New
Implementation Approaches for Pico Hydro-Electric Power in Developing Countries

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ABSTRACT

The term *pico hydro* describes hydropower with an electrical output of up to 5 kilowatts. Where suitable sites exist, this renewable energy option can be very cost-effective for village electrification.

A thorough investigation of existing practice in Nepal and Colombia has identified the factors contributing to the emergence of successful pico hydro programs in these countries. Using detailed field data collected during the research visits and computational methods to model scheme operation, ten schemes in Nepal were rigorously evaluated in terms of cost, performance and sustainability. This study identified a high degree of variability with the existing implementation practice. As a result, a versatile new design of turbine-generator unit and a new implementation strategy were developed in order to improve viability and encourage widespread adoption.

The field research and subsequent data analysis highlighted the difficulties faced by the developer when trying to select the most appropriate components to form part of an interrelated system, designed for a particular set of site conditions. A review of available computer software concluded that existing tools could not provide the broad range of functionality required for specification of an optimized pico hydro system.

New methods were developed to assist developers in minimizing the cost per kilowatt. A bespoke program was written that enables optimized selection of the turbine-generator, penstock and distribution cables from a database of locally available equipment. The program performs numerous iterative calculations to provide a system design tailored to the site conditions using off-the-shelf components.

The new turbine-generator design and implementation methods have been established through installations in Nepal, Kenya and Ethiopia. In addition to reliability and safety improvements, significant cost reductions have been demonstrated at these schemes, through the use of the optimization methods and implementation strategy developed as a result of the research.

CONTENTS

1 INTRODUCTION

1.1 *Rural energy demand and the benefits of electrification*

Electrification has been identified as a key component for development in countries with high levels of rural poverty [Foley 1990]. It can also help to alleviate rural poverty in the short term by providing opportunities for income-generating activities that use the electric power thus stimulating local economic development. These may take the form of small industrial enterprises such as sawmills and bakeries or in many cases, services such as grain mills and photocopy or Internet kiosks. In addition to increased commercial opportunities, other community initiatives can also benefit. Refrigeration, for example, not only allows shopkeepers to stock cold drinks but also enables health centres to store vaccines in a tropical climate.

Studies into rural lighting methods have concluded that electric lighting is more cost effective than the alternatives, including kerosene, paraffin lanterns and candles. This is even the case when the electricity source is solar power [Louineau 1994]. After the initial capital outlay to obtain a connection, monthly savings from reduced purchases of other fuel types can be significant.

At the domestic level, the increased day length brought about by the use of electric lighting, is a significant advantage in itself, allowing extra time to be spent on work and leisure activities. Greater opportunity for schoolchildren to study in the evening is an additional benefit mentioned repeatedly by families in developing countries [Gitonga 2002].

Other, less tangible benefits also result from electrification. These include a reduction in feelings of isolation and backwardness, which are often acute in undeveloped rural areas. This is achieved to some extent by the availability of power for radio and television and increasingly by the availability of modern communications such as mobile telephones and the Internet.

Given the wide range of social and economic benefits for rural communities which can result from electrification programs, the question remains as to how best to meet the considerable demand in an affordable and sustainable manner.

1.2 Grid electrification

In the developed world, the last fifty years has seen the grid extend out of urban areas and reach the majority of rural homes. Strong economic growth has fuelled increasing demand for power from urban and industrial consumers and has led to national programs that have increased generating capacity and consolidated and strengthened the grid in urban areas. The increased revenue to the utilities, and the relatively high proportion of urban to rural consumers, has helped to finance rural electrification. This has also been supported by long-term programs of infrastructure development such as road, rail and bridge-building, helping to connect rural areas with urban centres and providing the means for more uniform economic development.

There are considerable technical advantages to electrification using a national grid system. Firstly, it is simpler to distribute and regulate power from a few centralised generating sources. All that is required is a step-down transformer to supply the low voltage distribution and extra poles and cables. This requires considerably less maintenance, spare parts and fuel than an isolated generator, which needs regular attendance. Since the capacity of the grid is much larger than the individual loads, fluctuations in demand can be catered for more easily and as the demand grows, strategic increases in generating capacity are possible.

However, despite the advantages, many rural people in developing countries will never experience a grid connection in their lifetime. The inhibiting factors preventing widespread electrification in these countries are primarily economic, although topography often plays a significant role.

In the developed nations, utilities planning grid extension and re-enforcement have a public obligation to connect all consumers willing to pay for a connection regardless of their location. They benefit from dense load concentrations in urban areas, coupled with high levels of domestic electricity demand and are able to subsidize the cost of connecting the more thinly spread rural consumers.

Most electricity utilities in the developing world are state-owned and under strict legal obligation to break even after each year of investment. Usually they are extremely under-funded and stretched to capacity just to maintain the existing networks which often suffer frequent breakdown and supply interruption. This deters grid extension in areas where the tariff income is likely to be low in relation to the transmission and distribution costs. If expansion is planned at all, urban and industrial consumers who provide a higher return on investment are connected in preference to dispersed rural customers who have smaller amounts of disposable income to spend and are often located in highly inaccessible areas.

In some countries, consumers pay a levy to fund the rural expansion programmes. This happens in Kenya for example, where an additional 3% is charged on top of electricity bills. Despite this, grid extension in Kenya is still not widespread. By 1999 only about 61,500, less than 2% of the 3.7 million rural households, had been connected during 15 years of the national utility's program of rural electrification [Hankins 2000]. The current rate of new connections, at approximately 10,000 per year, is hardly keeping pace with rural population growth. Of those who do eventually receive a connection, most are upper and middle class households who can afford to make a significant contribution towards the connection costs and who do not represent the majority of the rural population. The situation is not dissimilar throughout rural Africa and many parts of Asia and South America. Rural populations in many parts of the world are greater in number than their urban counterparts and have less opportunity to improve their economic conditions and gain access to basic services.

Other challenges that are faced by utilities in such places include poorly maintained and insufficient generating capacity, endemic corruption and illegal tapping [Khalema-Redeby 1998]. Lack of civil infrastructure also hinders access to rural areas making installation and tariff collection difficult. In addition, the climatic conditions associated with tropical and subtropical regions can result in problems such as high incidence of lightning strikes, flooding, subsidence and widespread termite damage to wooden distribution poles.

1.3 Off-grid electrification

Despite the advantages of grid electrification where it is economically feasible, in the short to medium term, alternatives are needed for the large rural populations who have little chance of grid connection in the foreseeable future due to problems such as those outlined above. The key features of the alternatives are outlined below.

1.3.1 Mini-grids

While a grid extension may technically be the simplest solution, isolated networks or 'mini-grids' are increasingly being used to supply power to rural communities, often independent of the national utility control [The World Bank 1996].

The advantages of this approach include the following:

- Grid extensions are expensive; typical costs are US$6,000 to US$12,000 per kilometre for single phase (see analysis of break even costs in Section 1.3.4.)
- Mini-grids are better suited to dispersed communities as the point of generation can be located nearer to consumers, removing the need to maintain long transmission lines.
- Mini-grids can be linked together or grid-connected in the future, when consumption has increased to an economic level.
- Many popular modern loads have low power requirements. For example, energy efficient lamps, black and white TV's, radios and mobile telephones can all be powered by very small currents (see Table 1-1). Extensive use of low power loads is not in the interests of large utilities that need to sell large amounts of energy to provide a reasonable return on the sums invested in lengthy transmission and distribution systems. However, load limited power supplies can be provided very effectively by off-grid generators and deliver major 'quality-of-life' improvements at lower cost than fully metered grid connections.

Typical Low Power Loads	Typical current / power requirements at 220V AC
9W energy efficient lamp	55mA / 12W
Radio	22mA / 5W
Black and white TV	160mA / 35W
Mobile phone charger	22mA / 5W

Table 1-1 Power requirements of popular domestic loads suitable for a low-current electricity connection

- An additional advantage with mini distribution grids is that low cost distribution and installation methods may be employed because lower currents and voltages are being carried. These include the use of locally sourced and treated distribution poles and smaller insulated conductors. Such approaches can help to lower the cost of the program and enable households at a wider range of income levels to receive a connection to the generator than would otherwise have been possible.

1.3.2 Drawbacks with mini-grid systems

Disadvantages with mini distribution grids include the following:

- Mini-grids must often be financed locally or by donor funding since resources are not usually available from utility.
- Some types of power source, such as hydro, place significant restrictions on the generator location.
- Mini-grids require local expertise for installation, operation and maintenance.
- Depending on power available and type of generator, there may be difficulty running certain types of loads, such as motors. This may limit the possibilities for income generation.
- Low voltage systems are limited to a small distribution area unless transformers are employed.
- Continuous operation of the mini grid may be dependent on access to certain spare parts and fuel if the power source is a diesel generator.
- Upgrading the system is more complicated if conductors are sized for existing generator capacity.
- With renewables, the power available may be limited by weather conditions or otherwise by fuel supply if diesel generators are used.

1.3.3 Single household supplies

An alternative to grid connection or a mini grid is an individual electricity supply for a single household. The advantages of this are:

- No distribution system is required.
- Load management is greatly simplified.

The disadvantages with single household schemes include:

- Higher cost per household than mini-grids depending on location and nature of supply.
- The use of rechargeable batteries for household power is limited to those areas with charging stations.

1.3.4 Cost comparison of off-grid generation with grid extension

When programs of rural electrification are being considered for remote communities, a comparison should be made between the cost of grid extension and the use of a mini grid with it's own power source to supply the consumers. Although the remote energy source is usually assumed to be a diesel generator, this comparison can be extended to include other energy sources. The cost of grid extension increases with distance. Since off-grid systems are not significantly affected by distance from the grid, at some point a breakeven distance is reached, where the costs of grid extension exceed those of remote generation. The results of such a calculation, first considering only capital costs and then considering lifecycle costs are shown in Table 1-2.

Technology	Cost of energy ($/kWh)	Breakeven distance (capital costs only)	Breakeven distance (lifecycle costs)
Diesel generator	0.33	1.4 km	8.1 km
Micro hydro	0.14	3.5 km	2.1 km
Photovoltaics (PV)	0.51	18.0 km	13.9 km
Wind turbine	0.31	7.9 km	5.6 km

Table 1-2: Typical distances at which off-grid power supplies equal the cost of grid extension [Office of Technology Assessment 1992]

In order to make estimates of the energy unit cost from each technology, the assessment assumed a 10kW peak capacity electricity generating plant with storage (batteries replaced every 5 years over lifetime for wind and PV). Typical capital costs based on retail prices at the time of the study were combined with a capacity factor (20% in each case), typical operating and maintenance costs, system lifetimes, discount rate and fuel costs for diesel to give total energy costs shown. The cost of the grid power was calculated by combining typical costs for generation ($0.07 / kWh) with the costs of single phase grid extension. This was assumed to be of the low-cost 'single-wire earth-return' type assuming a baseline cost of $4,500 / km ($0.032 / kWh-km).

When set-up costs only are considered, the breakeven distance for diesel generators is the shortest, implying that this is the lowest cost method of providing an electricity service. However, when lifecycle costs are considered, the breakeven distance of diesel generators increases considerably, making the renewable energy technologies much more attractive. Nevertheless, given the high cost of grid extension, greater adoption of mini-grids and off-grid generation clearly merits consideration, at least as an intermediate measure, in areas where rural electrification programs are faltering.

The favourable performance of renewables, when compared with the lifecycle costs of diesel generators, has increased interest in their potential to provide power in rural areas of developing countries. This is in addition to worldwide grid-connected renewable energy programs that aim to reduce dependence on imported fuel supplies and stem the increase in emissions of greenhouse gases. When compared with increased fossil fuel dependence, the financial benefits of a 'fuel-free' power source to local communities in the developing world are self-evident. However, in addition to the economic comparison with grid extension, there are other considerations for the appropriate selection of off-grid energy systems.

1.4 Comparison of off-grid electricity supply options

Five options for rural power are compared in Table 1-3.

	Automotive batteries	**Solar home systems**	**Small-scale hydro generators**	**Wind power**	**Diesel generators**
Capital cost	Low	High	Medium	High	Low
Running cost	Very high	High	Low	High	High
Reliability	Performance diminishes	High reliability excluding battery degradation	Maintenance and management dependent	Maintenance and management dependent	Maintenance and management dependent
Power output	Approx. 300 watt hrs per charge.	7 hrs per day maximum	May run continuously	High fluctuation in most areas	May run continuously
Ease of installation	Very easy	Easy	Quite complex	Relatively easy for battery charging	Relatively easy
Agro-processing	No	No	Possible	Widely used for water pumping.	Possible
Availability	Widespread	Widespread	Limited in many countries at present	Highly limited for electrification	Widespread
Manufacture	May be manufactured locally	Usually imported panel	May be manufactured locally	May be manufactured locally	May be assembled locally
Sustain-ability	Environ-mental concerns for safe disposal due to lead content	As for battery only systems if lead acid battery used otherwise renewable energy	Fully recyclable components and renewable energy resource	As for battery only systems if lead acid battery used otherwise renewable energy	Dependant on fossil fuel supply, exhaust is polluting

Table 1-3 Comparison of off-grid electricity supply options

1.4.1 Battery-only systems

The most readily available source of electricity for rural people who are not grid-connected is from dry cell batteries. They are widely used for small loads with intermittent usage such as torches and radios. However, they are too expensive for larger loads.

Use of locally recharged automotive batteries for electricity supply by households who live near grid lines but do not have the opportunity of connection is widespread in many developing countries. Automotive battery charging may also occur in areas where there is no grid when local recharge facilities can be powered by hydro or diesel generators. The main advantages are their low cost and widespread availability, in addition to the ease of installation. At least 5% of rural households in Kenya use automotive batteries, which they recharge at a grid-connected charging station [Hankins 2000]. In many countries, the main application is often television such as Kenya where a new black and white set can cost around US$40. A 50Ah car battery can power a television for 3-4 hours each night for about a week before recharging is required. However, the drawbacks with this approach are considerable.

A typical charge from a grid-connected charging station in Kenya costs Ksh50 (US$0.64). The battery must be transported to the charging station, often over distances of several kilometres at considerable inconvenience and additional expense. Transportation costs may easily be equal to the charging costs. Where batteries are recharged at charging stations, the power is rarely used for loads other than radios and televisions due to the high cost and inconvenience of frequent recharging.

The battery chargers are often old, inefficient and unable to provide any indication of the charging levels. The consumer pays to be connected for a fixed amount of time and is unable to verify if the battery has been fully charged. Lead acid batteries designed for vehicle use are not designed for deep discharging. Most batteries are used until the load will no longer work and may then be left for several days or weeks before being recharged. Furthermore, they continue to self-discharge even when the load is no longer connected. Leaving an automotive battery in a fully discharged state is particularly detrimental [Trace Engineering 2002]. Little understanding of these limitations and almost non-existent use of charge indicators, leads to a rapid decline in performance and lifetime. As the battery performance diminishes, the required frequency of charging increases so the battery becomes progressively more expensive to run. This places an additional financial burden on the user. An additional drawback is that disposal of automotive batteries presents an environmental hazard due to their high lead content [Real 2001].

1.4.2 Solar home systems

The use of solar photovoltaic (PV) panels for battery charging is increasing in areas that are not serviced by national grids due to falling costs of the panels. For example, in 2000 it was estimated that cumulative sales of solar home systems in Kenya had exceeded 100,000 [Jacobson 200, Simm 2000] and current annual sales of panels total approximately 20,000. The largest part of these sales is now of amorphous silicon (a-Si) panels which typically have a rated power output of 10 –12W_p (W_p= output during peak sunlight hours). Crystalline panels have a higher efficiency and are proven to have a life of 20 years or more. However, they also have a higher cost per watt and are only available as panels with outputs of at least 20W_p. As the a-Si PV modules are available in smaller power outputs (10-12W_p) and at lower cost, they are increasingly popular as part of entry level systems with households previously unable to afford a solar home system. The battery is often connected to electric lamps as well as TV and radio since the power is effectively available free of charge once the panel has been installed.

Those rural households who can afford the capital cost of a panel often upgrade an existing battery only system. This can cause problems if the components are mismatched. A common problem in Kenya is the use of an automotive battery, which may have a capacity of around 50 Ah, with a 12W_p a-Si panel. With a panel of this size, such a large battery will rarely become fully charged and its performance diminishes quickly. Furthermore, tests on commercially available solar modules have shown that there is considerable inconsistency in the performance of a-Si panels with some brands falling well below the manufacturers rated power output [Kammen 1996].

1.4.3 Small-scale hydro

Small-scale or micro hydro (up to 100 kilowatts electrical output) is used in a number of developing countries for providing a wide range of energy services. The turbine and generator units may be connected to single households or to whole communities. Unlike battery and solar systems, they are very site specific, usually found in hilly areas with at least moderate amounts of annual rainfall. Different types of turbine are available capable of harnessing energy from sites with heads of a few metres, to those with over 100m. The flow may be provided by a small spring or a large river. The power may be produced at 12V for battery charging using a car alternator with some pico hydro systems (up to 5 kW), or at mains voltage using a synchronous or induction generator. The mains option has the advantage that community electrification for hundreds of households is possible, provided that sufficient power is available. In addition to requiring a suitable site, the design and installation of the system is more complex than with solar or battery systems which generally only supply single households. The capital cost to a community may be high but usually works out cheaper than solar power on a per household basis. Since the electricity is often available continuously, the cost per unit of power is also low but only if all the power can be used. Daytime loads that allow micro enterprises to develop are one way of increasing the 'load factor' and improving the economics of a scheme. Unlike large hydro projects, environmental effects are negligible since large amounts of water or big dams are not necessary. A major limiting factor with this technology is local availability of suitable equipment and the capability to carry out the design and installation. Where this exists and sites are abundant, such as in Nepal [ESAP 2001], the technology can flourish and benefit many thousands of people.

1.4.4 Wind power

Wind power is becoming increasingly important for large-scale power generation for feeding into grid networks. The advantages of wind power are the large number of suitable sites in rural areas of some countries and its environmental credentials as a renewable energy source. Wind can also provide a useful compliment to solar power as part of hybrid systems, due to correlation with periods of low insolation. Although widely used for water pumping from bore holes in remote locations [e.g. Karottki 2001], the application of wind power to off-grid electrification in developing countries is limited in most parts of the world at present. However a study in Inner Mongolia has indicated that there are at least 130,000 stand-alone small wind generators (100 watts peak output) which are used by remote farming communities mainly for battery charging [Scott 1999]. A principle disadvantage with wind is that the resource is much more unpredictable than hydro, so off-grid systems require battery storage to maintain an even power supply. Generally the cost per kilowatt is high although life cycle costs may be below those for diesel generation (see Table 1-2). Small wind generators (SWG's) are becoming more widely available although rarely manufactured in developing countries (except in Mongolia where there are 11 manufacturers) and hence all components must be imported at present. This has tended to make them prohibitively expensive for most rural people. Efforts are underway however to introduce designs of SWG's which are suitable for manufacture in small workshops in other countries such as Sri Lanka and Peru [Dunnett 1999].

Repair and maintenance costs are generally higher than for hydro turbines due to greater loading during fluctuations with the resource [Piggott 2000]. Inverters and transformers are required for supplies to mini-grids.

1.4.5 Diesel generators

Diesel generators are widely used to provide mains electricity in places where the grid is not available. This also includes for electrification of rural homes. As with hydro, a distribution system can be designed to connect the generator to many houses. Fuel and maintenance costs increase the unit cost of the power produced over the lifetime of the scheme (see Table 1-2). Chief advantages are that small diesel generators are widely available and can be located almost anywhere providing that fuel can be sourced at reasonable cost. In addition to providing domestic power, diesel generators are also widely employed to power water pumps for irrigation and other machinery, such as grain mills and welding stations. All these activities are also possible with small hydro systems where suitable sites exist.

