demand (volume-head product) is less than approximately 120 m^3 m per day. This corresponds to farms of less than 1.1 hectares (Fig 2) and to solar pumps of only around 400 Wp. There are however more than one million farms of less than 1 hectare in Pakistan. The market is unlikely to materialise in the short term however, because in reality, these farmers hire diesel pumpsets or buy water from wealthier neighbours at almost marginal cost. In effect the solar pumps are competing with larger better utilised diesel pumpsets even on the small farm. This has been shown to be the case when ADBP invited farmers nationwide to apply for loans to buy solar pumps. Even with high levels of subsidy and a requirement for only a small downpayment, the ADBP had few takers. It should be noted that there are particular cases where solar irrigation systems can be viable. For example, desert development and desertification control needs are for a more constant water demand. Solar irrigation systems to meet this application have been demonstrated often with high efficiency water distribution and application systems (33). In the semi arid regions of California and other US states, solar irrigation systems have been reported to be viable (34). It should also be noted that the long term prospects for solar irrigation systems are still promising. Should the cost of PV approach $1 per Wp, such that initial capital cost differential between solar and engine driven pumps is significantly reduced, the solar irrigation pump could yet be a common sight in some countries.

Village Water Supply

Village water supply is characterised by a more constant water demand from month to month. This characteristic, combined with the higher value of water for human consumption than for irrigation, results in water supply applications being far more economically viable. Most recent solar pumping projects have been for water supply applications.

The better economics can be shown by considering Pakistan as an example again. Figure 3 shows the life cycle or levelised unit water cost for PV pumps and diesel pumps under Pakistan conditions. At a PV module cost of $3/Wp, as used for the irrigation example, it can be seen that PV pumps are economic for water demands of up to 400 m^3m per day (eg, 20 m^3 per day pumped through 20 metres). This corresponds with PV pumps of around 900 Wp compared to irrigation pumps of only around 400 Wp being economically viable for irrigation applications in Pakistan. It should be noted that economically Pakistan conditions are less favourable for solar pumps than for Sahelian locations for example. When other factors are taken into consideration which are not easily analysed economically, such as reliability and sustainability, it is generally accepted that PV pumps for village water supply of up to 3000 Wp are economically viable in regions with worst month insolation exceeding 4.0 kWh/m^2/day.

In Indonesia surface water is abundant, but this is generally polluted. Water borne diseases are a major cause of mortality and morbidity. Biologically contaminated water can be treated to give clean, safe drinking water. An attractive process is the slow sand filtration system which is simple, cheap and requires only minimal unskilled maintenance. The use of a solar pump combined with a slow sand filter water treatment system is currently being demonstrated in Indonesia. In 1986, under the auspices of the Directorate of Water Supply, Ministry of Public Works (DPV) and The Agency for the Assessment and Application of Technology (BPPT) of the Ministry of Research and Technology, BP Solar installed a solar pump/Potapak treatment system at Kedung village, 65 km west of Jakarta. This takes highly contaminated water from an irrigation drainage channel and filters it, delivering drinking water which meets WHO standards. The installation has been well received by the villages who use the water and by the government departments responsible for water supply. In 1988, I T Power was commissioned to undertake an appraisal of the economic costs and benefits of solar water delivery systems in Indonesia, and to assess the extent to which this technology can be beneficially applied throughout Indonesia (35). The cost of water delivered by a PV pump was found to be comparable with using a diesel pump. For small communities (up to around 1500 people), the PV option is particularly attractive.

RECENT ADVANCES

Much of the research currently underway to improve the efficiency and reduce costs of PV pumps appears to be in Germany. Workers at Stuttgart University investigated a number of systems by measurement and simulation (36) and in particular examined methods of connecting a positive displacement pump to a PV array (37). This work has led to the development of an inverter for use with a progressive cavity pump driven by a submersible AC motor (38). The array is rated at 750 W and the prototype system pumps 14 m^3/day from heads around 40 m. Performance is similar to a centrifugal pump. Submersible progressive cavity pumps using surface mounted DC motors are commercially available, and are being evaluated in Sudan, as mentioned above. This type of pump gives high efficiency at high head and also good part-load performance. Its main drawback is its high starting torque.

DFVLR and WIP are also working on the development of the submersed, AC motor/progressing cavity pump concept, with testing being undertaken by the Bundeswehr University (39, 40). This is part of a German-Egyptian co-operation. This work has shown that under low levels of insolation the progressing cavity pump out-performs the centrifugal pump. PV pump development is also underway at the Fraunhofer Solar Institute (41).

SUMMARY OF ACHIEVEMENTS

The progress made with solar pumping technology is summarised in Figures 4 and 5, while Figure 6 illustrates the growth of the market.

Figure 5 illustrates the reduction in prices of PV modules and pumping systems ($ 1988). It can be seen that there has been a steady decline in module prices to around $4-5/Wp today. Complete pumping systems cost in the range $8-15/Wp. Further reduction in module costs, to as low as $1 to $2/Wp are confidently projected. It is more difficult to summarise efficiency improvements, because of the lack of laboratory and field data for systems. Figure 5 illustrates the steady improvement in average module efficiency to approximately 12% at present. Further improvements are expected.

The two data ranges for overall pumping system efficiency are taken from the UNDP/World Bank project. It is expected that there have been further improvements but published data has not been located.

The growth of the market is illustrated in Figure 6. Today there are around 6000 PV pumps installed in the world, with sales of approximately 1500 per year and increasing steadily. However it must be noted that a significant proportion of the sales are not in developing countries but in Australia, the United States and South Africa. Sales achieved so far are only a tiny part of the potential market.

CONCLUSIONS

In the past ten years, solar pumping technology has progressed to the point where proven products are available and can be shown to be cost-effective compared to alternatives. With anticipated reductions in PV module prices, combined with further improvements in system efficiency, the next ten years should show solar pumps maturing and making a significant market impact.

REFERENCES

1. K Butti and J Perlin. 'A golden thread: 2500 years of solar architecture and technology'. Cheshire Books, 1980.

2. H Tabor. 'Power for remote areas'. International Science and Technology, 1967.

3. J M Durand, M G Clemot, J P Girardier and M Y Vergnet. 'Utilisation of solar energy in the development of arid zones: solar water pumps'. In Technology for Solar Energy Utilisation, UNIDO, 1978.

4. Dornier System GmbH/Bharat Heavy Electricals Ltd.

5. D Campana, A Castiel, J A Roger, P Lavit and M Lepert. 'Alimentation par photopiles d'un systeme de pompage'. International Conference on Solar Electricity, Toulouse, March 1976.

6. J A Roger. 'Water pumping systems using photovoltaic converters (panels-motor direct coupling)'. June 1977.

7. D V Smith and S V Allison. 'Micro irrigation with photovoltaics'. MIT Energy Laboratory, Report No MIT-EL-78-006, 1978.

8. Halcrow/ITDG. 'Testing and demonstration of small scale solar powered pumping systems - State-of-the-art report'. UNDP/GLO/78/004, The World Bank, December 1979.

9. Halcrow/ITDG. 'Small scale solar powered irrigation pumping systems - Phase 1 project report'. UNDP/GLO/78/004, The World Bank, July 1981.

10. P L Fraenkel, E M Mitwally and D E Wright. 'Testing and demonstration of small scale solar water pumps - The UNDP/World Bank Project'. Proc. ISES Solar World Forum, Brighton, August 1981.

11. A Derrick, P L Fraenkel, B McNelis and M R Starr. 'Small scale solar water pumps - The state-of-the-art'. Proc. ISES Solar World Forum, Brighton, UK, 1981.

12. A Derrick, R J Hacker, A P Napier and A R O'Hea. 'Performance monitoring of small scale solar powered pumping systems'. Proc. ISES Solar World Forum, Brighton, UK 1981.

13. M W Duffy, P L Fraenkel, E M Mitwally and E P Evans. 'A practical mathematical simulation model for the evaluation of small-scale solar photovoltaic pumping systems'. Proc. ISES Solar World Forum, Brighton, UK, 1981.

14. Halcrow/I T Power. 'Small scale solar powered pumping systems technical and economic review'. UNDP/GLO/78/002, World Bank, September 1981.

15. P L Fraenkel, M A S Malik and D E Wright. 'The UNDP/World Bank Solar Pump Project - Preparatory for Phase II.' 4th EC Photovoltaic Solar Energy Conference, Stresa, Italy, May 1982.

16. Halcrow/I T Power. 'Small-Scale Solar-Powered Pumping Systems: The Technology, Its Economics and Advancement. Project UNDP/GLO/80/003, The World Bank, June 1983.