1.5 Summary and project aims

The combination of low cost per kilowatt and potential for income generation through productive end-uses makes small-scale hydro potentially the most appropriate option for rural electrification in developing countries where suitable sites exist. However, this potential is presently untapped in most countries due to lack of suitable turbine-generator equipment and local implementation capacity.

The aim of this project is to develop a strategy to enable widespread adoption of small-scale hydropower for rural electrification. A holistic approach will be taken.

1) Firstly a rigorous assessment of current approaches to the implementation of small-scale hydro projects will be carried out. This will involve detailed analysis of existing schemes including site survey, turbine and scheme design, and installation methods.
2) Building on this assessment, the project will identify possible improvements to the current practice and their likely benefits particularly in terms of cost per kilowatt of newly installed schemes and longer term sustainability.
3) New and innovative approaches to system design and implementation will be developed from this assessment in collaboration with existing manufacturers and rural development experts.

2 EXISTING PRACTICE FOR IMPLEMENTATION OF PICO HYDRO

2.1 Costs of small-scale hydro in Nepal and Sri Lanka

The design approach and standards adopted by implementation agencies when tackling micro hydro projects (up to 100 kW) tended, in the past, to be based on scaled down versions of those for large projects [Foley 1990]. This has led to unfavourable attitudes towards micro hydropower despite the many inherent advantages for rural electrification. As a result, new approaches have been developed in order to take advantage of the unique design and implementation opportunities presented by schemes of less than 100 kW. New approaches for micro hydro include emphasis on community labour, locally manufactured components, local installation and ownership of schemes. Examples of the new approaches have been described in Inversin [1986] and Harvey [1993].

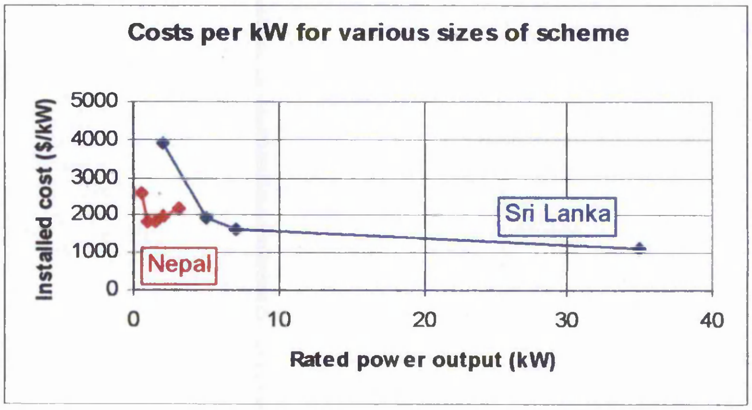


Figure 2-1 Cost per kilowatt for various sizes of small-scale hydro

Successful commissioning of a number of schemes below 5 kilowatt has demonstrated that additional changes in approach to the design and implementation can have major additional benefits for schemes in this size range. Schemes of up to 5kW are termed pico hydro in order to differentiate them. In order to highlight the approaches to design and implementation, several small schemes in Sri Lanka and Nepal have been compared in terms of cost per installed kilowatt in Figure 2-1and shown enlarged for Nepal in Figure 2-2 [Jayalath 1997, Kapali 1997].

The costs of each scheme comprised of the turbine, generator and load controller, penstock, distribution cables, house wiring, building materials and other accessories. Labour was provided free of charge by the beneficiaries.

Figure 2-1 compares the cost of four schemes of different rated outputs that were commissioned in Sri Lanka. A similar design and implementation approach was adopted for each. The rising costs per installed kilowatt, as the schemes become smaller in size, are a result of the economies of scale associated with larger projects. The cost of survey, design and installation varies little with the rated output and hence larger schemes are more favourable.

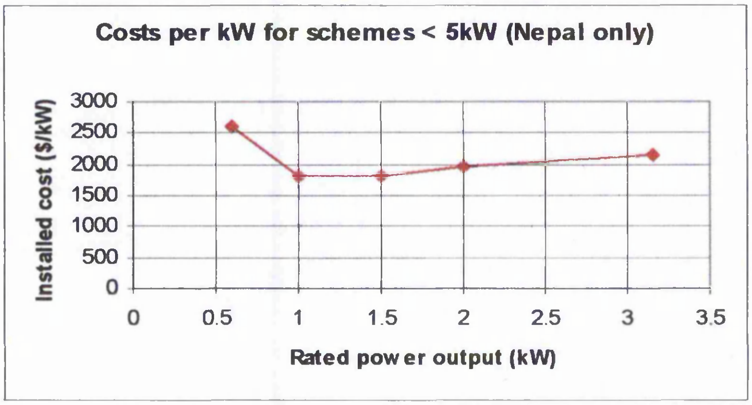


Figure 2-2 Cost per kilowatt of pico hydro schemes in Nepal

(Enlarged from Figure 2-1)

In contrast to this, Figure 2-2 highlights the substantially lower costs per kilowatt for pico-hydro projects achieved by manufacturers in Nepal.

Pico hydro implementation was investigated in two countries where successful commissioning has occurred. Research visits were carried out to Nepal and Colombia so that the existing practice could be documented to enable key components for success to be identified.

2.2 Pico hydro in Nepal

2.2.1 Country and geography

Nearly 90% of the 22 million people in Nepal live in rural areas, 40% of whom in what the World Bank describes as 'absolute poverty', having incomes below the levels to support a minimum daily calorie intake. Few nations have as low a per-capita income as Nepal, where basic indicators of human well-being, such as infant mortality, literacy and life expectancy are also among the lowest in the world [Majot 1997].

The inadequacy of Nepal's energy supplies has become increasingly problematic over the last few decades. Lacking any appreciable reserves of fossil fuels, this landlocked country is forced to import petroleum, coal and kerosene via India, putting a strain on already meagre foreign exchange earnings and threatening political stability if and when the supplies are cut off.

One of the few natural resources that Nepal has in abundance is water. There are 6,000 rivers that cascade down from the Himalayas and countless more small streams and tributaries. The government is keen to exploit this vast potential, estimated at more than 80,000 Megawatts [IEA 2001], as means of fueling industrial growth and modernisation. However, small-scale hydro resources connected to mini distribution grids could also improve living conditions and opportunities for economic development for the large rural population, most of whom live in the Himalayan foothills and rely principally on subsistence agriculture for their existence. Micro hydro also has the potential to alleviate some of the pressure on other natural resources. Some estimates suggest that Nepal's forests are being harvested at 4 times the sustainable rate to provide fuel wood, the principal energy source amongst the rural population.

Micro hydropower, in the form of traditional water mills called *ghattas*, has existed in Nepal for centuries [Aitken 1991]. However, the first modern micro hydropower plant was installed only four decades ago. Since then thousands more have followed, initially just for milling but more recently to provide a local electricity supply which is distributed to the surrounding houses [Riley 2002].

A number of key factors have been noted which have contributed to the success of these systems in Nepal. They can be broadly catagorised into turbine-generator design and implementation methods.

2.2.2 Turbine-generator design

The capacity in Nepal for manufacture of hydroelectric power systems has existed since the 1960's [Maher 1998]. The most popular type of locally manufactured turbine-generator arrangement to emerge in Nepal over the last decade is the 'Peltric Set.' This is a Pelton turbine used to directly drive a vertically mounted induction generator. This design, developed into a commercial product by Kathmandu Metal Industry, lends itself well to batch production due to a high degree of standardisation.

The key advantage of the design is its simplicity, with only a very small number of component parts required as, in addition to being a direct drive unit, the turbine case acts as the base to support the generator and can itself be anchored to the floor.

Other manufacturers were also quick to adopt the idea and to date, at least 810 of these units have been installed in Nepal, benefiting in excess of 50,000 people. The units are manufactured in a range of sizes up to 5 kilowatts. The smallest sizes however are the most popular, particularly the 1 kilowatt model which only requires a flow rate of around 5 litres per second with a 40 metre head.

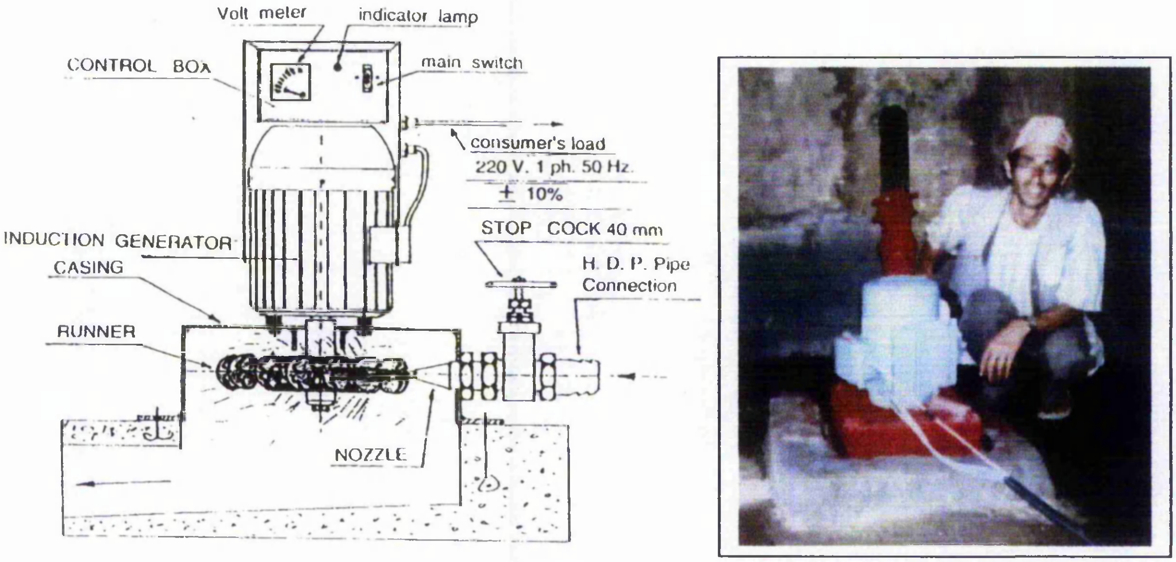


Figure 2-3 Key features of the Peltric Set (left) and installed unit (right)

2.2.3 Implementation practice

1) Low cost civil works

Low cost approaches to building work such as using locally available materials and rudimentary design methods for intake and powerhouse construction enable scheme costs to be reduced. Some schemes in more remote areas are built without any cement or concrete. The simplest power house designs may be no more than a wooden casing around the turbine generator unit which can be lifted off. Most however, use a minimal amount of cement and local stone.

2) Use of mass-produced components

Mass-produced components are widely available and at lower cost than custom-built counterparts. Components such as the induction motors, imported from India or

China are examples. HDPE (High Density Polyethylene) water supply pipe is generally used for all penstocks in the pico hydro range. A variety of different pressure ratings and diameters are found even in remote areas. Local expertise in 'low-tech' jointing methods using heated plates is widespread, as the same material is used for water supply lines.

3) Storage ponds

Since many pico hydro schemes in Nepal use a small stream or spring as their energy source, small reservoirs are often constructed to maximise year-round benefit from small water supplies. Water can be stored up during periods when the available flow is not sufficient to run the turbine continuously. The turbine is then operated for a few hours each day during the morning and evening to provide lighting during periods of peak demand. Since flows required are small, storage capacity does not need to be very large. The largest pico hydro reservoir witnessed in Nepal had a storage capacity of approximately 224 cubic meters (Appendix 10.1.5).

4) Low cost distribution systems

Since the currents flowing in a pico hydro distribution system are small, it is often cost-effective to use insulated copper conductors to connect the consumers. Since these cables are available in smaller diameters than non-insulated conductors, the maximum current carrying capacity can be more precisely matched to the load current requirements. In addition the insulation also improves safety and ease of installation. Tensioning to within precise limits, required with non-insulated conductors, is not critical as the conductors can be tied together. Distribution poles made from local trees can be used and the need for pole brackets and insulators is removed with insulated conductors reducing the system costs further.

5) Different models for survey and installation methods

In Nepal, four models have been identified by which new sites are located and the survey and installation carried out. These enable manufacturers to access potential sites across a wider area and achieve sufficient sales to warrant batch production of the turbine units.

Survey / installation conducted by:		Quality of resulting scheme	Cost	Potential coverage	Other considerations
1.	Manu-facturer	High	High	Low	Possibility exists for local training to be given. Manufacturing may be affected.
2.	Manu-facturers technician	Medium to high	Medium to high	Medium	Other local schemes can be visited for servicing and new surveys carried out.
3.	Local agent	Medium to low	Low	High	Local expertise is developed and remote areas may be targeted. Financial incentive for agent exists. Good agents may be hard to find.
4.	Villager represent-ative	Generally low	Low	High	Sales are direct from company workshop. A poorly installed scheme is unlikely to promote further sales.

Table 2-1 Comparison of survey and installation models which exist in Nepal

2.3 Pico hydro in Colombia

2.3.1 Country and geography

The South American country of Colombia is a country rich in natural resources. However due to long term political divisions and civil war, the benefits of these have not been realised for the majority of the people. The population is around 42 million, about 30% of whom live in rural areas. There are estimated to be at least 6 million rural poor *campesinos,* most of whom have no access to grid electricity.

Despite its problems, Colombia is a country with abundant hydro resources. Two thirds of the national grid is supplied from large hydro plants. Many rivers run down from the Andes Mountains into the Amazon Basin on the eastern side and into the Pacific Ocean on the West. The first Pelton turbines were installed in rural areas of Colombia during the early 1920's. Initially, the primary uses of hydropower were for mechanised production of coffee, extraction of cane sugar and for driving sawmills. During the 1950's, many of the old turbines were upgraded for the production of electricity. AC generators became more widely available, and were often carried to remote areas by mule.

As grid electricity spread to many parts of Colombia, most of these small hydropower plants fell into disrepair and became forgotten. A number of these turbines have now been resold and installed elsewhere, often being used to supply power to small farms. This has encouraged greater interest in pico hydro amongst rural communities, most of which are still not served by the grid because of the high connection costs. One region where this has happened is the Guatiquía River Basin, on the eastern side of the Andes foothills [Proyecto Río Guatiquía 1999]. A small organisation, 'FTDA' (*Fundacion para el Desarollo de Tecnologias Apropriadas*), has been installing small-scale hydropower systems here since 1980. In 1988 local production of Pelton turbines using the 'lost wax' casting method began and an innovative turbine generator design was developed [Gnecco 1992].

2.3.2 Turbine-generator design

Although still using a Pelton turbine as with the Peltric Set, a different design has evolved in Colombia which suits the local market. Rural homes in Colombia tend to be more dispersed than those in Nepal where clusters of houses in small villages are the norm. Smaller proportions of people live in the countryside and they tend to farm larger areas of land. Power supplies for individual households are in demand rather than community schemes, and battery charging is a common option since few people can afford to buy and run a diesel generator.

The small Pelton runner drives a car or truck alternator via a V-belt pulley. The power produced is at 12V DC but since there is little demand for distribution to groups of houses, this is sufficient to provide a satisfactory supply in many cases. DC lighting, such as car headlamp bulbs can be connected directly to the alternator or an automobile type battery can be charged. The existing alternator pulley can be used and the turbine and alternator are mounted on a steel-angle base frame. Simple turbine nozzles are fabricated using screw-fitting PVC pipe caps that can be bored to the correct diameter on a small lathe. An installation of this design is shown in Figure 2-4.

Figure 2-4 Installation of an FTDA Pelton turbine.

There are several advantages to this design. No extra control system is required other than the voltage regulator, already included with the alternator. Since DC (direct current) is generated, no frequency regulation is required. Connection of other machines in place of the alternator is possible because of the horizontally mounted turbine shaft and driver pulley. This arrangement has been used with considerable success to drive refrigerator compressors allowing ice manufacture [Gnecco 1997]. The simplicity of the design and the adoption of mass-produced components keeps the cost to a minimum. A single turbine-generator unit sells for US$250. The lifetime of automobile alternators is much shorter than induction generators, but almost any automobile workshop can provide a repair and replacement service.

2.3.3 Implementation practice

1) Low cost installation

A powerhouse is rarely constructed for these Colombian turbines. Instead, a wooden or plastic casing is built around them, or they are merely covered by a simple shelter, constructed using four posts supporting a pitched roof to provide protection from the rain. A small amount of cement or concrete may be used to build a secure footing and enable the exiting water to be channeled away from the installation. The intake is designed simply by anchoring the penstock pipe in a sufficiently deep pool, often with large stones. A plastic drum with holes punched through serves as a screen against debris, which could block the turbine nozzle.

2) Highly standardized design

The design approach has been to manufacture one size of runner (100mm pitch circle diameter) which provides a suitable shaft power and speed to connect to a standard car alternator. Changing the drive pulley and nozzle diameter can vary the head requirements from 25 m to 45 m and provide a sufficiently broad range of sites.

3) Sales and promotion

Since the turbine and generator arrangement is simple, it is possible for local artisans to replicate it easily and subsequently carry out any maintenance and repairs. This is encouraged to promote sales of the runner. This method has helped to propagate pico hydro systems widely throughout the country and approximately 400 runners have been sold in this way. As a result, FDTA has become widely known and receives many enquiries for other services such as micro hydro systems and wind pumps, which are their other main sources of income. Market development has been carried out through the targeting of specific areas, with both high potential and high demand such as the Guatiquia River basin. Since the technology helps to promote sustainable development and encourage protection of the watershed from deforestation, it has also attracted support from local environmental projects. Local radio stations are used for promotion in the rural areas. Although the people who purchase the pico hydro systems are predominantly very poor, they have been found to be extremely trustworthy. This has enabled the manufacturer to extend credit to many customers and occasionally accept interim payments in kind, usually in the form of farm produce. This flexible approach to scheme financing has helped encourage further local sales of pico hydro equipment which, for most families, still represents an investment of considerable size.

2.4 Summary

The key advantages of pico hydro are:

- In remote regions, where hydropower is used to form an isolated energy supply, maximum efficiency is less important than reliability and cost per kilowatt. A standardized design allows satisfactory operation over a range of heads and flows. It also permits batch production rather than one-off designs, thereby significantly reducing manufacturing costs.
- Standardized design allows a greater sense of familiarity with the technology to develop in areas where several units are installed. This promotes the technology and improves scope for local implementation.
- Since smaller flows are required for pico hydro, many more potential sites exist. In most countries, pico hydro has been overlooked during previous resource estimates. A separate focus encourages these to be re-examined since the resource is often sufficient to have a significant impact on rural energy needs.
- Remote areas that are inaccessible by road are not necessarily excluded since porters or animals are usually able to carry pico hydro equipment.
- Despite maximum electrical power outputs of pico hydro installations being limited to 5 kilowatts, the potential exists for large numbers of houses to benefit from a single scheme if energy efficient loads are used. This increases the affordability, as the proportion of the capital costs per household is less. Installation is more straightforward with small schemes and may require less training and experience, allowing potential for further cost reduction.
- Local management of a community scheme is necessary for sustained operation. Many rural energy programs encounter problems with the operation and management in areas where no previous experience exists. This lends weight to an argument that it is better to start small and build up so that if difficulties such as tariff collection or load management cause a

scheme to stop operating, a large capital investment has not been lost. Once a scheme is operating successfully in a particular area, then there is a strong chance that a larger scheme will be successfully managed and upgrading can be considered where suitable potential exists.