17. M R Starr and B McNelis. Recent Improvements in Photovoltaic Pumping Technology. Proc. Solar World Congress, Perth, 1983.

18. J P Kenna, P L Fraenkel and D E Wright. The prospects for Solar Water pumping case studies of agricultural and water supply application in the developing world. Proc. Solar World Congress, Perth, 1983.

19. A Derrick, J P Kenna and W B Gillett. 'Small-scale solar thermodynamic pumping systems: a review of developments. Proc. Solar World Congress, Perth, 1983.

20. J P Kenna and W B Gillett. 'Solar Water Pumping: A Handbook'. I T Publications, UK, 1985.

21. I T Power. 'Solar powered pumping systems: their performance costs and economics'. Contract report to the World Bank, Washington DC, USA, July 1986.

22. B McNelis. 'Photovoltaic water pumping - a 1986 update', 7th EC Photovoltaic Solar Energy Conference, Sevilla, Spain, October 1986.

23. A Derrick, C Francis and V Bokalders. 'Solar photovoltaic products: A guide for development workers'. I T Publications, UK, 1988.

24. I T Power Inc. 'Evaluating the technical and economic performance of photovoltaic pumping systems: a methodology'. Contract report for USAID, May 1985.

25. M Diarra, N Diarra, J P Kenna, B McNelis and C Traore. 'Development and application of an evaluation methodology for photovoltaic pumps - a proposal for a global standard'. 6th European Photovoltaic Solar Energy Conference, London, April 1985.

26. I T Power. 'Western Savannah Project. Phase II: Investigation of alternative forms of pumping - preliminary assessment'. Contract Report to UK Overseas Development Administration, 1986.

27. P Baz (GTZ-GATE). Private Communication.

28. A Delas. 'Solar pumps in the Sahel'. The Courier (European Community), September/October 1977.

29. Invitation to Tender No 2731. Supplement to the Official Journal of the European Communities, 29th March 1988.

30. Institute of Development Studies. 'The potential for small scale solar powered irrigation in Pakistan'. IDS, Sussex, UK, 1982.

31. National Energy Conservation Centre, Pakistan. 'Energy use in Pakistans Agricultural Sector'. National Energy Conservation Centre, Ministry of Planning and Development, Government of Pakistan, 1986.

32. UNDP/World Bank. 'Pakistan: Economic evaluation and preliminary market assessment of photovoltaic applications'. Report of the Joint UNDP/World Bank Energy Sector Management Assistance Program, World Bank, Washington DC 20433, USA, Draft 1988.

33. F Assabghy and A Derrick. 'Experiences with a deep well solar powered irrigation system for desert development'. Proceedings of the Third Conference on Energy for Rural and Island Communities, Inverness, UK, 1983.

34. US Agency for International Development. 'Renewable Energy for Agriculture and Health'. Directorate for Energy and Natural Resources, USAID, Washington DC 20523, USA, 1988.

35. I T Power. 'Solar photovoltaic water delivery systems for Indonesia - An economic study'. Report to The British Embassy Jakarta, April 1988.

36. B Herrmann, H Karl, E Kopf and G Lehner. 'Experiences with photovoltaic water pumping systems'. 6th European PV Solar Energy Conference, London, UK, April 1985.

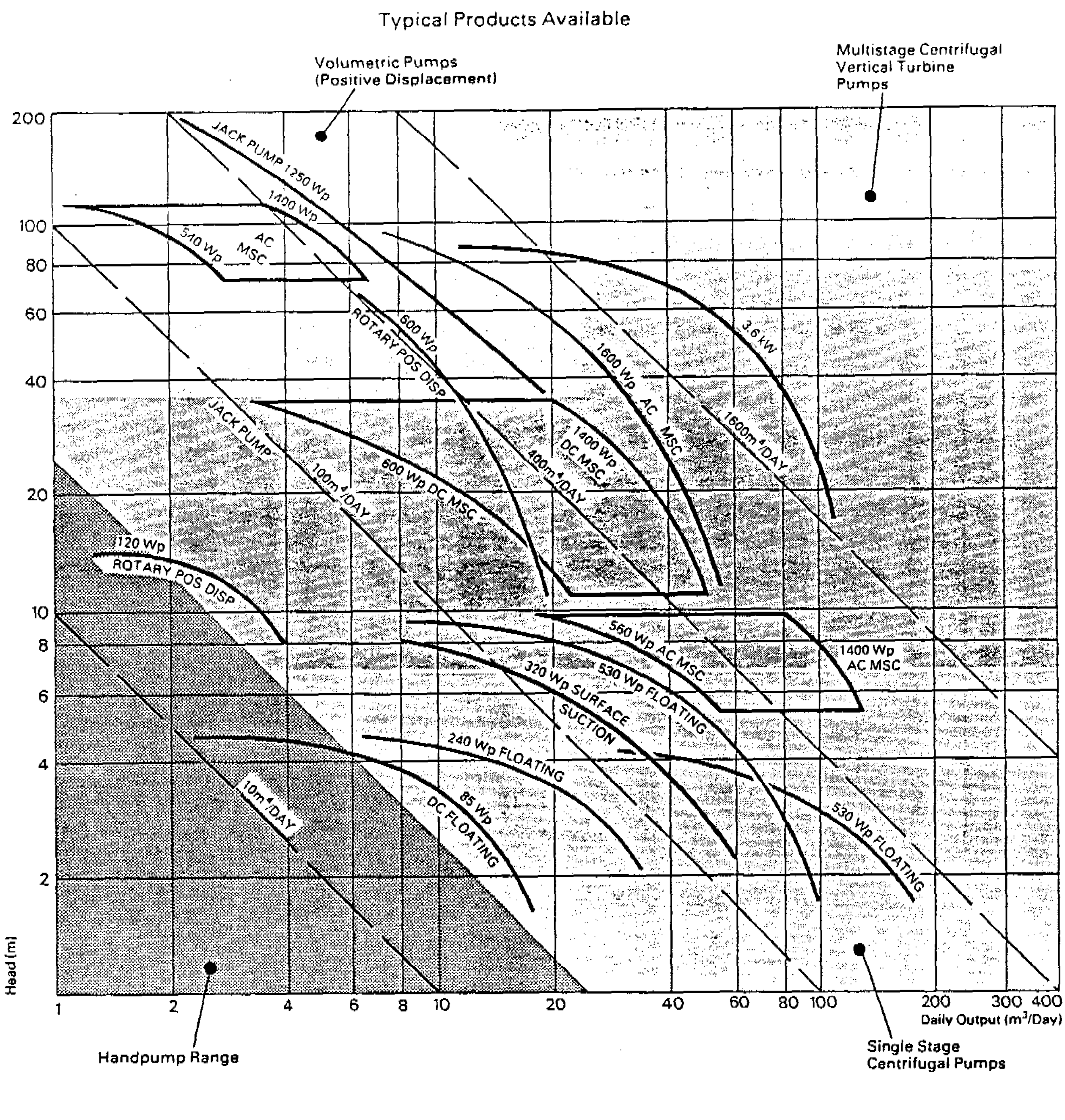
37. B Herrmann, H Karl, E Kopf, G Lehner and G Saupe. 'The problem of connecting a positive displacement piston pump to a PV array - an approach to a solution'. 7th European PV Solar Energy Conference, Sevilla, Spain, October 1986.

38. B Herrmann, H Karl, E Kopf, G Lehner and G Saupe. 'Photovoltaic water pumping system with progressive vacity pump'. 8th European PV Solar Energy Conference, Florence, Italy, May 1988.

39. Dr W Bucher. 'Development and initial test results of a pv powered rotary displacement water pumping system'. ISES Solar World Congress, Hamburg, 1987.