Examination of the turbine designs and implementation approaches taken in Nepal and Colombia has highlighted the advantages which standardisation of pico hydro systems can bring about. However, further research and development is required to enable the potential of this emerging technology to be realized more widely.

3 ANALYSIS OF CURRENT IMPLEMENTATION PRACTICE

3.1 Scope of research and data analysis

During 1998, research was conducted in Nepal in order to evaluate existing pico hydro schemes with a view to developing a generic implementation methodology that could be used as a basis to encourage adoption in other countries.

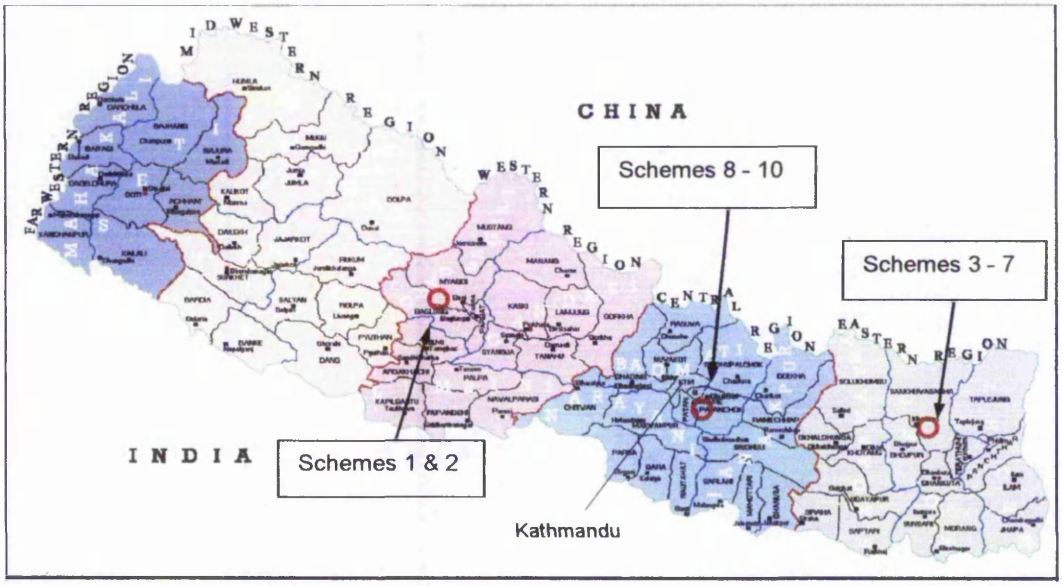


Figure 3-1 Map of Nepal indicating location of schemes visited [Thakhur 2003]

3.1.1 Methodology of site selection

Selections of schemes from the two main manufacturers were visited across three different regions. All were installations of the Peltric Set described in Section 2.2.2 and served village communities. Each had between 7 and 45 houses connected. Since the schemes were similar technically, specific comparisons were possible. All had a single nozzle and used a four-pole induction generator with rated outputs of between 1 kilowatt and 3 kilowatts. Although the manufacturers were able to give indications of areas where there were high concentrations of schemes, allowing a number of visits within a relatively short time, local knowledge was used to identify the particular sites to ensure unbiased selection. Accessibility was also a factor that determined which schemes were visited as all were within 3 days walk of the road. The following data was gathered in order to assess scheme performance.

3.1.2 Hydro potential

The head was measured using a digital altimeter at each site and the flow was either measured or calculated in order to determine the hydraulic input power. The salt-gulp method of flow measurement [Harvey 1993] with a digital conductivity meter was used where possible. The flow could not be measured directly at some sites because the tailrace from the powerhouse was too short to allow the required mixing of the salt solution. In such cases, an estimate was made using the measured gross head and the penstock and turbine nozzle diameter. The results of the modelling carried out for each site and used to determine the flow and net head conditions are given in Appendix 10.2. This data allowed a calculation of the likely efficiency of each scheme, and an evaluation of the sizing of the scheme components (e.g. penstock, turbine, generator) for that site.

3.1.3 Electrical measurements

The electrical power was measured at each site using a hand-held clamp meter, which provided current, voltage and power readings. The power output was compared to the manufacturer's rated power output as an initial gauge of how the schemes were performing. The voltage, frequency and line currents were measured at the generator terminal box. The results are shown in Appendix 10.1.4. Low voltage levels indicated excess loading on the system. High frequency indicated that the excitation capacitance connected across the generator windings was insufficient or partially damaged. Comparison of the generator line currents allowed the correct connection of the capacitance to be verified. A 3-phase induction motor requires correctly sized capacitance to be connected in a C-2C arrangement across two of the three windings to provide balanced operation as a single-phase generator [Smith 1996].

3.1.4 Specification of scheme components

The sizes of the penstock, turbine, generator and distribution cable were noted at each site. The penstock diameter and length allow the head losses to be estimated. The turbine and generator sizes were compared to the site conditions to assess the suitability of the match. This data also enabled estimation of the scheme cost.

3.1.5 Location of consumers.

The positions of the houses connected to each generator were recorded. Using the cable data and details about the loads connected, voltage drops along the distribution system were calculated and scheme layouts drawn. An example is given in Appendix 10.2.1.

3.1.6 Consumer loads

The total load on each generator was compared with the electrical output to give an indication of how much the system was overloaded. Recommendations about the suitability of the loads and conclusions about load management could be drawn from this data.

3.2 Summary of scheme data

Figure 3-2 compares actual power output versus the manufacturer's rated power at the 10 community schemes visited (Table 3-1). The results show large discrepancies in the manufacturer's intended or claimed power output and the actual performance of the schemes. In most cases the schemes were performing at less than 50% of their rated power. Only at scheme Number 9, was the power output close to the rated power. This was an unusual case as the rated power was actually exceeded.

	Name of Site	District	Manu-facturer	Rated power (kW)	Gross head (m)	Installed by
1	Gairaphat	Baglung	KMI *	1.0	64	Village rep.
2	Simswara	Baglung	KMI	1.0	75	Village rep.
3	Thulo Phako	Sankhuwasabha	KGEW**	3.0	46	Technician
4	Sabra	Sankhuwasabha	KGEW	1.5	60	Technician
5	Bulke	Sankhuwasabha	KGEW	2.0	63	Technician
6	Tamaphok 2	Sankhuwasabha	KGEW	3.0	45	Technician
7	Mude Sanishare	Sankhuwasabha	KGEW	3.0	40	Village rep.
8	Chandanpur	Lalitpur	KMI	1.0	60	Manufacturer
9	Gotikhel No.6	Lalitpur	KMI	1.5	137	Village rep.
10	Paratu	Lalitpur	KPT***	3.0	60	Manufacturer

Table 3-1 Details of sample schemes surveyed in Nepal

*KMI = Kathmandu Metal Industry, Kathmandu, **KGEW = Krishna Grill Engineering Works, Biratnagar, ***KPT = Krishna Pradan Turbines, Lalitpur

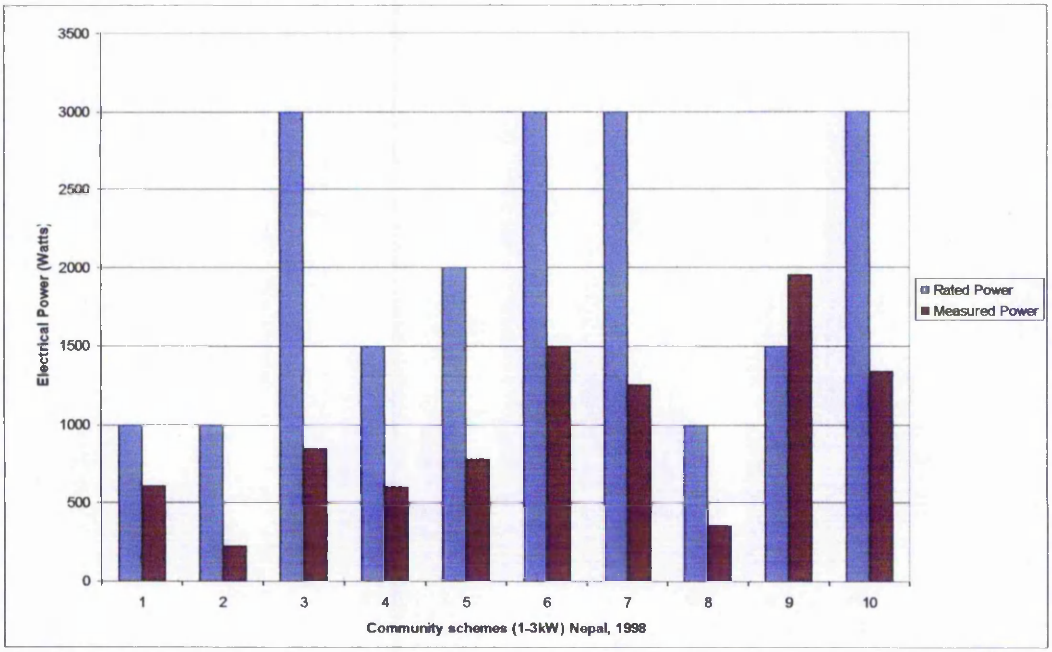


Figure 3-2 Rated versus actual power output of Peltric Sets surveyed in Nepal

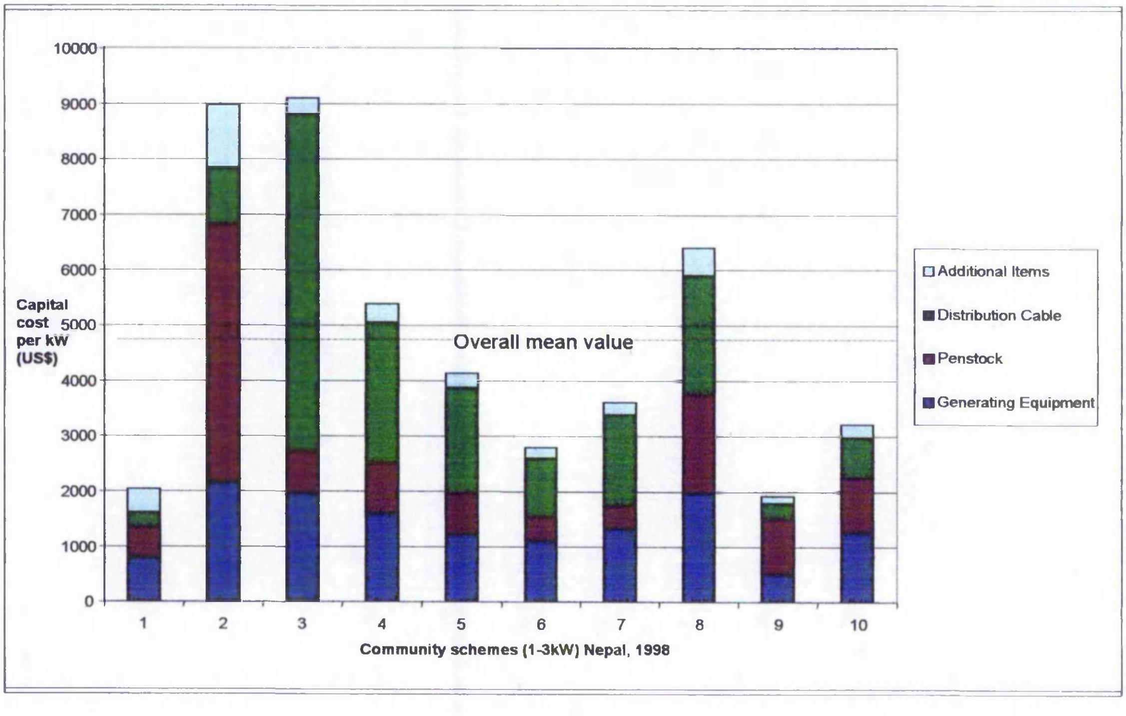


Figure 3-3: Cost per kilowatt of schemes in Nepal (cost excluding VAT@18%)

Although an obvious means of appraisal, these results give no information about the underlying reasons for the large discrepancies. A more thorough analysis is required to understand the reasons for the poor performance and high degree of variability.

The cost per kilowatt is a useful a guide when comparing particular methods of power generation and provides an objective means of drawing comparison between sites. The rated power of the equipment, as stated by the manufacturer, is commonly used to calculate the cost per kilowatt. However, an unrealistically low cost per kilowatt is obtained if equipment fails to provide the rated power output. The measured power output was combined with data about the scheme components and local prices in order to calculate true cost per kilowatt data. Examples of complete costings are given in Appendices 10.1.1 and 10.1.2 The combined results for all the schemes are shown in Figure 3-3. The mean cost per kilowatt has also been included for comparison. The total capital cost for each scheme has been broken down into four main components as shown in Table 3-2. 'Other components' included packaging, delivery, tools and miscellaneous items. It was assumed that labour, civil works and distribution poles, were provided free of charge by the local community as this was the case at most of the sites visited. The mean value and standard deviation for these components are as follows.

Component	Mean value (US$ per kilowatt)	Standard deviation	Percentage of mean value (%)
1. Turbine-generator	**1385**	**531**	**38**
2. Penstock	**1199**	**1277**	**106**
3. Distribution Cable	**1781**	**1697**	**95**
4. Other Components	**367**	**298**	**81**

Table 3-2 Average cost/kilowatt for different scheme components

3.3 Analysis of cost per kilowatt

Figure 3-3 reveals a huge variation in the cost per kilowatt of the schemes visited, from around $2,000 to $9,000 per kilowatt. Maintaining consistently low cost per kilowatt of pico hydro schemes is crucial to making it a widespread energy solution for low-income households in developing countries. The following analysis has been divided into discussion of the three major scheme components: turbine and generator unit, penstock and distribution system. The aim is to determine which factors have a significant effect on the cost per kilowatt.

3.3.1 The turbine-generator unit.

As indicated in Table 3-3, the variation in the cost per kilowatt of turbine-generator systems at the sites visited was small. The cost increases almost linearly with power output with only a small saving for the largest machine. The retail prices of the two main Nepalese manufacturers of Peltric Sets, Kathmandu Metal Industry (KMI) and Krishna Grill Engineering Works (KGEW) located in Biratnagar, have been given in table Table 3-3. The prices exclude VAT at 18%. The prices from the two manufacturers are almost identical, differing only slightly with the 3 kilowatt unit. There is therefore little scope to improve the cost per kilowatt through the choice of rated turbine-generator power output, providing that the unit has been matched correctly to the site.

	KGEW				KMI			
Rated power (kW)	**1.0**	**1.5**	**2.0**	**3.0**	**1.0**	**1.5**	**2.0**	**3.0**
Peltric set (US$)	483	708	899	1033	483	708	899	1177
IGC + ballast (US$)	208	283	375	477	208	283	375	500

IGC = Induction Generator Controller

Mean cost / kilowatt of complete unit (US$)	**630**
Standard deviation	**66**

Table 3-3 Cost per kilowatt for Peltric Sets, Nepal 1998

If the unit has been wrongly selected for the site conditions then the cost per kilowatt can be affected in two ways:

1) Power Rating. The head and flow is less than required for the selected power rating and a unit with lower power rating, and therefore lower cost, could have been used.

2) Efficiency. The head available is insufficient for optimum operation of a turbine of that diameter. The efficiency of both the turbine and generator decrease with the result that the electrical power output is less than predicted for the site conditions.

Appraisal of power rating

Table 3-4 compares an estimate of the power available to the turbines with the likely output, assuming a typical turbine generator efficiency of 45%. Alternative selection of turbine generator units would have been preferable at up to 7 out of the 10 schemes visited, given the conditions of flow and net head. At four sites (3,6,7,10) the recommended rated power is less than that chosen by the manufacturer, resulting in an immediate cost reduction.

Scheme number	Actual rated power (kW)	Estimate of hydraulic power (W)	Electrical output @ 45% turbine-generator efficiency (W)	Recommended rated power (kW)
1	1.0	**1558**	701	Selection Ok
2	1.0	**602**	271	Input power too low
3	3.0	**3665**	1649	2.0
4	1.5	**4547**	2046	2.0
5	2.0	**3832**	1725	Selection Ok
6	3.0	**3560**	1602	2.0
7	3.0	**2994**	1347	1.5
8	1.0	**2601**	1170	1.5
9	1.5	**9980**	4491	5.0
10	3.0	**4845**	2180	Selection Ok

Table 3-4 Comparison of available power with rated power

Turbine Efficiency

The efficiency of the Pelton turbine varies with its speed. The optimum speed depends on the runner diameter and the available head. This relationship can be represented by the following expression [Harvey 1993]:

$$N_{opt} = \frac{38\sqrt{H}}{D} \qquad (1)$$

where D = pitch circle diameter of the turbine runner

H = Net Head

N_{opt} = turbine speed for most efficient operation

Since the Peltric Set comes in standard sizes with a fixed range of runners and generators, it is possible to predict the optimum conditions for the unit which was installed at each site visited. The Pelton turbine efficiency characteristic for a runner of the same design as those installed at the sites visited is shown in Figure 3-4. This demonstrates that speed variations of up to ±20% of the optimum value are acceptable without a significant reduction in efficiency.

When the difference in optimum and actual speed is large however (> ±20% optimum speed), there can be a significant efficiency penalty with the Pelton turbine. This occurs if the net head is much higher or lower than the design head. Heads for optimum turbine operation at the schemes visited are given in Table 3-5.

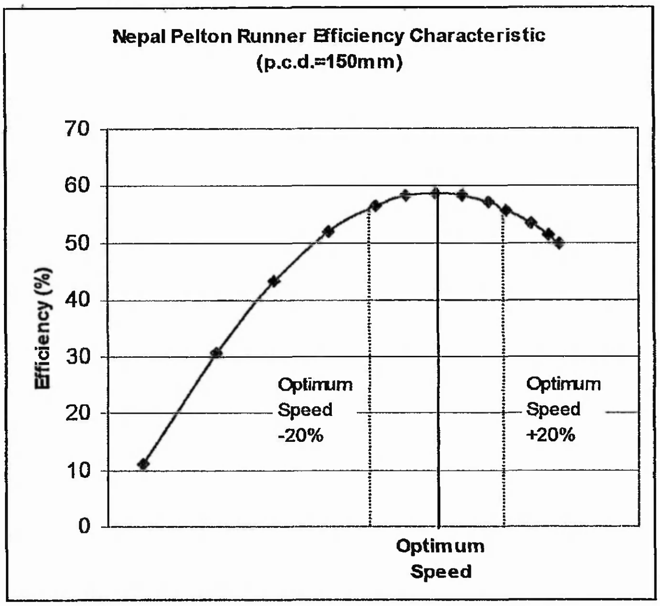


Figure 3-4 Pelton turbine efficiency characteristic

Rated output assuming generator efficiency of 70% (kilowatt)	Nozzle diameter assuming turbine efficiency = 65% (mm)	Runner p.c.d.[1] (mm)	Net Head required for optimum turbine efficiency with a 4 pole generator at 50Hz (m)
1.0	16	150	40
1.5	19	150	40
2.0	16	185	60
3.0	19	185	60

Table 3-5 Peltric set dimensions and ideal net head when generating at 50Hz with a 4 pole generator

For a directly coupled turbine generator unit such as Peltric Set, the actual runner speed is set by the operating speed of the induction generator. The speed of the generator is fixed, depending on the number of poles and the required frequency of the supply. With an induction generator the frequency is adjusted by connecting varying amounts of capacitors across the motor windings. The actual speed of the rotor, N, is given in revolutions per minute by the following:

$$N = \frac{120 \times f}{p}(1-s) \tag{2}$$

where f = frequency (50Hz or 60Hz)
p = number of poles on generator (2, 4 or 6 pole)
s = slip, negative for a generator

---

[1] p.c.d. = pitch circle diameter (effective diameter of turbine runner)

A new optimum speed was calculated from estimations of the net head available at each turbine using Equation 1 and the actual turbine speed was calculated using the measured frequency. At two of the schemes surveyed (2 and 9) there was more than 20% variation from 4 pole generator speed at 50Hz with 5% slip (1575rpm) indicating that the turbine would be performing inefficiently at rated generator speed due to inappropriate head conditions (see Figure 3-5).