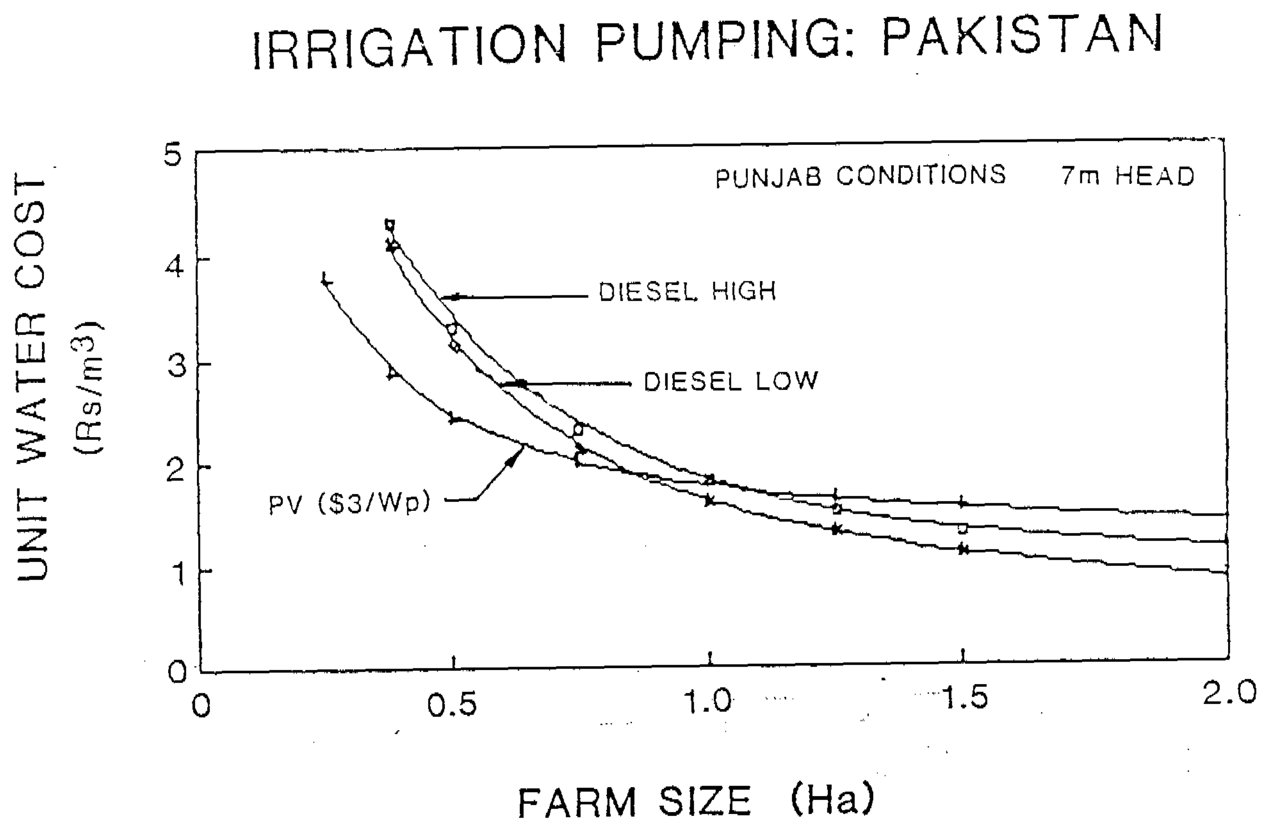
40. Dr W Bucher. 'Engineering aspects of PV powered pumping systems', DFVLR, Florence, May 1988.

41. J Schmid and W Roth. 'Photovoltaic supplied devices of small and intermediate power range'. Fraunhofer Institut fur Solare Energiesysteme, Florence, May 1988.



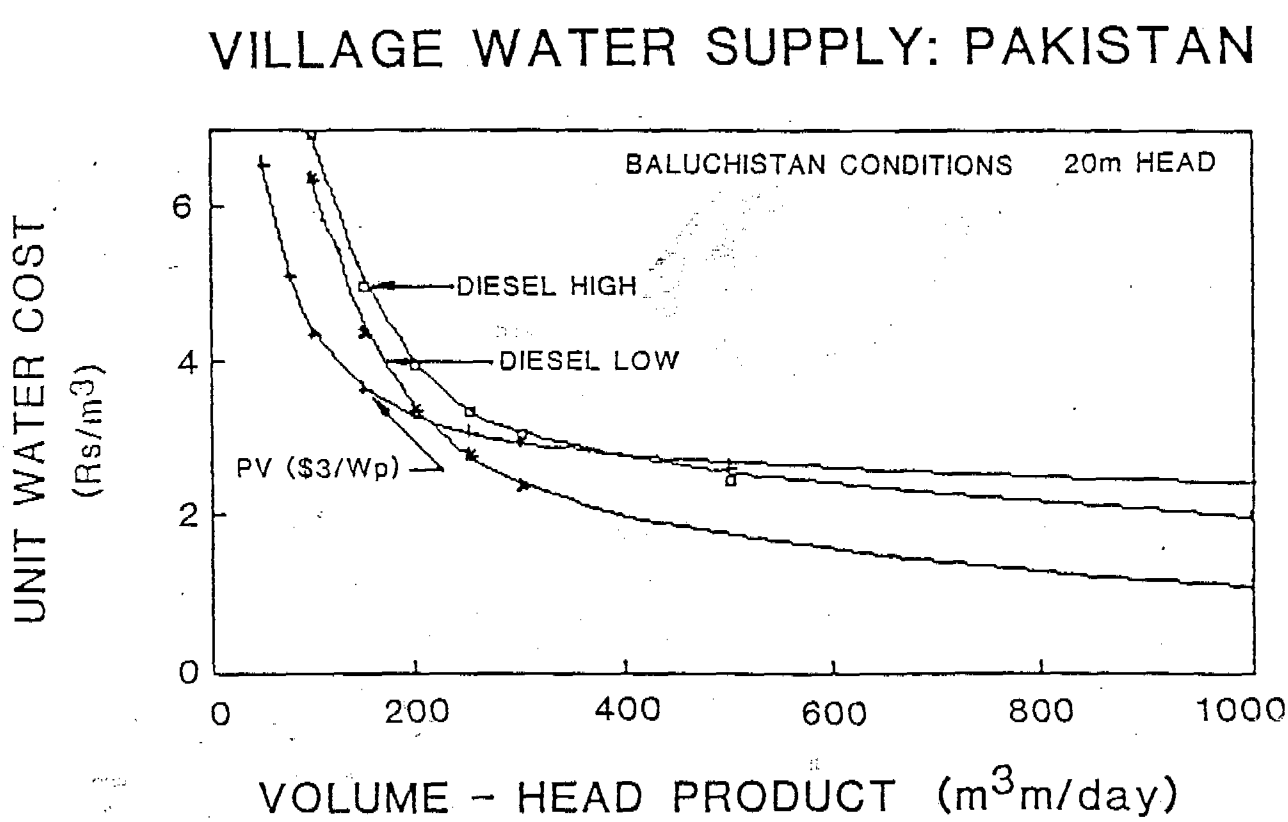
Head/flow characteristics of commercially available photovoltaic pumps

Figure 1



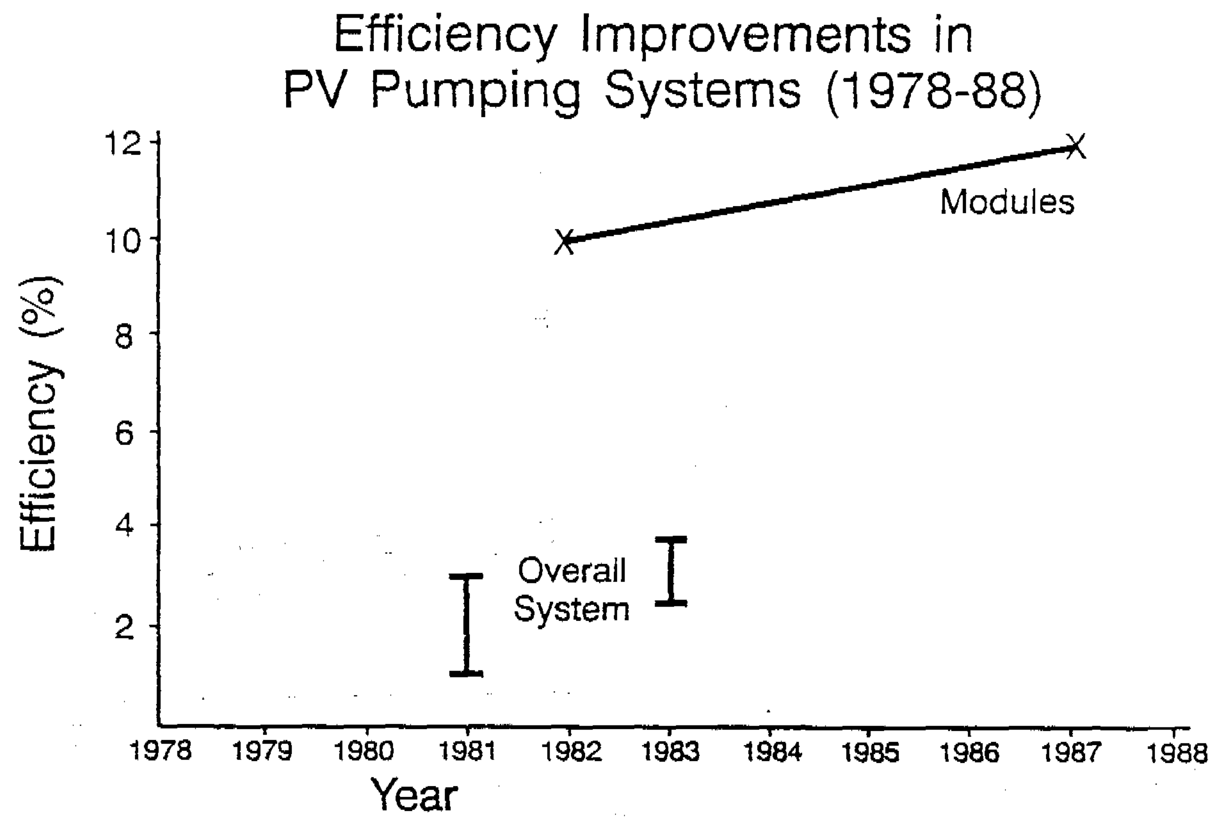
Cost of water delivered by photovoltaic and diesel pumps - irrigation