At sites where the actual speed was much greater than the design generator speed, i.e. schemes 1, 8 and 10, the difference can be attributed to insufficient or damaged capacitance or significant overloading.

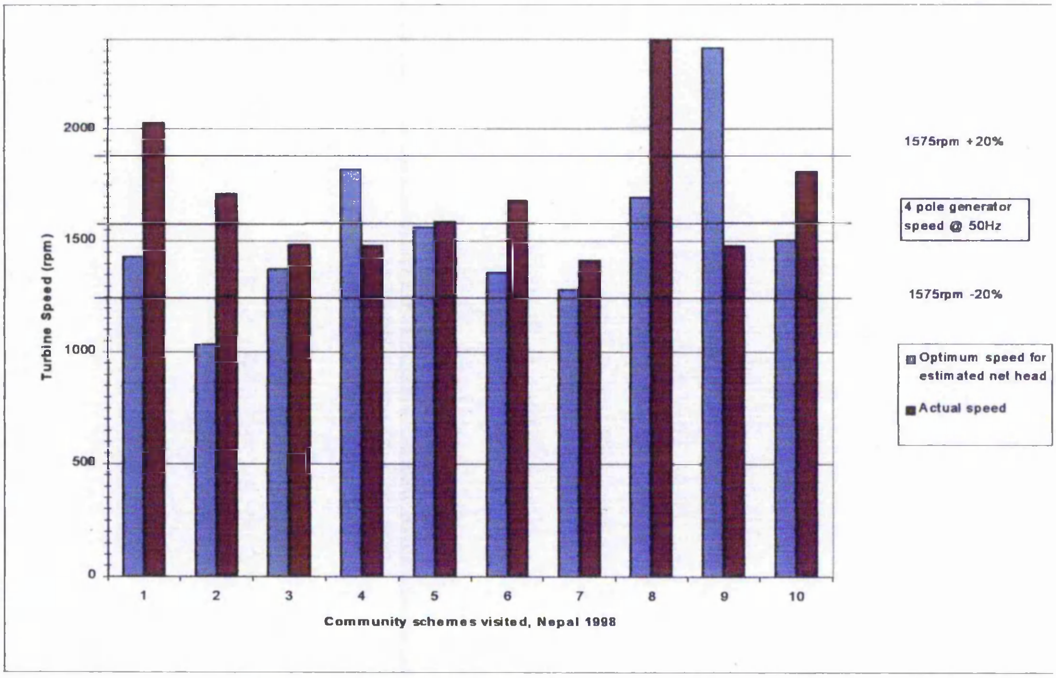


Figure 3-5 Actual and optimum speeds compared

Generator Efficiency

There is a penalty in terms of the induction generator efficiency when the rated power is much greater than the actual electrical power output, although in practice this is quite small unless the output, is a quarter or less than the motor rating. When operating as a generator, the best efficiency point is at approximately 80% of the motor power rating. Although it wasn't possible to determine the motor rating from the machine nameplates at the sites visited as these had been changed, an estimate was made from the frame size. None of the machines surveyed were thought to be oversized by more than 20%. The rated generated power was close to the rated motor power in all cases. Eight out of ten of the schemes surveyed had power outputs of half or less than the rated power (see Figure 3-2). This causes the generator efficiency to fall from a maximum of about 75% at rated output, by 2% or 3% at half of rated power. At a quarter of rated power the efficiency falls by around 10% [Smith 1996].

3.3.2 Penstock length

Results from the site surveys indicate that the cost per kilowatt of the penstock is large and also has the highest degree of variability of any of the scheme components (Table 3-2). At some sites the penstock is the largest single cost item. One reason for the high degree of variability in cost is the topographical differences between different sites. Figure 3-6 compares the ratio of head to pipe length with the cost per kilowatt of the pipe. At an ideal hydro site the length of penstock required to gain sufficient head for the turbine is short. This enables sites with steep gradients to have the lowest penstock cost per kilowatt if all other variables, such as gross head, turbine efficiency and pipe diameter, are kept the same. Clearly if the gradient is very steep, such as a vertical drop over a waterfall, then problems arise with installation and support of the pipe.

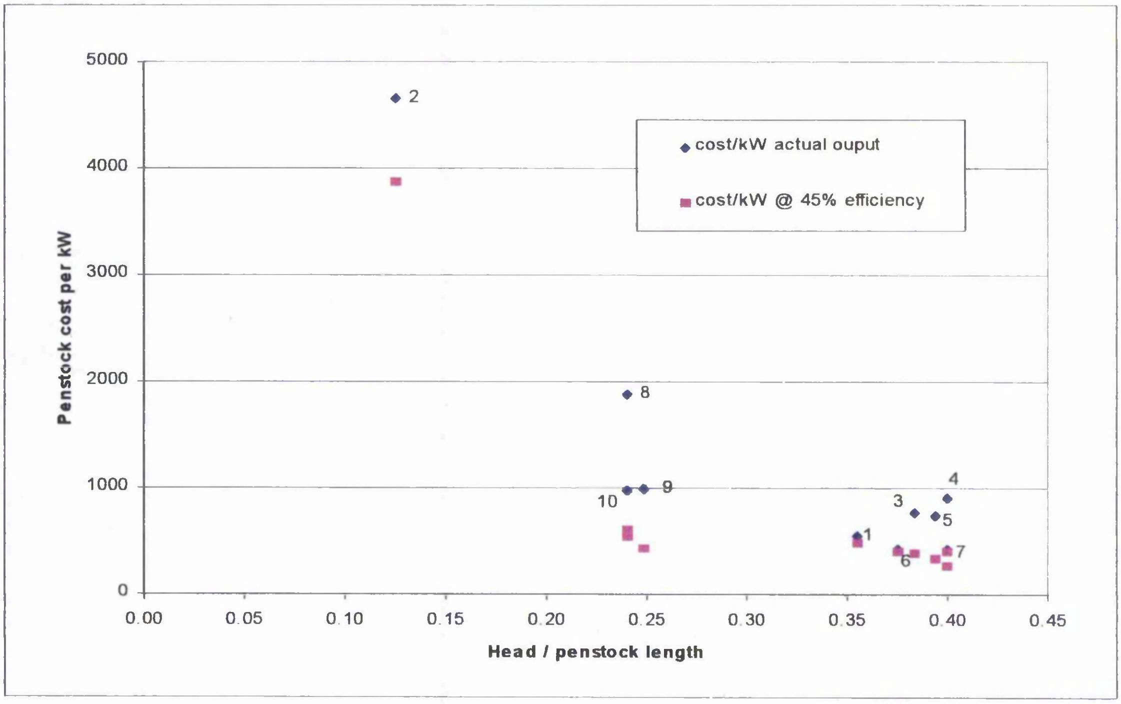


Figure 3-6 Comparison of penstock length and head with cost per kilowatt

Obtaining suitable head over a short distance is not always possible with Pelton turbines, which require at least 25m net head for operation with reasonable efficiency. Generally a reduction in gradient increases cost, as the length of the penstock must increase for a particular head. Although there is a high variation in the penstock cost per kilowatt due to scheme performance in addition to gradient, the graph indicates that sites with gradients of less than 0.1 (or 10%) will be uneconomic to develop unless the penstock can be shortened, for example by using a power canal.

3.3.3 Penstock diameter and pressure rating

All penstocks at the schemes surveyed were made from 6 bar HDPE (High-Density Polyethylene) pipe which is widely available in Nepal. Diameters up to 63mm (2.5") are available in 100m rolls, simplifying transport and installation. Larger diameters are supplied in 6 metre lengths. The lengths of pipe are fused together on site using a hot metal plate. The losses in each penstock were calculated based on estimates of the flow, the actual gross head (measured with a digital altimeter) and pipe length, and conservative estimates of the roughness coefficient for HDPE. The results are illustrated in Figure 3-7.

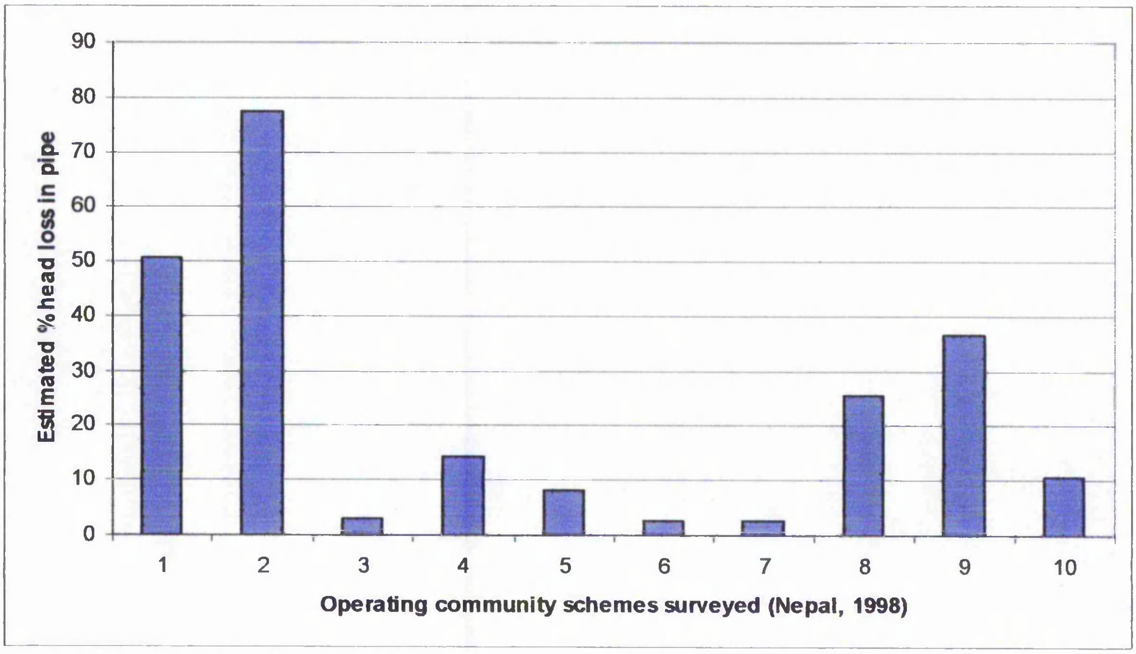


Figure 3-7 Estimated penstock friction loss as a percentage of gross head.

Schemes 1 and 2 used a smaller diameter pipe close to the powerhouse in order to reduce the cost of the high-pressure pipe section. However, since the power output depends on the net head, the penalty in terms of power lost due to friction in these pipes was significant. A compromise needs to be reached when designing a penstock as the benefits of price reduction associated with smaller diameters must be traded off against the increase in the frictional losses. It can be shown that the friction loss in a pipe is approximately proportional to the square of the flow rate if Reynolds number is neglected, the effect of which is small for the turbulent flow conditions experienced in penstocks (see Appendix 10.3).

Power also varies with flow rate and head loss due to friction. The maximum power from a pipe of given diameter occurs when the head loss is 33% of the gross head. This is illustrated in Figure 3-8.

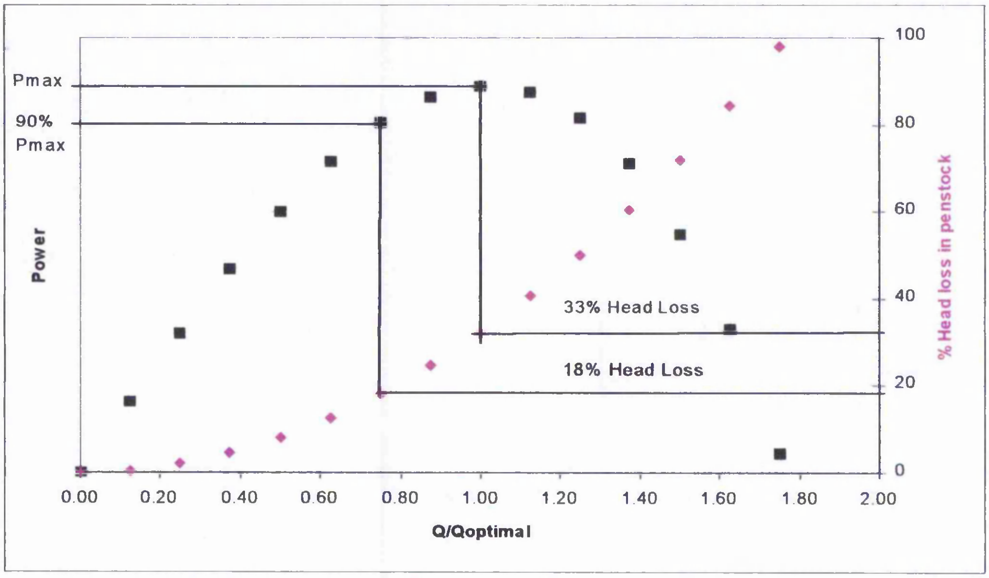


Figure 3-8 variation of power with flow and head loss

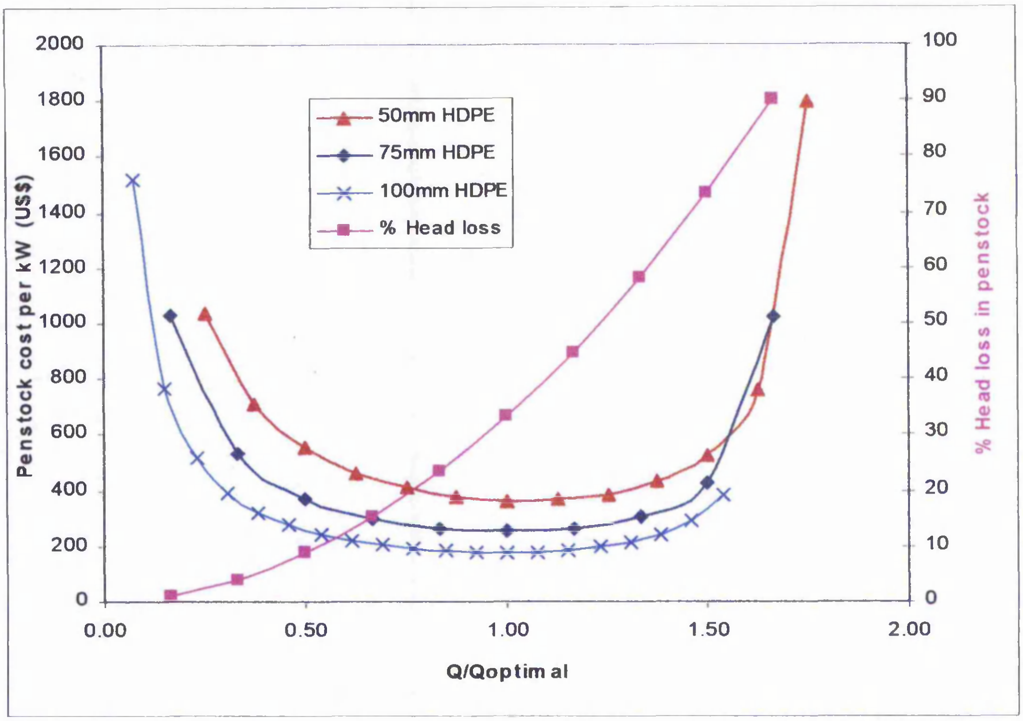


Figure 3-9 Penstock cost per kilowatt of various HDPE pipes of fixed length (gradient =0.3) over varying flow and hence head loss range (diameters = I.D. for 6 bar pipe).

The maximum power from a penstock of given diameter can also be predicted as follows:

$$P = k_1 Q H_{net}$$

$$H_{net} = H_{gross} - k_2 Q^2$$

where:

P = power (W)

H_{net} = net head (m)

H_{gross} = gross head (m)

Q = flow rate (m^3/s)

k_1 and k_2 are constants

$$P = k_1 Q (H_{gross} - k_2 Q^2)$$

Differentiating w.r.t. Q and setting to zero to obtain the maximum:

$$\frac{dP}{dQ} = k_1 H_{gross} - 3k_1 k_2 Q^2 = 0$$

$$\Rightarrow H_{gross} = 3k_2 Q^2$$

$$\Rightarrow k_2 Q^2 = \tfrac{1}{3} H_{gross}$$

Since the power output is at a maximum when the head loss is 33% of gross head for a given pipe size, the cost per kilowatt is at a minimum, as seen in Figure 3-9. This is true regardless of the ratio of head to pipe length or pipe diameter. The minimum cost per kilowatt reduces slightly with larger pipe diameters due to marginally greater economies with material and production costs.

Head Loss	No. of Schemes
0-5%	3
6-32%	4
>33%	3

Table 3-6 Estimated head losses at the schemes visited

The ten schemes surveyed had penstocks with widely differing head losses. In terms of cost per kilowatt, 4 schemes had penstocks with fairly cost-effective pipe diameters giving between 6% and 32% head loss. In 3 cases the head loss was greater than 33% indicating a false economy in pipe diameter and excessive power loss. At the remaining three sites the head loss was less than 5%. From Figure 3-9, it is apparent that below 5% head loss, the cost of the pipe rises steeply compared to the small gain in power output and will therefore have an adverse effect on the cost per kilowatt.

Although the cost per kilowatt is at a minimum when the head loss in the penstock is 33%, there are a number of reasons why a head loss of this size is not usually considered to be practical:

1. The first priority of pico hydro system design is to achieve a close to optimum net head for the diameter of the turbine runner. Often the head available is not sufficient to allow a 33% loss and still give optimum conditions for the available turbines (cost effective in themselves only when provided in standard sizes). This is particularly true for directly coupled turbine-generator units where there is no scope for adjusting the speed of the turbine with pulleys.
2. Many pico hydro schemes require storage to ensure operation during the dry season. Reducing the required flow rate will reduce the size and therefore the cost of the required storage area. A head loss of 15 % to 20% gives almost the same power output at a much smaller flow rate as shown in Figure 3-8; a head loss of 18% gives 90% of the maximum power but only 75% of the flow is required.

3. Friction loss is likely to increases over time due to corrosion (metal pipes) or fouling of the pipe with algae.

3.3.4 Distribution system

Details of seven distribution systems out of the ten schemes visited were collected. Using the cable diameters and layout plans, voltage drops at the furthest points in each system were estimated by assuming that each consumer received an equal proportion, of first the measured and second the rated power output. The national voltage of 230V was assumed if schemes are operating at rated output and the measured voltages were used to calculate percentage drops based on measured power. Houses connected to a particular spur were all assumed to be clustered at the end of the line, forming a single load and giving a slight over estimate of the voltage drop. Since nearly 100% of the loads were resistive elements in the form of incandescent lamps, the power factor was assumed to be unity. Figure 3-10 illustrates the estimated voltage drops at the sites where data was available. In one case, No.9, the drop based on the measured power was greater as the generator was producing more than its rated output. In all other cases, the volt drop at measured power was considerably smaller as the power output was lower than rated.