Figure 2



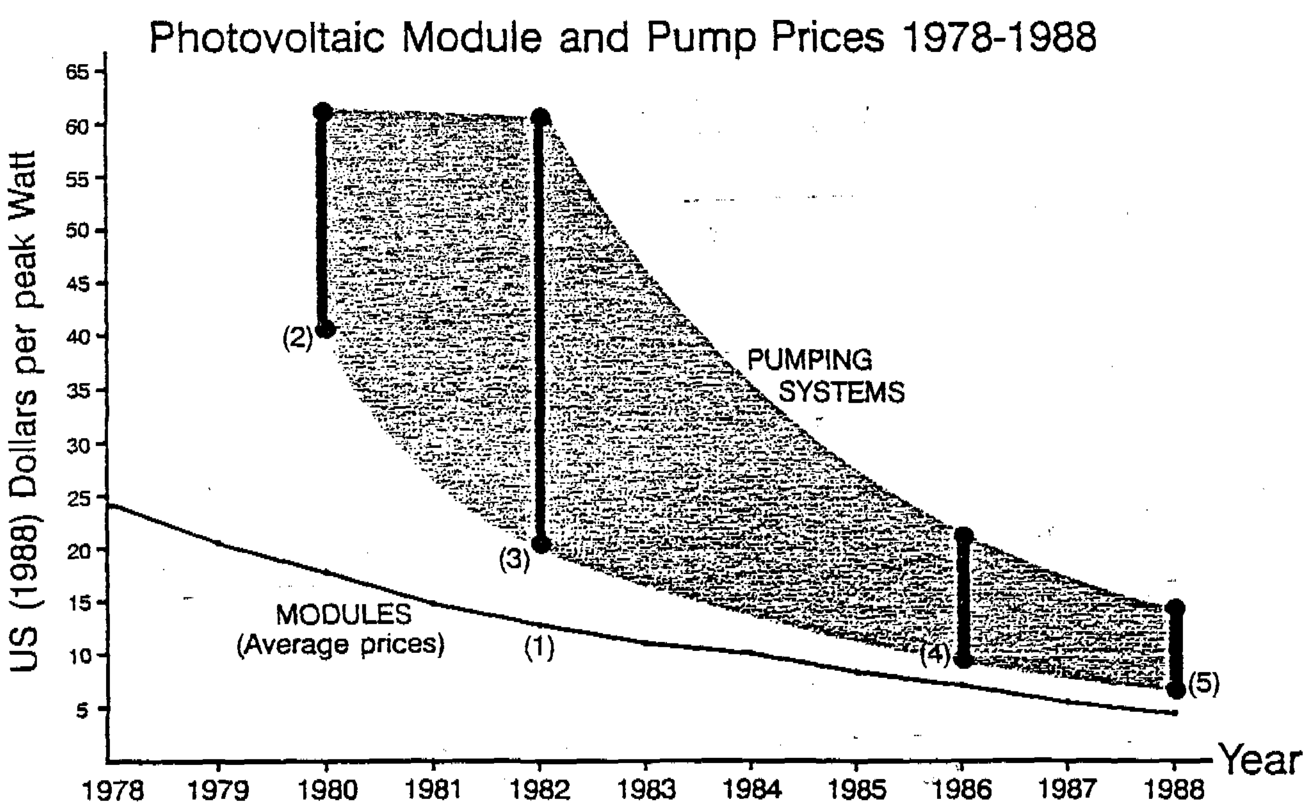
Cost of water delivered by photovoltaic and diesel pumps - drinking water supply