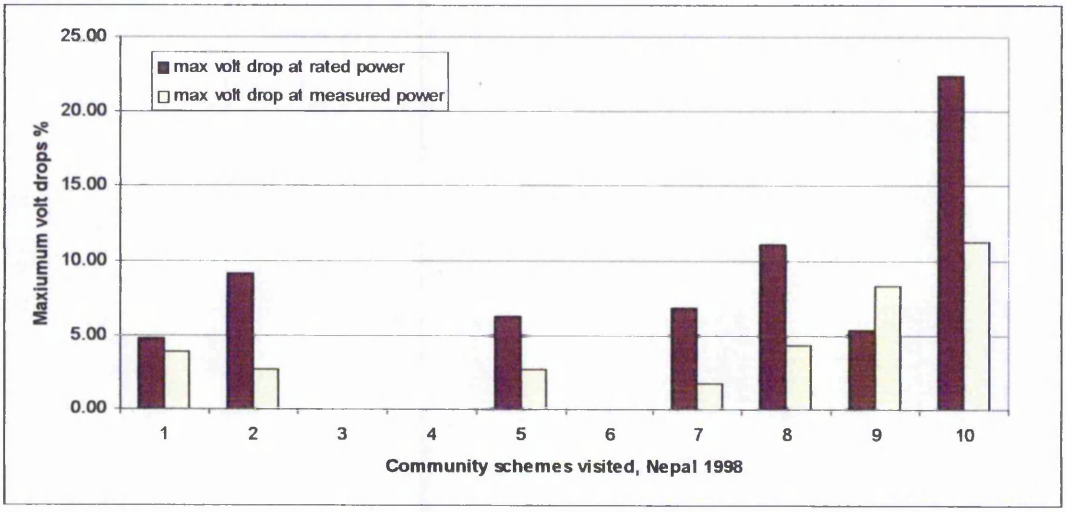


Figure 3-10 Maximum voltage drops estimated where distribution system data could be collected.

The length of the distribution cable per scheme varies with the number of consumers and their relative distances from the generator and each other. When designing low cost distribution systems for pico hydro, the major constraint on reducing the diameter is the permissible voltage drop. This varies from country to country. Variations of +10 / -6% of the nominal national voltage are the limits in the UK but many utilities in developing countries fail to achieve this, especially in rural areas. There is a small power loss associated with the voltage drop.

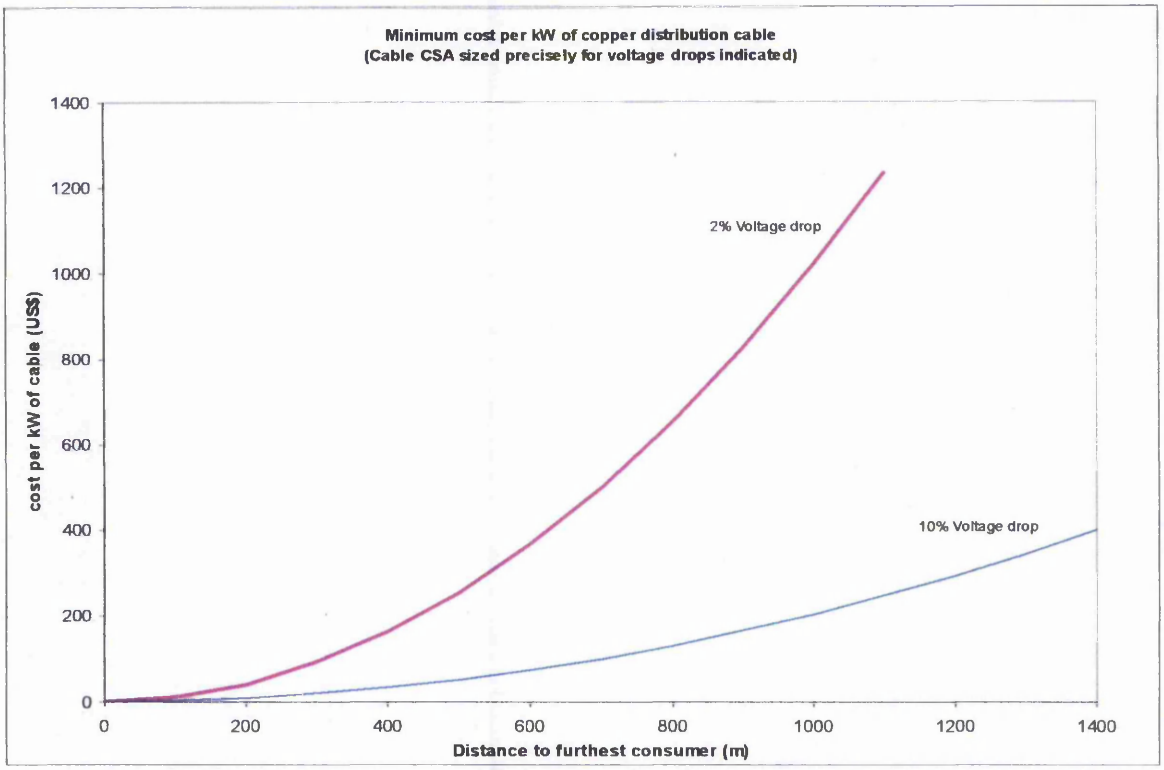


Figure 3-11 The cost per kilowatt of distribution cable can be improved considerably by allowing the maximum voltage drop at the extremities of the system to increase

Figure 3-11 demonstrates how significant reductions can be made in the cost per kilowatt of cable used for the distribution system if the cable is sized to allow for the maximum voltage drop. Such considerations are important when considering design of medium and high voltage grid-connected transmission systems [Laithwaite 1980], but apply equally to low voltage off-grid distribution. Since the price of the cable varies almost linearly with the mass of conductor, costs per kilowatt have been predicted for different lengths of system. Each system assumes a fixed power output and assumes that consumers are equally spaced and receive an equal share of the power. Since the currents flowing in a pico hydro distribution system are small, it is often cost-effective to use insulated copper conductors to connect the consumers.

The graph assumes that copper cables of constant diameters have been used, to give exactly the required resistance for voltage drops of 2% and 10% respectively. Although cables are only available in a few discrete sizes, in practice it is possible to combine conductors of varying length to give the voltage drop required. The costs given assume a copper conductor price of US$0.057 per metre for a cross-sectional area of 1mm^2, found by taking an average of cable prices from Nepal in 1998. They ignore the cost of the distribution poles. At a distance of 1km (often the accepted limits for economic distribution at 230V) the cost per kilowatt is approximately US$1000, allowing a 2% voltage drop. When the drop is increased to 10% the cost falls to US$200, representing a significant improvement whilst maintaining a supply of sufficient quality to the furthest consumers. The range increases over which economic distribution is possible. At 2km the minimum conductor cost is US$815 per kilowatt if the allowable voltage drop is increased to 10%. With a pico hydro generator, it is possible to set a higher voltage at the generator and increase the voltage drop further. For example, if the nominal voltage is 230V and the generator voltage is increased to 230V + 6% (244V) then consumers near to the powerhouse still have a power supply within the acceptable limits. The maximum voltage rating for light fittings and electrical sockets is 250V where the nominal voltage is 230V such as the UK [BS7671 1992]. However a total voltage variation of 12% over the systems is now possible whilst still providing a voltage of 230V-6% (216V) at the extremities. This is also a more equitable means of power distribution if current limiters are used to prevent overloading, as otherwise a reduced voltage will reduce the watts available to the furthest consumers.

At short distances, i.e. within 200m of the generator, it can be seen from Figure 3-11 that the cost difference between the conductors for 2% and 10% voltage drop is not significant. At this distance, sizing for a smaller voltage drop is likely to be preferable due to the benefit gained from the small increase in power. For example, the cost difference between 2% and 10% voltage drop at 200m is US$32 for 1 kilowatt. Considering an 'average' volt drop over the whole line for the two cases (5% and 1% respectively), the extra power is 4% of 1 kilowatt, representing a cost of just US$800 per kilowatt. This is likely to be favourable when compared with the scheme costs.

Although the calculations are based on rated power, the results indicate that in most cases there is considerable scope for increasing these maximum voltage drops to 10% or 12% and thereby reducing the cost per kilowatt. This is particularly true when considering that these are the largest drops at each system. Scheme No.10 is the only example of an undersized system, with a maximum voltage drop 12% above the acceptable limits, assuming rated output. The cable diameter, along this spur at least, should be increased to ensure that the quality of supply for all consumers is satisfactory.

For such distribution systems, where small diameter insulated conductors are used, it is reasonable to ignore the inductive losses in the cables since these are small relative to the resistive losses particularly when the conductors are insulated and so can be twisted or taped together. This is demonstrated in Appendix 10.2.3 (e.g. the reactive losses for a $6mm^2$ copper cable are typically less than 10% of the resistive losses). Although the inductive losses increase slightly for small diameter ACSR (Aluminum Cable Steel Reinforced) which are non- insulated and have larger cross-sectional area, this is more than compensated for by assuming that all loads are permanently connected when sizing the distribution system (i.e. diversity factor = 1) which will tend to oversize the cables.

3.3.5 Additional technical problems

This analysis is primarily concerned with identifying the main factors that affect the cost per kilowatt of pico hydro schemes from the design stage. However, in addition to inappropriate matching of scheme components to the site conditions prior to commissioning, a number of other technical problems were observed during the visits which have subsequently affected the power output and hence current cost per kilowatt. These are listed in Table 3-7.

	Technical problems	Frequency which problem was mentioned	Frequency which a breakdown resulted from the problem	Duration (months) of the breakdown
1	Faulty MCB	5	--	--
2	Bearing worn	0	--	--
3	Poor connections	4	2	3, 1
4	Cable faults	1	1	12
5	Capacitors damaged	1	1	2
6	Leaking penstock	1	1	not known
7	Voltmeter	2	1	0.5
8	IGC	7	--	--
9	Ballast	2	--	--
10	Valve seized	1	--	--
11	Lightning damage	3	1	3+
12	Over-loading	7	1	9

Table 3-7 Additional technical problems observed at schemes visited

The additional technical problems result from inadequate practice in the operation, maintenance and/or scheme management. An induction generator controller had been fitted at many of the schemes but in almost all cases was no longer connected. The voltage and frequency of the supply was not regulated automatically and therefore manual adjustment of the flow was the only means of matching the power output to the connected load. Subsequent changes to the load result in fluctuations of the supply voltage. The majority of the problems with the IGC's (Induction Generator Controller) could be attributed either to a faulty ballast, lightning damage or poor quality manufacture. In many cases the voltage at full power output with the loads connected was less than the nominal voltage, indicating that the schemes were overloaded. The electrical loads connected were mainly incandescent light bulbs (15W, 25W, 40W). At one scheme some compact fluorescent bulbs had been used (15W, 11W and 5W). Other loads included radios (2W to 20W) and a few black and white televisions (35W to 50W). Without an operating IGC with ballast meter, the operator had no means of knowing how much power was being produced and therefore how much load could be connected. At low operating voltages, the quality of consumer power diminishes in equal measure with their satisfaction as incandescent light bulbs dim and fluorescent tubes fail to ignite.

3.4 Summary

The cost per kilowatt can be significantly affected by design decisions taken before the scheme is commissioned. The research identified a high degree of variability in the approaches and accuracy of methods used to implement pico hydro in Nepal.

Poor selection of turbine-generator units for site conditions had an impact on scheme performance and hence the cost per kilowatt. In two cases, an inappropriate runner diameter was selected for the available head, resulting in lower turbine efficiency. At four sites, a lower power rating of turbine generator unit could have been selected at lower capital cost.

Penstock cost per kilowatt increases with decreasing gradient. Sites with gradients less than 15% should be assessed carefully to see if the required pipe length can be reduced, for example by using a canal. Considerable scope exists for more careful design of penstocks, to give head losses that accurately match the head requirements of available turbines. Greater understanding of the cost and performance implications of different diameters and more rapid methods of head loss prediction are required in order for scheme designers to make informed decisions.

The lengths of the distribution systems vary, depending on the location and number of consumers relative to the generator. Accurate system design allows prediction of the likely voltage drops with different cable diameters, but this is time-consuming and tedious for the developer. Significant cost reduction is possible however, by reducing cable diameters whilst keeping the supply to the furthest consumers within acceptable voltage limits.

The results of the analysis indicate that costs as low as $2000 per kilowatt are achievable at carefully designed and properly functioning schemes in Nepal. However there is inconsistency in every area of the current implementation practice and significant room for improvement, particularly in scheme design and component selection. The wide variation in implementation practice can be partly attributed to who carries out the survey and installation, whether the manufacturer, a technician or a local agent, and the degree to which they understand the design considerations.

4 NEW APPROACHES TO PICO HYDRO IMPLEMENTATION

4.1 Steps towards broader adoption and improved performance

Developing countries have large rural populations that are often among the most marginalised groups and usually characterised by low income and highly limited access to healthcare and education. Yet despite this, the demand for electricity and its benefits in such areas is growing rapidly and, in Nepal at least, this demand has encouraged a micro and pico hydropower industry to become established. The technology survives and continues to be adopted, albeit supported by a degree of government subsidy towards the cost of hardware purchase, regardless of the highly variable quality of installations and the 'knock-on' effects this has on power output and reliability. Four areas of the implementation practice have been identified where improvement is possible. These are as follows: turbine design, electrical safety and demand-side load management, selection of scheme components, and scheme-sizing and community involvement. The new approaches are described below.

4.2 New turbine design

The power generated by most of the community pico hydro schemes in Nepal is used primarily for electric lighting. The ability to carry out agro-processing or workshop related activity using the shaft power from the turbine would enable extra income to be generated during the daytime when there is less demand for domestic electricity. Productive end-uses would help to repay the capital cost more swiftly and provide additional incentive for regular maintenance. However, the current pico turbine designs do not allow shaft power to be used for direct drive applications. A further limitation of the current design is the difficulty in gaining access to turbine runner and nozzle. A different turbine-generator arrangement and case

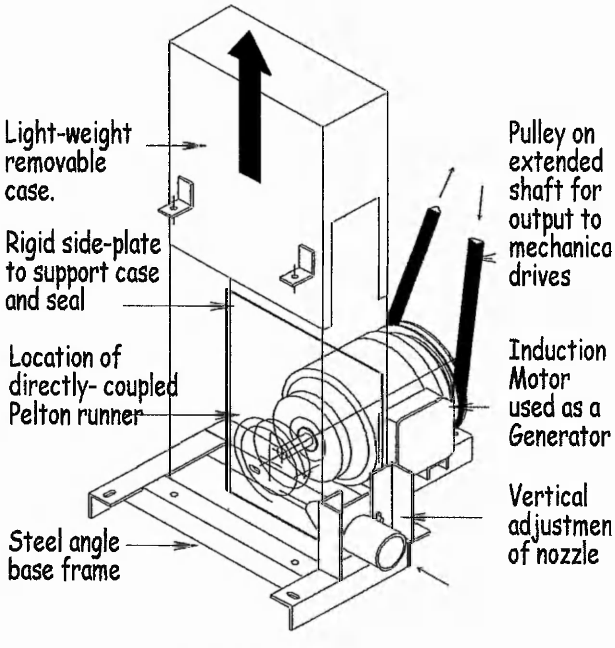


Figure 4-1 The Pico Power Pack

design would facilitate access for easier maintenance and repair, and could provide opportunities for mechanical power to be used.

A significant output of this research has been the design of a new turbine arrangement to increase the versatility and ease of maintenance. The key features are illustrated in Figure 4-1 and Figure 4-2. Inspiration for the design came from the Peltric set which is prevalent in Nepal, and a Colombian pico hydro unit that can provide mechanical shaft power to drive machines or connect to a DC alternator [Maher 2000b]. The design is characterised by the following new features:

1. Modified Pelton turbine design which accepts larger jet diameters

The development of Pelton buckets which maintain efficiency at high flow rates enable single jet designs to be used for a wider range of sites, simplifying the turbine, and reducing costs and maintenance.

2. Standardisation of Pelton turbine runner diameter to three sizes.

A key reason for the high cost per kilowatt of pico hydro systems is that customised designs, as used for larger schemes, are often applied. However, unlike larger schemes, a high degree of standardisation is required for pico hydro turbine units if they are to become cost-effective. This involves an element of compromise with the turbine efficiency, since the combination of diameter and induction generator speeds will be limited. Three sizes of Pelton turbine unit have been selected which cover the widest range of head and flow conditions and, when combined with induction generators of two, four or six poles, can be used for all pico sites of 25m head and above.

3. 'One-size-fits-all' steel case and frame

In order to repeat the success of the Peltric set in lowering the manufacturing cost, design for batch production was a recognized priority. The overall dimensions of the base frame and casing do not change for the three sizes of runner and for all sizes of generator used in the pico hydro range. Only the height at which the nozzle is fixed and the hole where the generator shaft enters the case must be altered for different generator frame sizes and runner diameters. These are detailed in a table in the manual. It was also recognized that for the new design of turbine to be adopted in developing countries, manufacture in rudimentary workshops where access to tools and materials often is more limited must be possible. Standard sizes of angle iron and mild steel sheet are the raw materials and the quantity is minimised to keep costs and weight low, thereby improving affordability and facilitating transport to remote sites.

4. Lightweight, removable casing.

The simplicity of a generator, mounted vertically on the turbine case, which characterises the Peltric Set, has the critical drawback that inspection of the runner is problematic without disconnecting the penstock. The new unit is designed with a lightweight case, folded from a simple pattern, which allows access to the turbine and nozzle for unblocking, realignment and repair.

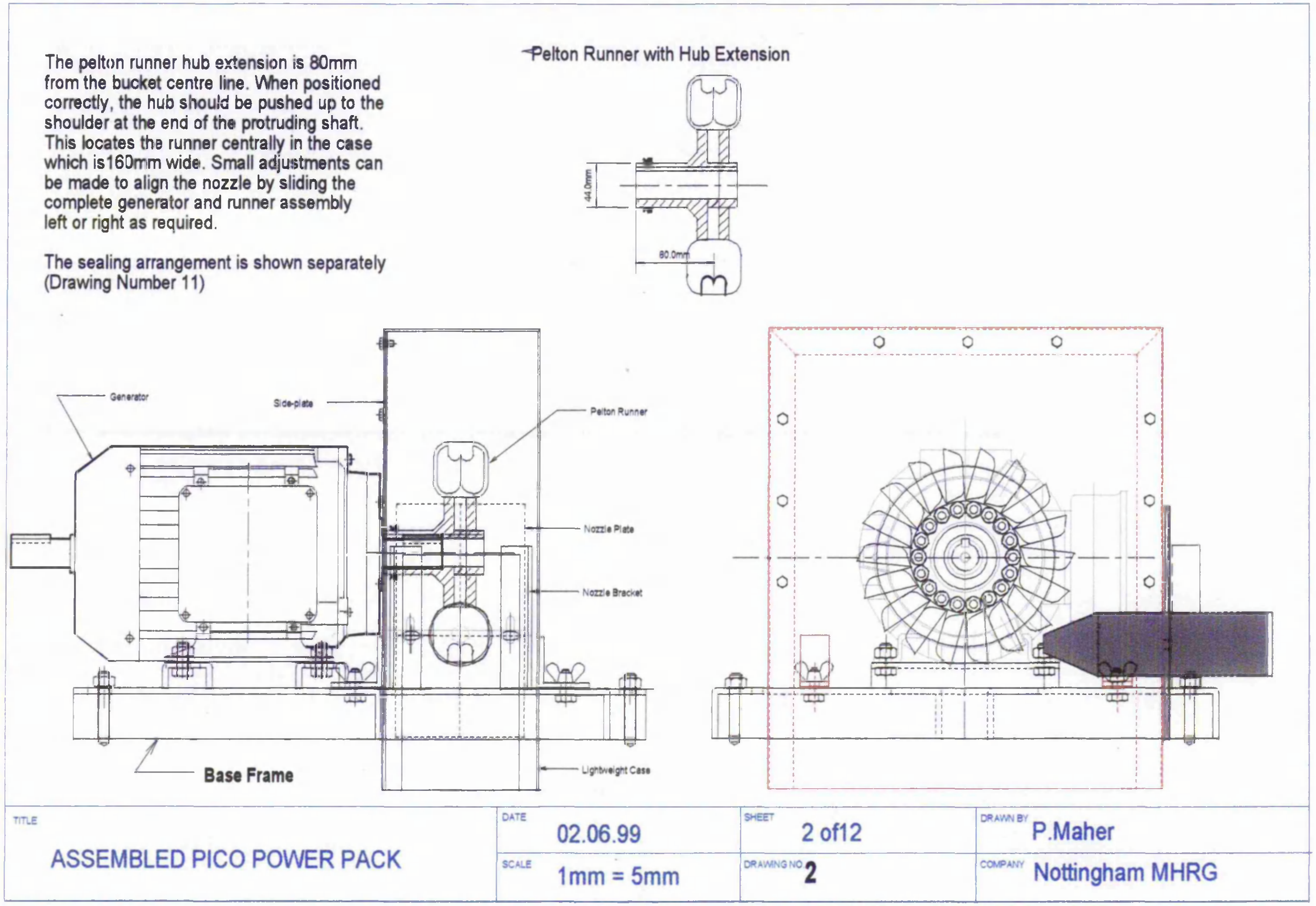
5. Horizontal and vertical nozzle adjustment.

The nozzle and runner can become misaligned during transportation or during attachment of the penstock pipe. Slotted generator mounting points allow alignment of the nozzle with the centre of the bucket splitter ridge. Laboratory turbine testing at NTU has also indicated that small, vertical adjustments of the nozzle, effectively fine-tuning the central point of jet and runner interaction, can improve performance. The theoretical optimum position changes slightly in practice with different nozzle diameters. Inconsistencies in runner manufacture also lead to small variations in the optimum p.c.d. (pitch circle diameter). Slotted mounting-points on the nozzle bracket allow vertical adjustment of the nozzle plate and fine-tuning of the effective runner p.c.d. at the site.

Conventional (larger scale) Pelton turbines have a single optimum p.c.d. and operate with nozzle diameters of up to 10%. The Pico Power Pack, on the other hand, has relatively large buckets and can operate with nozzle diameters at least 15% p.c.d. Optimisation of the nozzle position, in terms of the p.c.d., may take into account two variables, i.e. the available head and the nozzle diameter. There are two main loss mechanisms that are dependent on the vertical nozzle position [explained more fully in Thake 2000]. Firstly, there are losses due to water passing right through the bucket notch without interaction, which occurs if the nozzle is set at too large a p.c.d. Also, there are losses due to water leaving the buckets in a wide range of directions. These are greater if the nozzle is set at too small a p.c.d. For the Pico Power Pack, there is a range of p.c.d's in between these two outer limits over which good performance may be achieved. Within this range, it is possible to adjust the nozzle position to achieve the optimum jet velocity to bucket velocity ratio according to the available head at the turbine. The significance of the vertical adjustment is therefore not just to enable a good efficiency to be achieved, but also to enable the effective p.c.d. of the turbine to be adjusted to match a range of site heads. Each of the fixed diameters and speeds of turbine can be used for a small range of site heads, and allowance for this has been included in the software to assist with scheme design as explained in Section 6.6 (Page 89).

6. Provision of a free generator shaft.

There is high demand in rural areas for motive power, which enables the mechanisation of agricultural processes and reduces drudgery. This is well proven in Nepal where a large number of hydro systems are used for providing mechanical power only [Williams 1989]. A limitation with small generators is that problems arise with starting motors, particularly those driving high starting-torque loads such as grain mills. Mechanical drive of such loads is possible with a hydro turbine and this is a key advantage with the Colombian design since the alternator drive can be disconnected and the belt from the turbine shaft reconnected elsewhere. A simpler arrangement is a shaft extension, either provided by the motor manufacturer or retrofitted in a workshop. This enables both the generator and belt drive to remain connected. The additional benefit of this arrangement is that the generator acts as a brake, controlling the speed during mechanical processing. A free shaft provides a means of generating income during the daytime when lighting is unnecessary [Harvey 2000].



The pelton runner hub extension is 80mm from the bucket centre line. When positioned correctly, the hub should be pushed up to the shoulder at the end of the protruding shaft. This locates the runner centrally in the case which is160mm wide. Small adjustments can be made to align the nozzle by sliding the complete generator and runner assembly left or right as required.

The sealing arrangement is shown separately (Drawing Number 11)

TITLE ASSEMBLED PICO POWER PACK
DATE 02.06.99
SCALE 1mm = 5mm
SHEET 2 of12
DRAWING NO 2
DRAWN BY P.Maher
COMPANY Nottingham MHRG

Figure 4-2 Pico Power Pack assembly

4.3 The electrical system: safety and demand-side load management

Analysis of the electrical systems at the sample group of research sites revealed that all could benefit from new approaches to improve safety, reliability and performance.

4.3.1 Safety and protection

It is common practice for off-grid electrification systems not to have an earth connection except for at the generator. This was the case with at least half of the schemes visited in Nepal. Two further schemes had no earth at all and the earthing status of the remainder could not be determined (Appendix 10.1.6). Obtaining earth connections of sufficiently low impedance to allow the operation of protection devices, such as fuses and circuit breakers, in places where access to suitable earth-making and earth-testing equipment is limited, is very difficult [Mackay 1990]. However, connecting appliances to a common earth if the earth connection is not of sufficiently low impedance, presents even greater danger than having no earth at all, as one earth fault can make all metal cased appliances live, multiplying the risk of electric shock. The lack of a low impedance earth connection represents a significant safety compromise for rural consumers with off-grid electricity services. The turbine operator risks a potentially dangerous electric shock, as equipment in the powerhouse is invariably metal-cased. In addition, consumers have no shock protection should an earth fault in a metal-cased appliance develop. The use of non-insulated cable without adequate earthing for the distribution also presents a hazard, as poles often collapse due to damage from weather or termites.

Guidelines have been developed to protect consumers and equipment from earth faults on pico hydro schemes, without the need for low impedance earth connections. If an RCD (Residual Current Device) is connected, the supply will be disconnected should an earth fault cause a large enough current to flow to the ground. A correctly sized RCD will easily detect a fault current flowing through a low-cost earth connection or even someone touching a live wire. Low-cost earth connections, such as those observed during the research visits, can be achieved using galvanized pipe, coppers plates or coils of bare wire buried in the powerhouse foundations. An RCD with a tripping current of 30mA is sufficiently sensitive to protect people from a fatal shock, providing that the impedance of the earth connection is not greater than 1kΩ. This is generally easy to achieve without specialist equipment and can be obtained near to the powerhouse where the soil is usually damp. Ideally, each household should have their own RCD. However, to minimise cost on small schemes, a single

RCD in the powerhouse provides sufficient earth fault protection, although fault location may be more time consuming.

4.3.2 Lightning protection

Many areas that have good pico hydro potential periodically experience intense stormy weather and significant amounts of lightning. There is a risk of damage and injury from both direct lightning strikes on the distribution line and indirect strikes in the surrounding area. A number of the sites visited in Nepal had experienced problems with lightning. At one site the generator was being replaced after having caught fire during a storm. At another, more than 60 fluorescent bulbs had been permanently damaged during lightning strikes. Both situations resulted in considerable expense for the communities. At another site which was not visited, several members of the same family had been killed whilst asleep inside their house due to a direct strike on the distribution line. None of the schemes visited had any suitable lightning protection.

Both direct and indirect lightning strikes can be harmful to people and equipment. No equipment can provide full protection in the event of direct strikes. The most vulnerable part of a village electrification scheme is the distribution system. For this reason it is essential that the risk of direct strikes is reduced as much as possible by careful routing of the distribution cables. Recommendations have been made for as to how this should be done [Maher 2000a]. Whilst the voltages from an indirect strike are not as high as those from a direct strike, they are still dangerous, particularly for electronic equipment such as CFL's (Compact Fluorescent Lamps) and load controllers. Since voltages during indirect lightning strikes are induced both between live and neutral and neutral and earth, protection arrangements are required which can mitigate the effects in either case. Standard practice is to earth the neutral at regular intervals to allow dissipation of surge voltages and prevent the breakdown of insulation, which can occur in the event of an indirect strike. However, this is not possible if an RCD is connected. Recommendations have been made for the selection and installation of low-cost spark gap arrestors and varistors to minimise the risk of damage from indirect strikes. A path from neutral to ground can also be provided in this way, as shown in Figure 4-3. In addition to protection with lightning arrestors, the 'line-to-neutral' voltage surge can be reduced by twisting the cables together, if insulated conductors are used.

Varistors can protect more sensitive loads, as they have a lower breakdown voltage rating than lightning arrestors. They provide extra protection in the powerhouse (Figure 4-3) and for consumer loads (Figure 4-4). Several varistors connected in parallel allow greater current handling to reduce the voltage across the sensitive electronic components. Other measures, such as protection of equipment during storms through the use of double pole switches to isolate the distribution systems, have also been recommended.

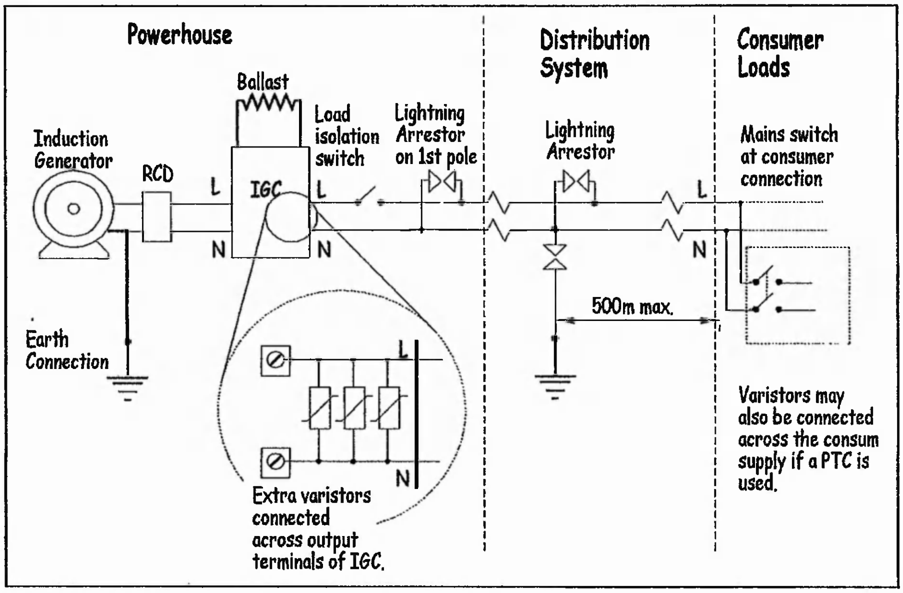


Figure 4-3 Connection of lightning arrestors and varistors prevent damage to electrical equipment and reduce danger to electricity consumers

4.3.3 Demand-side load management

The voltages measured at the majority of the sample sites in Nepal were well below the nominal level of 220V, indicating that the generators were overloaded (Table 4-1). Overloading is a common problem with off-grid electrification schemes. The power available from a limited off-grid supply where many consumers are connected will, at some point, become outstripped by increasing demand unless strict demand-side management is practiced.

Measured Voltage at Generator	Number of Schemes
< 180 V	4
180 - 209 V	4
210 - 230 V	2

Table 4-1 Generator voltage levels measured during field visits (Nepal)

Conventionally, consumers are charged for their electricity consumption by means of an electricity meter that records the number of kilowatt-hours drawn from the supply. This is not appropriate for pico hydro schemes, as it neither prevents overloading of the small generator nor encourages consumption of electricity during 'off-peak' periods such as during the night, when electricity is still available and often goes to waste. A better option is a limited current connection, where the consumers pay a fixed monthly fee that allows them to draw a current up to a prescribed limit on a continuous basis. The use of load limiters has been recommended for the following reasons:

- Load limiters are less expensive and more easily installed than electricity meters. Consumers cannot draw more power than they have subscribed to.
- Tariff collection is simplified as the amount is fixed each month.
- The total consumer load can be matched to the generator output. This means that the generator will not become overloaded and the system voltage and frequency will be maintained.
- Domestic wiring is automatically protected from high currents

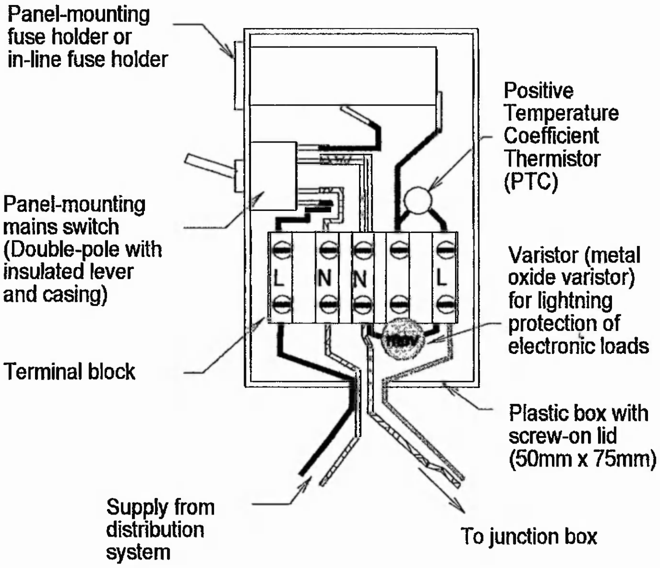


Figure 4-4 A suitable design of low current load limiter for a single household

Basic lighting requirements for most low-income households can be satisfied with less than 100W. However, the use of miniature circuit breakers (MCB) is not feasible since these are not available with tripping currents below 0.5 amps. An alternative design of low cost load limiter has been recommended, using a positive temperature coefficient thermistor (PTC) as the load-limiting device. A suitable design of low-current load limiter is shown in Figure 4-4. The PTC has a current level at or below which it is guaranteed not to trip. This is used to determine which PTC should limit a load of a particular size. The double-pole switch allows safe rewiring of domestic circuits and increases the ease of fault detection by allowing the domestic circuit to be easily isolated from the supply. With a single-pole switch, faults that caused the

RCD to trip would be difficult to isolate because the neutral would still be connected. A fuse must be connected in series with the switch in the live and sized to protect the PTC from high currents that could cause it to fail. Equipment wire fuses are suitable and are available in small current ratings. Fault currents on small induction generators are low, typically limited to approximately twice the rated current (e.g. 40A for a 5 kW generator). Mains rated fuses typically have a breakdown current of 6000 Amps, which is easily able to provide sufficient protection.

A suitable enclosure for the load limiter was found to be a 20 Amp 'water-heating' switch. These double pole switches have a fuse and fuse holder, as well as a neon lamp to indicate when the power is on. They are mass-produced, robust and easily adapted with the addition of a cable connector to connect the PTC and MOV housed in a patrass box. An identifiable label is also applied across the switch plate and patrass box to prevent unauthorised alteration such as rewiring or removal of the load-limiting PTC. This design was used very successfully on schemes in Kenya and Ethiopia.

4.3.4 Use of compact fluorescent lamps (CFL's)

The primary use of the electricity at all the schemes visited in Nepal was for domestic lighting. In all except one community, this was achieved exclusively with incandescent light bulbs. These are extremely inefficient as only about 10% of the energy used is converted to light, the rest being given off as heat. A scheme can quickly become overloaded as consumers realise that the light output increases when a 25W bulb is replaced with a 40W bulb. As the overloading increases, the supply voltage falls further. The cost of CFL's has fallen steadily over recent years and now these lamps are widely available for around US$3.50 or less. With adequate regulation of supply voltage and frequency, they have a lifetime between 5 and 10 times greater than incandescent bulbs and can give an equivalent light output, whilst using only 20% of the power. The use of CFLs enables the number of beneficiaries at one scheme to be increased substantially. This results in a major reduction in the per-household cost of a community scheme and markedly improves affordability, even in areas with very low income. The largest number of consumers at any of the schemes visited in Nepal was 30, at a scheme with a rated output of 3kW. A significant output of this research was to successfully demonstrate the exclusive use of CFL's on community schemes. A scheme is now installed in Kenya with a generator output of 1.1kW, but with 65 consumers, each with approximately the same level of benefit as the Nepal community i.e. one or two lamps and a radio socket. However, the use of CFLs and the resulting increase in the number of consumers at a scheme is only possible in association with appropriate voltage and frequency regulation, use of load-limiters and clear consumer agreements (see Section 4.5.5).

4.4 Optimization for lower cost per kilowatt

Optimization of scheme layouts and component selection enables the cost per kilowatt to be minimised whilst maintaining supply quality. Scope for optimization exists particularly with the penstock and the distribution system. These are the two elements where most flexibility of design exists and typically they account for around two thirds of the total scheme cost when a batch produced turbine is used. Unlike the turbine-generator unit, which has a relatively fixed price for a particular power rating, the cost of these elements can vary considerably from site to site, as illustrated in Figure 4-5.

Analysis of schemes in Nepal has shown that penstocks and distribution cables are often far from optimized, leading to excessive losses or over-sizing. This results from manufacturers having too little time to spend comparing different scheme design possibilities in an attempt to reduce costs and stay competitive. It also results from inaccurate survey data and, in some cases, poor understanding of the sensitivity of component sizing on system losses and cost per kilowatt.

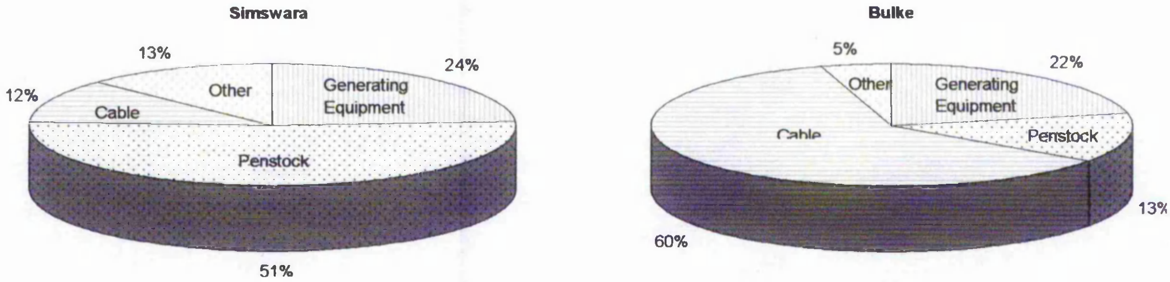


Figure 4-5 Cost breakdown of two pico hydro schemes in Nepal

Operating conditions at the sites described above were modelled in Excel spreadsheets from survey data collected during research visits (See Appendix 10.2). A large proportion of the scheme cost at Simswara (Scheme 2) is due to the penstock. Despite this, the head losses are unusually high, resulting in a net head of less than 30m for a 75m gross head. As a result the cost per kilowatt of 9000 $/kW is also very high (See Figure 3-3, P. 32). Selecting larger diameter pipe for the penstock would reduce the losses. If larger pipe is selected, the cost of the scheme would rise, but so would the power output. If the overall cost per kilowatt is reduced then the choice will have been beneficial.

Table 4-2 illustrates two possibilities for improving the existing penstock. The first is to replace the last 50m of pipe, which has a narrower diameter than the rest (38mm), with 50mm pipe. As indicated in Table 4-3, this would increase the costs only marginally but the net head would also increase, resulting in improved power output. The second solution is to use a larger diameter pipe for the whole penstock. The increase in cost would be approximately $400, but the cost per kilowatt would fall from nearly $9,000 to less than $4,300. It is also likely that the efficiency would improve, as the turbine would be operating much nearer to its design head of 54m. A more realistic turbine generator efficiency would therefore be 35%, which would give a power output of 810W and result in a cost per kilowatt of approximately $3000 (full data in Appendix 10.1.1).