Figure 3



Improvement in PV Pumping Technology

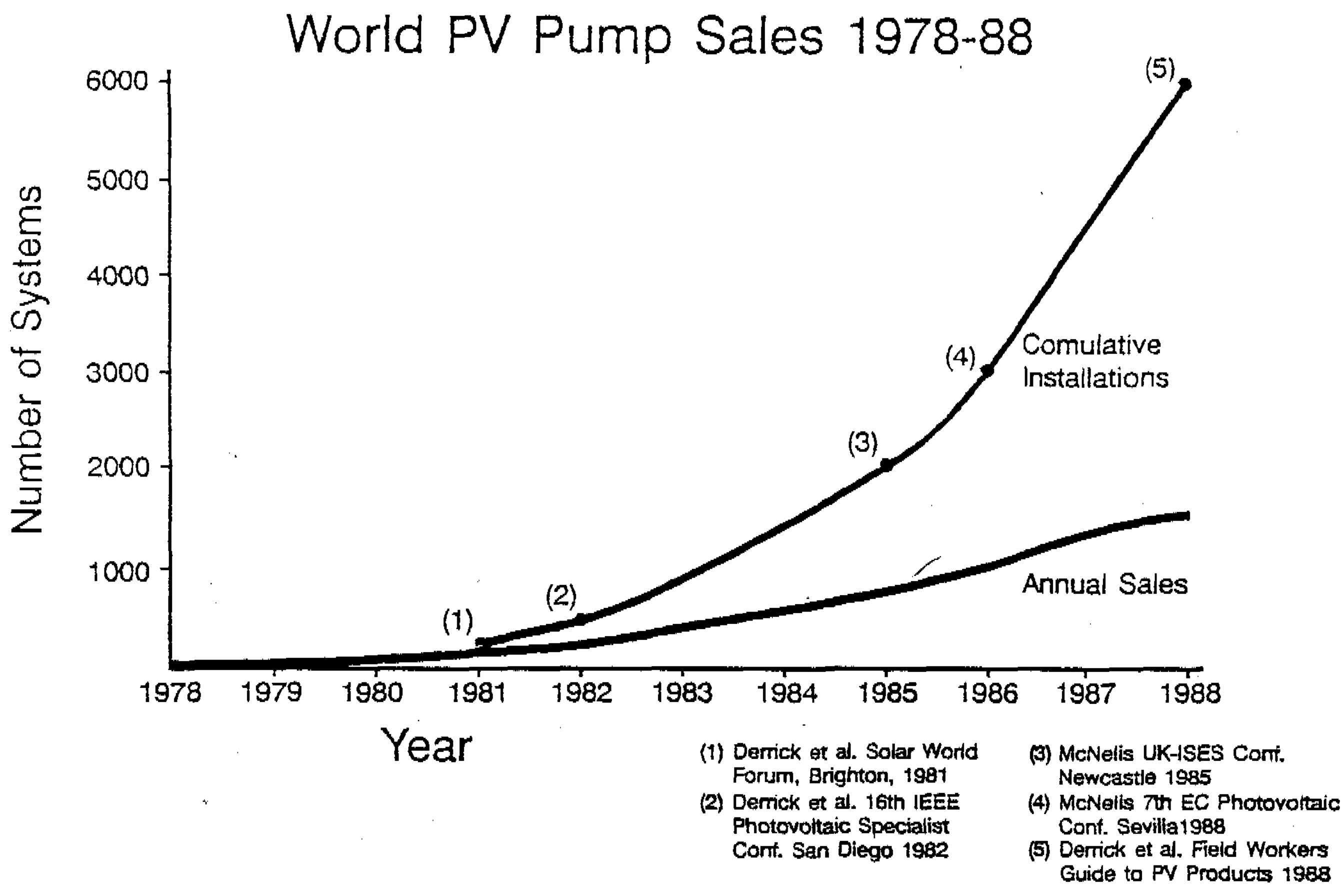
Figure 4



Sources : (1) Derrick et al, Field Workers Guide to PV Products 1988
(2) Halcrow/ITDG, World Bank Study 1980
(3) Halcrow/IT Power, World Bank Study 1982
(4) McNelis, 7th EC Photovoltaic Conf, Sevilla 1986
(5) Derrick, African Technical Review 1988

Photovoltaic Module and Pump Price History

Figure 5



World PV Pump Market History

Figure 6