	Diameter and length of pipe sections (m)			**Flow rate (l/s)**	**Gross head (m)**	**Net head (m)**	**Head loss (%)**	**Power (constant efficiency)**
Pipe dia.	38mm	50mm	63mm					
Existing pipe	50	550		3.19	75	29.1	61	225 W
Solution 1		600		3.41	75	33.6	55	280 W
Solution 2			600	4.34	75	54.4	27	579 W

Table 4-2 Optimization strategies for the penstock at Simswara (Scheme 2)

	Penstock cost (US$)	**Scheme cost (US$)**	**Cost per kilowatt (US$ / kW)**		
			@ 25% efficiency	**@ 35% efficiency**	**@ 45% efficiency**
Existing pipe	1048	2023	8991	6336	4934
Solution 1	1055	2030	7250	5165	4019
Solution 2	1465	2440	4214	3012	2342

Table 4-3 Costs per kilowatt at Simswara

At Bulke (Scheme 5), the distribution cable was over-sized. Modelling of the losses in the distribution system indicated that the maximum voltage drop, at design power output, was less than 5% of the generator voltage. By using thinner conductors, a 25% reduction in total scheme cost could be achieved without the voltage drop exceeding 10%. A maximum volt drop of 10% is acceptable if the generator voltage is set at 5% above the nominal voltage level (230V in Nepal), still enabling power to be supplied to every consumer in the system within acceptable limits of +/- 5% [Smith 2000a].

	Cable	Cost per coil ($)	Highest volt drop (design power output)	Highest volt drop (actual power output)	Power loss (design) W	Power loss (actual) W	Scheme cost per kilowatt
Existing system	7,18	38.30	4.71%	2.24%	54.14	9.93	4143
Optimized system	7,22	16.67	8.06%	3.89%	92.47	17.48	3090

Table 4-4 Optimization of the Distribution System at Bulke (Scheme 5).

The significant reduction to $3090 per kilowatt represents a saving of over $1000 per kilowatt. This takes into account the small additional power loss due to the higher cable resistance (full data in Appendix 10.1.2, 10.2.1, and 10.2.2).

4.5 Scheme sizing and community involvement

It has been demonstrated that rural electrification programs using pico hydro can be affordable even for poor rural communities if measures such as those described above are adopted [Maher 2003]. Assessing a community's willingness to pay for a particular level of service is crucial in order to find out if a scheme is financially viable and what minimum power output is required. Since electrification represents a major developmental step for a rural community, this assessment is complex because the desire to be connected may far outweigh the ability to pay and the results of the demand survey may therefore be misleading. Additionally, only providing electricity for those who can afford high connection charges can be extremely divisive, leading to great resentment amongst those who have been left out of the scheme [Brown 1995]. An important output of this research was the development of a method by which the demand could be realistically assessed, allowing an appropriately sized scheme to be specified. The method also allows households at all income levels to receive at least a basic level of service, providing that they live within an agreed distance from the generator.

4.5.1 Site survey

Firstly, a site survey must be carried out to establish the extent of the hydro resource and approximate number of households in the vicinity. This must be done, if at all possible, without unduly raising expectations and risking disappointment should the scheme not go ahead or not all households be able to be connected. Until recently, surveying of consumer numbers and location within a particular area was a painstaking process, particularly in areas where the majority of the housing is informal and no detailed maps exist. The use of Global Positioning Systems (GPS) for surveying of both hydro resource and consumer locations allows boundaries for the distribution system to be established quickly and efficiently. Satellites are used to triangulate a position and a three-dimensional bearing (longitude, latitude and altitude) can be stored which is accurate to within 10 metres. Since as many as 500 points can be stored in the memory of most GPS units, positional data for all the site features can be recorded. From this data, an accurate site plan can be constructed and the lengths of components, such as distribution cable and penstock, estimated for an accurate cost assessment.

4.5.2 Estimating the cost per connection

Once the extent of the resource and consumer numbers is known, demand assessment can begin. If the power could be provided at zero cost, then there would certainly be a high demand for every last watt. However, the cost of the power is an important factor affecting the demand and so it is often necessary to assume an 'average' cost per kW so that an estimate can be made. A typical average cost is $3000 per kilowatt. The use of load-limiters and 'light packages' allows the connection charge and monthly tariff to be established. A light package is an electricity supply that is sufficient for one lamp and a radio. By providing the electricity in light packages, the cost of the service can be easily compared to the benefit obtained. In addition, the poorest households have a chance of receiving a basic connection at low cost. If fluorescent lighting is used, a single light package may require just 15W. For example, if the scheme cost is $3000/kW and each light package is 15W, then the capital cost of one light package will be $45. This enables the electricity to be shared amongst many people even if the power available is only a few kilowatts. Load-limiters restrict the power depending on the number of light packages subscribed to. The consumer pays a fixed monthly fee per light package to cover expenses such as operator wages and maintenance costs.

4.5.3 Demand survey

Rough estimates can be made about the potential for electricity generation at the site from the head and flow measurements. The maximum number of houses that can be connected can be estimated using the power requirement per light package. Combining this with the GPS data about consumer positions, it is possible to work out the boundaries of the distribution based on an average number of light packages per house. The demand survey can then be conducted. It is necessary to obtain a firm commitment from each household within the boundary area as to how many light packages they wish to subscribe to so that the scheme can be sized. Providing that sufficient total funds exist to deliver the scheme and the total design power is not exceeded, small adjustments to the numbers of light packages subscribed to can be made at a later stage. It is beneficial in the long term to encourage all households within the boundary to join the scheme, thus promoting unity and community ownership. This can be done by allowing extra time for poor households to pay the connection fee or by reducing the cost of the first light package for everyone.

Before committing to a payment, many households will want to know how the light from one bulb compares with existing methods such as kerosene lanterns. Helping consumers to gauge the brightness of fluorescent lamps can be achieved by using an 'emergency light' with a pre-charged battery.

4.5.4 Financing the scheme

Financing of any infrastructural development in rural areas of developing countries is typically very difficult due to the lack of state funds and low income-levels. The high capital costs associated with rural power projects certainly make them no exception. However, the demand for electricity is such that large numbers of solar home systems are now sold in countries like Kenya, and many more households charge automotive batteries at very high cost per unit of power received [Maher 2003]. Pico hydro generators can provide a useful electricity service to a large number of households by dividing the total power available into light packages, as described above. The per-household cost is very low since a single scheme can be financed amongst many households. A fixed monthly tariff is charged for operation and maintenance depending on the number of packages to which a consumer has subscribed. If the local capital is insufficient, a scheme can also be financed through a bank loan. In this case the tariff contains a proportion of the loan repayment, which is again fixed, per light package. An alternative method of financing which may be appropriate in some areas is part-financing of the equipment by the installer or manufacturer. The turbine-generator unit continues to belong to the manufacturer until the final payment is made. As a deterrent against non-payment, the unit may be de-commissioned and removed if the final installments are not received within an agreed time period. This model has worked on a limited scale for one manufacturer in Colombia [Gnecco 2000].

4.5.5 Consumer agreements

Since the success of a community project depends on a large number of individuals, it is necessary to avoid disputes during the installation and subsequent management of the scheme. The terms need to be decided on and agreed in advance to enable smooth implementation. It is important to clarify exactly what benefit the consumers will receive and at what cost and level of labour contribution. The key points of the consumer agreement are as follows:

- What a light package is and the implications of a limited electricity supply (e.g. which appliances can and cannot be connected if a socket for an electric plug is provided).
- The costs per light package (connection charge, cost of house wiring, monthly tariff) and how the monthly tariff will change with time.
- If the electricity will be provided between particular times of the day (e.g. 4pm to 11pm) then this should be stated. During the dry season the times may vary due to reduced availability of water.
- The labour contribution required for construction of the powerhouse, penstock, intake and distribution poles.
- Penalties for illegal connections or non-payment of tariff.
- Compensation for the owner(s) of the land on which the scheme is constructed (e.g. provision of a free light package).

4.6 Summary

Clear advice regarding good implementation practice is required to ensure that all pico hydro developers, regardless of their experience or education, have the means to install consistently reliable and safe schemes, which achieve power outputs comparable with the initial estimates. Examples of good practice observed during field visits have been combined with the new approaches developed through this research into a ‘how-to’ manual for new and existing developers of pico hydro systems [Maher 2000a]. It attempts to provide commonsense approaches to all aspects of scheme planning and implementation. Since the target readership is primarily non-native English speaking, extra lengths were taken to ensure that the methodology is clearly explained and illustrated with a large number of figures and ‘look-up’ tables.

All fabrication details for the new design of turbine and generator unit, the Pico Power Pack, have also been made available in an illustrated guide [Maher 2000b]. The design has subsequently been manufactured and installed in several countries including Nepal, Kenya [Maher 2002a, b], Ethiopia and Nicaragua [Leaf 2003]. The manufacturers in Nepal and Nicaragua have experience of other designs and therefore adoption of the Pico Power Pack is thought to be a good endorsement of the design.

The first drafts of the manuals were used as the basis for a series of training courses. Manufacturers and developers from a total of 17 developing countries attended the courses, which were held in Kenya, Nepal and Peru during 2001. Feedback on the new approaches obtained during the courses was very constructive and enabled further refinements to be made. A version also has now also been written in Spanish, translated by one of the course participants in Peru.

The implementation manual and the accompanying manufacturing and end-uses booklets are available for downloading as a series of p.d.f. files from the research web-site [http://eee.ntu.ac.uk/research/microhydro/picosite]. This has enabled access to a very wide readership. Since being made available, people in more than 40 developing countries have downloaded them and the download page is currently scoring between 200 and 300 new 'hits' a month.

5 COMPUTER TOOLS FOR SCHEME DESIGN – EXISTING METHODS

5.1 Rationale for using computer tools

The multi-disciplinary nature of hydropower projects increases the engineering expertise and time required for well-designed installations. This is cost-effective for larger grid-connected systems but not for pico hydro. As a result, corners are often cut at the survey and design stage in an attempt to reduce costs and enable developers to achieve a sufficient turnover of systems. This can also cause the quality of installations to suffer, as research in Nepal has indicated. In order to improve the consistency with which schemes of this size are designed and implemented, innovative approaches to managing survey data and component selection are required.

Computers are extremely useful for data storage and retrieval, as well as performing numerous design iterations. Software capable of providing a suitable design and listing the required components could play an important part in improving the quality of schemes. The developer would then have an informed basis on which to make purchasing decisions. Furthermore, the cost per kilowatt could be reduced through careful component selection and accurate matching of equipment for site conditions. Feasibility studies could be completed more quickly and more accurate and detailed customer feedback provided. Records of sites and scheme designs would, additionally, be available for future reference.

5.2 Application of existing software to community pico hydro

A review has been conducted of potentially useful software for the feasibility assessment and design of small hydro projects. Two programs described (TURBNPRO and HydrA) are commercial developments. The rest can be downloaded free of charge and either result from government programs to promote the use of renewable energy sources (ViPOR, RETScreen), or efforts to encourage DIY developers (PC-Hydro) and, in one case, additionally promote sales of company turbines (JLA software). Alongside these, an example of a program developed through academic research with the aim of improving micro hydro implementation in developing countries (MICADO), has also been reviewed.

A brief description of each program has been given, outlining the format and general scope and then an assessment has been made of the level of application possible to pico hydro projects. The first three programs (MICADO, PC-Hydro, JLA) were developed using MSDOS based formats which have now been superseded by MS Windows. However, they illustrate that the potential of computers to assist with the planning of small hydroelectric projects was recognised long before the widespread use of computer technology.

5.2.1 MICADO [Anderson 1993]

This program was written in PASCAL as part of a Ph.D. study in 1992. MICADO attempts to encompass all aspects of micro hydro scheme design, provide engineering analysis and assess economic feasibility for manufacturers and developers. The aim was to help standardize approaches to micro hydro implementation, particularly in Nepal where the software was targeted and tested. It was designed to overcome three principle reasons for the high incidence of scheme failures:

1) Faulty and sub-optimal design
2) Inefficient installation and operation procedure
3) Poor or non-existent maintenance routines, identified by Anderson [1989, P189].

The program adopts a modular structure and guides the user through aspects of the design process in the following areas:

- Hydrological resource assessment
- Demand assessment
- Scheme layout selection
- Specification of civil works
- Electro-mechanical equipment selection
- Transmission / distribution network specification
- Economic viability assessment

The program was also designed to store scheme data files and provide maintenance records to enable the developer to keep an accurate log of installed schemes and specify equipment for maintenance and repair. The format consists of a series of questions that requiring a multiple-choice type selection (e.g. material for canal lining) or a numerical answer (e.g. cost and specification of penstock pipe).

Application to Pico Hydro

The program was an ambitious undertaking, attempting to encompass all aspects of micro hydro scheme design into the highly limited user interface techniques available at the time. More specialized tools are possible for pico hydro since the range of suitable equipment is more limited, and design decisions restricted by standard component sizes.

Certain aspects of the program have greater relevance to higher-budget projects, and are unlikely to be useful for the pico hydro developer. For example, a significant section of the program is given to hydrological resource assessment. Little long-term information is available for many pico hydro sites and emphasis is often placed on dry season flows and local knowledge rather than flow duration data from gauged rivers. Additionally, detailed design of canals and settling tanks is rarely required for pico hydro. Irrigation canals are often used to enable penstock lengths to be reduced. These are within the capabilities of local people and rarely require much engineering design time as they are often hand-made and earth-lined.

MICADO allows penstock losses to be calculated and compared with a user-defined percentage design head loss through entry of pipe diameter and material, number of joints and dimensions of bends. Losses due to bends and joints have little impact on the overall power output with medium and high head pico hydro and can therefore be ignored to simplify the design process. Often, HDPE pipes are available in suitable sizes. These can be purchased in long lengths, which reduces the number of joints and are flexible so elbows are not required.

Under the turbine specification program section the user inputs all data, including efficiency and anticipated load demand, for comparison with the hydro potential. Suitable turbines are listed from which the user makes a selection. This can be simplified for pico hydro as fewer designs are cost-effective and the range of sizes required is more limited. Peltons, crossflows, pumps-as-turbines and propeller turbines are generally the types used. Guidance with selection of turbine and generator combinations from those available locally for a given head, and calculations of power estimates using predicted efficiency data would be highly beneficial.

Generator specification in MICADO recommends de-rating levels according to altitude, although this is rarely an important consideration for pico hydro generators even in Nepal as induction motors selected as generators should be additionally de-rated by around 20% in any case and are usually even further oversized. In addition, the reduced ambient temperature at higher altitudes compensates to some extent for thinner air [Smith 1995].

In the distribution section, cable sag is calculated using a multiplying factor from user-inputs of estimated line length. The program prompts the user that a transformer is required if transmission distances are over 1km. Losses can be calculated for each conductor length and for different conductor types but inductive losses are ignored. This could be simpler for pico hydro schemes, since transformers and three-phase systems are rarely cost-effective. Using insulated conductors twisted in pairs incurs negligible inductive losses, as the gap between the line and neutral is small. Since branches in the distribution system are dealt with individually, the user must calculate the line currents at the branching point and accurately sum the voltage drops and the costs for each part of the system.

Overall, MICADO was a thorough attempt at addressing issues relating to scheme design and useful as a training tool for users new to micro hydro. However, existing developers and manufacturers found the large number of decision making and data entry screens too time-consuming [Anderson 1992]. For experienced developers, the application of computer technology is most useful at particular points in the design process where a number of options can be evaluated to improve the cost per kilowatt.

No results were available as to what degree MICADO was able to support the design or installation of micro hydro projects since, as Anderson [1993 p199] states, it is usual for a period of 3 to 5 years to elapse between survey and commissioning. Pico hydro schemes however, due to their lower capital cost and shorter installation time, can be commissioned considerably faster.

5.2.2 PC-Hydro V3.1 1991 [Carson Electronics 1991]

This early shareware program by Carson Electronics in Canada, consists of an array of cells in a similar format to a spreadsheet. The cells correspond to various system parameters given in imperial units. Once all required values have been entered, one value can be changed and others are automatically recalculated. In addition to providing details about the anticipated power output, turbine speeds and pulley sizes can also be calculated. This program demonstrates the extent to which modifying one element can effect the rest of the system and underlines the difficulties encountered by the developer when comparing a variety of designs in order to make an objective evaluation without the use of computer tools.

Application to Pico Hydro

The program is useful for calculation of hydro potential and sizing mechanical components although the format has now been superseded by spreadsheets. The ability to recalculate and display all other parameters when one is changed is useful for rapid comparison of layout options. Uptake would be limited since metric units are not used. Selection of the best design in terms of cost per kilowatt is not possible since the cost of components is not featured.

5.2.3 JLA Software [WILLOT 1998]

This is an MS DOS based program that performs specific calculations relating to micro hydro schemes. It was written by a turbine manufacturer to promote micro hydro and their own turbine design. The user is able to select from the following program functions:

- Flow calculation based on entered values for a measurement weir
- Slope calculations for a trapezoidal channel
- Diameter for a penstock with a specified head loss
- Voltage drop in a transmission cable
- Turbine selection from the JLA series given particular site conditions

Application to Pico Hydro

The program has a straightforward menu system interface with user language options of English, French or Spanish. It could be used to help design part of a system despite heavy reliance on the user to evaluate solutions to calculations and the presence of bugs gives rise to errors. For penstock design, the diameter of pipe is calculated for a particular head loss. However, custom-made pipes are not suitable for pico hydro which relies, as far as possible, on mass-produced components to minimise costs. The user must still be able to assess what effect a different head loss will have on the turbine output and will not be able to use the program for comparison of different penstock designs. The program is therefore of very limited use, as the cost of components is not taken into consideration.

5.2.4 Small Hydro Project Model [RETScreen International 2000]

The RETScreen International Renewable Energy Decision Support Centre in Canada, analyses the technical and financial viability of energy projects in order to promote the use of renewables. The Small Hydro Project Model is designed to evaluate energy production, life-cycle costs and greenhouse gas emissions reduction for grid-connected and grid-isolated small hydro projects. Version 2000 additionally includes product, cost and hydrology databases, an online manual and a training course.

Application to pico hydro

This spreadsheet-based program is principally concerned with the viability of grid-connected systems and the focus lies on feasibility assessment rather than optimising scheme design. Scope for use with pico hydro is further limited since sufficient flow data, required for estimating the feasibility of small hydro schemes where return on investment depends on estimates of annual energy capture, are not available for the vast majority of pico hydro sites especially in developing countries. Many suitable pico hydro sites have very small flows and are in areas where detailed rainfall and flow gauging data are not collected.

5.2.5 TURBNPRO [http://www.turbnpro.com/]

TURBNPRO selects a suitable turbine design for the given site details. Typical performance and dimensional characteristics of the hydro-turbine size and type are calculated based on available head and flow, as well as estimates given of likely power output. Advantages, disadvantages and limitations of the various hydro-turbine configurations and arrangements are discussed. The user can input performance data for additional turbines if available and these can be included in the evaluation. This software is available to purchase at US$ 695.00.

Application to Pico Hydro:

This is a useful program for selecting suitable turbine and generator designs for a new site, particularly for inexperienced hydro developers. In addition to approximate specification, diagrams are displayed which give some suggestions for installation layouts for hydro schemes of any size. The application for developers exclusively of pico hydro systems is more limited. Firstly, because selection of particular turbine-generator combinations does not guarantee local availability and secondly, because pico hydro systems are usually only cost-effective when the turbine-generator design is highly standardized. It is therefore very likely that the bespoke turbine-generator selections would not be viable for most developing country applications. Performance data for small direct-drive designs would need to be exclusively entered by the user, assuming it was available. Furthermore, the price makes this software prohibitive for some developers.

5.2.6 HydrA [Institute of Hydrology 1996]

HydrA is a resource assessment tool for small hydro projects. It contains average rainfall and evaporation data per square kilometer, which is then used to estimate rainfall run-off for a given catchment area defined by the user through Ordnance Survey grid references. Different country-specific versions of the package are available, although until recently only for those where comprehensive rainfall and vegetation data was readily available. Now a version for Nepal has been added, and other countries with good small hydro potential are likely to be included in the future. Flow duration curves are plotted and annual energy capture can be estimated for different turbine-generator combinations. The results for catchment analysis, flow data, and power estimates are summarised into report pages which can be copied easily into other documents, thereby helping to speed up feasibility studies. Hydra UK is available to purchase for around US$600. The flow data predicted with HydrA UK for given catchments has been compared with gauging station data provided by the Environment Agency and found to be within 10% of the measured conditions. Some error is expected depending on the local geology, particularly with catchments that have a high spring-fed contribution.

Application to Pico Hydro

The major limitation of this package for application in developing countries is the rainfall data on which it relies. This data is not yet available in many countries with good pico hydro potential. A further constraint is the availability of good quality topographical maps on which to plot the catchment area of new sites. It is therefore likely in the majority of cases that flow measurements will need to be taken directly for some lower head sites where the flow duration is uncertain, as the accuracy of flow prediction will be highly variable. Higher head pico hydro requires only small flows, which are often spring sources. These cannot be accurately plotted with HydrA and flow duration analysis is rarely necessary since the schemes are designed for operation under constant flow conditions.

Estimates of energy capture per year, useful for potential grid-connected small hydro projects, are rarely sought for pico hydro schemes where cost per kilowatt, reliability and ease of installation are generally more important criteria when assessing viability. However, tools such as HydrA may begin to play an important part for site assessment in developing countries as access to accurate meteorological data and information technology increases. This is particularly the case for grid-connected systems, which are generally designed to maximise energy capture.

5.2.7 HOMER and ViPOR [NREL 2003]

The main function of HOMER (Hybrid Optimization Model for Electric Renewables) is to provide a means of comparing methods of electrification given cost and resource data of different options. The solutions, which may be hybrids of different systems, are ranked in order of the relative cost of energy in $/kWh. Sensitivity analysis can be performed by modifying the various input parameters and noting the effect on the cost of energy. In order to model the costs of a particular technology, a variety of cost data relating to the source is required. If sufficient cost data exists, then a satisfactory model can be created with an appropriate 'cost curve' associated with it, allowing comparison of different sources and different power outputs. Models for gensets, solar home systems and stand-alone wind turbines can be created quite successfully as the technology can be scaled up to take advantage of a particular resource. Similar modelling of hydropower generators and production of accompanying cost curves is more complex due to the variation of hydropower resource limits between different sites. However, if sufficient cost data exists, production of a suitable power source to represent a pico hydro power station is possible. This can then be loaded into ViPOR.

ViPOR (Village Power Optimization Models for Renewables) is an optimization tool that allows layouts and cost of distribution systems to be compared. Using information about load positions, size and equipment costs, ViPOR decides which houses should be powered by isolated power systems (like solar home systems) and which should be included in a centralized distribution grid. Cleverly, the distribution grid can be designed with consideration to the local terrain by the designation of different terrain areas, each with their own user-defined cost multipliers. An optimization algorithm called *simulated annealing* is used to design the least-cost system. Simulated annealing works by repeatedly making random changes to a system, allowing it to evolve towards the optimum. Any change that results in a lower total cost, called a downhill move, is accepted and the system is allowed to continue to evolve from that point. Some changes that result in a higher total cost, called uphill moves, are also accepted during the early stages, but as the process continues, it becomes less and less tolerant of uphill moves. It is this feature of the algorithm that allows it to search out the global optimum without getting caught in local optima.

Application to Pico hydro

Using HOMER to compare various technologies and rank them in terms of the energy cost is of less importance to consumers who live near suitable pico hydro sites. It has been demonstrated that the per-household energy cost of a properly implemented pico hydro system should be several times lower than that of any other available technology [Maher 2002]. ViPOR has the following applications for pico hydro scheme design:

- The optimum layout for a distribution system containing scattered consumers can be identified taking into account terrain variations affecting installation costs.
- Various generator positions can be specified and comparison made between the cable lengths required.

The ability to identify optimum layout patterns is clearly advantageous for mini-grid design. The principle limitations are that only one low voltage line type can be specified, and that voltage drops are not a design parameter but only maximum line length. This indicates that further analysis is required in order to identify the minimum cost for a particular scheme. This is important at the feasibility stage, since modifying the cable sizes to allow a larger volt drop can have a significant effect on the cost per kilowatt and hence the financial viability of schemes for low income consumers.

5.2.8 GPS Utility [Murphy 2003]

This program allows coordinates stored on a GPS unit to be downloaded to a personal computer. A map can be drawn and text files of co-ordinates can be created. A free evaluation copy, with certain limitations, is available for downloading from the Internet. To obtain the full version, registration is required which costs 25 UK pounds.

Application to Pico Hydro

This program helps to reduce the time needed to process survey data collected in the field. Without GPS Utility, each 'waypoint' stored in the GPS memory during survey of consumer loads must be hand-typed into a spreadsheet. This can become tedious and error prone. The principle drawback with the evaluation copy when downloading scheme data is that the number of waypoints, and hence consumer points, is limited to 100 per file.

5.2.9 Summary of software review

The review of the software packages has been summarised in Table 5-1.

	Availability	Operating environment	Focus	Optimization algorithm used	Can be used selectively for scheme design	Application to p. hydro. (*** = highly applicable)
MICADO	Limited	MS DOS	Whole scheme design and costing	No	No	*
PC-Hydro	Free	MS DOS	Allows sizing of mechanical components	No	No	*
JLA	Free	MS DOS	Whole scheme design	No	Yes	*
TURBNPRO	$695	Windows dedicated program	Turbine design	No	Yes	**
RETScreen	Free	Windows (Excel-based)	Small hydro financial feasibility	No	No	*
HydrA	$600	Windows dedicated program	Resource and energy capture assessment	N/A	no	*
HOMER and ViPOR	Free	Windows dedicated program	Distribution layout and costing	Yes	Yes	***
GPSU 4.03	Free	Windows dedicated program	Automatic downloading of GPS co-ordinates from Garmin12 GPS unit.	N/A	N/A	***

Table 5-1 Summary of key attributes of reviewed software

5.3 Software utilisation

The review in the previous section focused on a broad range of software, some of which have recently become available and others that rely on outdated programming techniques.

To produce the required specification for an ideal pico hydro software, the pre-installation phases of a pico hydro scheme have been divided into three broad stages: site survey, technical design and financial feasibility. Methods of applying computers are described in Table 5-2 and reference has been made to existing software if use of these can prevent duplication.

Development stage	Constituent parts	Methods of application	Achieved by which software?
Site survey	Head measurement	GPS co-ordinates of penstock route, with head measurements at several points, can be used to find length of pipe needed at each available pressure rating.	**GPS Utility** for downloading GPS co-ordinates
	Flow measurement	Flow rate calculations with salt gulp measurements can be vastly simplified.	**MS Excel** for analysis of salt gulp.
	Position of loads	GPS co-ordinates of consumer positions stored for analysis	**GPS Utility** for downloading GPS co-ordinates
	Demand survey	Storage of load data with co-ordinate points.	**GPS Utility** for downloading GPS co-ordinates
Technical design	Civil works	Rapid design of penstocks using available pipes and channel dimensions	**Not achieved** for pipe combinations
	Turbine-generator combinations	Using details of head and flow, the most appropriate combinations can be selected from available equipment. Power output prediction possible if manufacturers performance data is available.	**TURBNPRO** for some systems but **not achieved** for direct drive and standardized turbine units
	Distribution system layout	Finding the shortest route to connect up all the loads using an optimization algorithm	Can be achieved and modelled by **ViPOR**
	Distribution system cable sizing	Optimization of cable sizes by allowing voltage to drop within regulatory guidelines.	**Not achieved** for more than one cable with one load.
Financial feasibility	Comparison of capital cost with power output or revenue.	Rapid assessment of viability using optimized technical designs giving cost per kW and cost per household for developer evaluation.	Cost assessment with optimized components **not achieved.**

Table 5-2 Software utilization in stages of pico hydro scheme development

At present, elements of the existing programs can be of some use to a scheme developer. However, there is still scope for significant improvement of planning methods. Computer tools can additionally be used to store details of locally available components, interpret site survey data and produce designs for optimized schemes based on selection of the most appropriate equipment. Exactly how this can be achieved, with a combination of new and existing software, is explored in the remainder of the thesis.

5.4 Summary

5.4.1 Turbine-generator selection

TURBNPRO provides broad turbine selection advice but assumes a considerable degree of bespoke design, which is not cost-effective for pico hydro. An appropriate pico hydro turbine-generator combination can be selected for a given site from a limited number of design permutations. Small efficiency penalties are admissible to reduce costs and enable selection from a finite range of off-the-shelf systems. Turbines suitable for pico hydro (e.g. Pelton runners, pumps-as-turbines and propellers) are usually available in a strictly limited range of sizes and most use directly coupled induction motors as generators which fixes the approximate speed for a given frequency. A calculation of power output that takes into account the turbine efficiency would be useful, providing that suitable turbine data could be obtained. This could then be used to accurately assess the magnitude of loads or extent of distribution system that could be supplied.

5.4.2 Penstock design

Most penstocks on schemes installed to date have uniform diameter and wall thickness. Modifying the pressure rating and diameter at different points to reduce the pipe cost and give the most appropriate head loss for the selected turbine, can result in considerable cost saving and improved performance. A computer program could select the most appropriate pipes from a list if sufficient turbine and site data was available.

5.4.3 Distribution cable sizing

Once a distribution layout has been designed using a program such as ViPOR, cable lengths between nodes need to be identified so that cable diameters can be calculated. A program that stores the relationship between spurs and branches, so the volt drops are correctly calculated throughout the system, would significantly improve the ability to find an optimum solution. What is ideally required is a graphical interface to help optimize the cable layout based on generator and load locations. Automatic selection of optimum cable combinations to provide a supply within specified limits would be particularly useful as a planning tool for isolated community schemes and increase the likelihood of this level of planning taking place.

6 COMPUTER TOOLS FOR SCHEME DESIGN – NEW APPROACHES

This chapter describes the development of further computer-assisted methods for improved scheme design, which have been developed during the course of the research.

6.1 Pico hydro mini-grid design using GPS Utility and ViPOR

As outlined in Table 5-2, using a combination of GPS equipment and freely available software, it is possible to optimize a network layout for connection of rural consumers more rapidly and accurately than would previously have been possible. The method developed is described below in order to demonstrate the advantages over manual techniques.

Step 1 Collection of location data using Global Positioning Systems

During a survey of the site, the proposed generator location and the positions of all consumers within a pre-determined radius are stored as waypoints. Waypoints are positional markers with particular co-ordinate dimensions and identifying references. These are conventionally used for marking new routes so that steps can easily be retraced.

Step 2 Download data to computer

The GPS unit is connected to a computer using a serial cable and the points are downloaded using software such as GPS Utility described in Section 5.2.8. Once the points have been downloaded, the co-ordinate format can easily be changed using GPS Utility. In order to minimise the reformatting required for use by other software, it is recommended that the data format be changed to the Universal Transverse Mercator (UTM) co-ordinate system. In UTM, a location is described by an X-coordinate called an Easting, a Y-coordinate called a Northing, a zone number, and a hemisphere (North or South). The main advantage of this format is that no additional syntax (i.e. degree or minute symbols) is used, a fact which enables direct uploading of the co-ordinates for layout modelling in ViPOR. This program will not recognise the co-ordinate data if syntax is present. When the appropriate format has been selected, a new text file containing the data is saved in GPS Utility.

Step 3 Export data to ViPOR

Before the GPS data, now stored as a text file, can be opened in ViPOR for layout modelling, removal of unnecessary text is required as this cannot be uploaded into

ViPOR. Unwanted text can be removed with MS Excel. The format of the remaining data should be as follows:

Index	Easting	Northing	Load type (user defined in ViPOR)	Description or reference.
0	310041.0	9948468.0	0	House24
1	310064.0	9948497.0	0	House25
2	310038.0	9948554.0	1	School1

Table 6-1 Expected format for UTM co-ordinate data in ViPOR

Step 4 Plot optimal cable layout

Load types (e.g. house, workshop, school) can be predefined in ViPOR thus allowing the user to differentiate the power requirements. Relevant cost data is entered into ViPOR and then the optimization algorithm is used to connect all the loads to the generation point using the most cost-effective route. An example of a village layout, designed by ViPOR, is shown in Figure 6-1 (left).

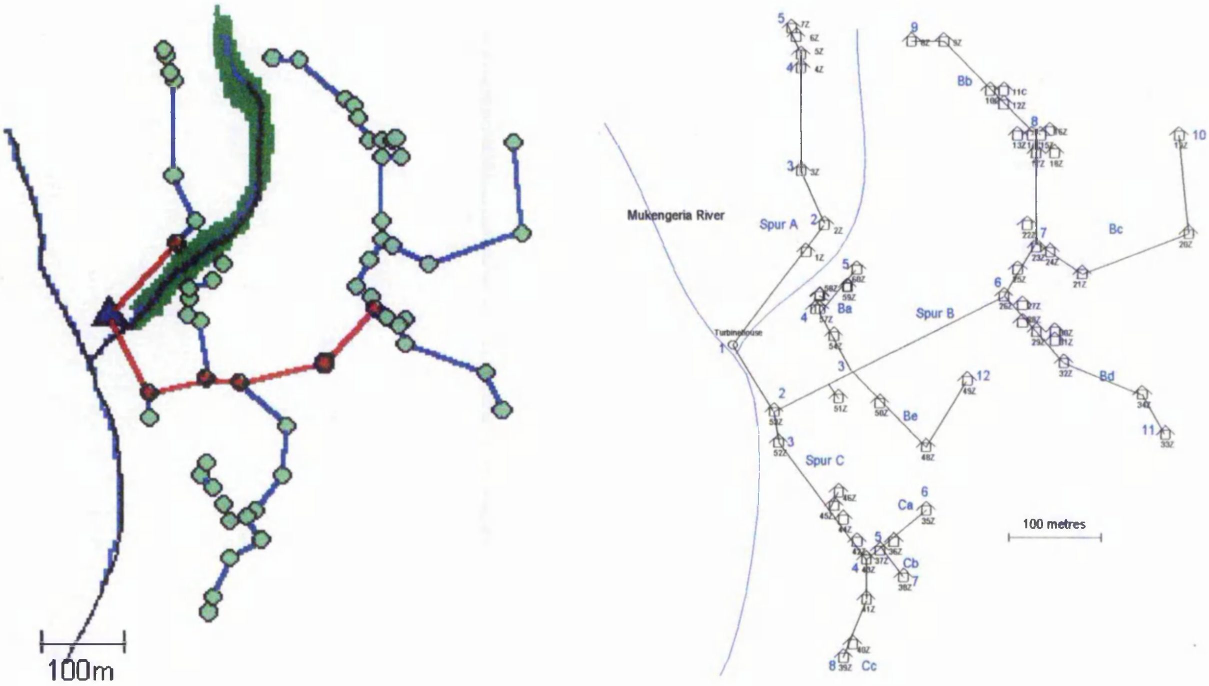


Figure 6-1 Kathamba distribution system designed using ViPOR (left) and layout installed which was drawn intuitively (right)

ViPOR can dissuaded from crossing areas of difficult terrain, such as the steep valley along the stream, by defining terrain types (shaded blue for water and green for valley) with high cost multipliers. It is assumed that all the loads are equal. A scale drawing produced using CAD with a cable layout drawn intuitively is also illustrated in Figure 6-1 (right).

	New method	**Previous method**
Collecting positional data	3 hours using GPS	3 hours using GPS
Creating site map	15 minutes	3 hours
Designing layout	1 minute	30 minutes
Length of cable used	4,864m	5,000m

Table 6-2 Comparisons of layout design methods. 'New method' designed using GPS Utility and ViPOR and 'Previous method' drawn intuitively using CAD.

This distribution system was installed at a village in Kenya to connect a 1.1 kW pico hydro generator to 65 consumer houses (see case study in Appendix 10). The two methods of creating the layout design have been compared in Table 6-2. The time taken to collect positional data is identical in both examples, since a GPS unit was used, hence the very close correlation of consumer positions in both layouts. From experience at other sites, the time taken to collect much less accurate positional data by hand measurement would have been 12 to16 hours for a scheme of this size. Creation of the site map and layout according to the new method assumes the use of GPS Utility and ViPOR. The previous method consisted of entering the bearing and length associated with each point separately into a scale drawing using CAD, and the layout was drawn by trial and error to find the shortest practical solution. The comparison indicates a close correlation in the lengths of cable used and therefore inspires confidence in the optimization technique of simulated annealing employed by ViPOR. The time taken to complete the layout was substantially reduced in addition to a modest reduction in the length of cable required. More complex distribution systems would benefit to a greater degree.

Step 5 Add node references

Node references are added to the layout so that each cable section can be identified independently. A valuable function of the GPS unit is its ability to determine the distance and bearing of one stored waypoint from another, either held in the memory or entered by hand. This enables the length of cable required between two nodes to be established. The lengths required can also be estimated from the GPS layouts as these are drawn to scale.

Step 6 Size cables

Distribution cable sizes can now be selected to connect all points in the layout and voltage drops calculated. Where the voltage drops are too high or too low at the extremities of the system, cable diameters must be reselected. Spreadsheets have been developed which allow modelling of the voltage drops to enable optimum cable sizing (Section 6.2. 2).

6.2 Use of MS Excel to address gaps in the design process

Attempts at introducing computer programs to assist with micro hydro scheme design ten years or more ago, met with limited success [Anderson 1992] because the programs tended to be difficult to use and at that time few small manufacturers owned computers. Nowadays however, most manufacturers have computers and many are also familiar with spreadsheet programs for bookkeeping purposes. Spreadsheets can be a useful first step towards making rapid appraisals of design choices and improving component selection. Two spreadsheet models have been developed during the research to facilitate improved penstock design and distribution cable selection.

6.2.1 Spreadsheet model for penstock design: SELECT_PIPE

This spreadsheet is divided into four parts:
Sheet 1: Introduction to penstock design and user guide.
Sheet 2: User defined pipe specifications and prices.
Sheet 3: Worked example.
Sheet 4: User template to be copied for each new scheme.

SELECT_PIPE enables design of a penstock that is user-optimized for diameter, pressure rating and cost. The user enters the key site parameters: gross head, penstock length, and design flow. Three design stages are successively applied to allow a refinement of the solution. During first stage the smallest penstock diameter of sufficient pressure rating which gives an acceptable head loss is selected from a list of locally available pipes. The acceptable range of head loss is from 5% to 33% of the gross head as explained in Section 3.3.3. The second design stage is to successively reduce the pressure rating of pipe sections towards the intake (whilst holding the nominal diameter constant) in as many steps as pipe availability will allow. This lowers both the cost and the overall head loss as pipes of lower pressuring rating have reduced wall thickness. The final stage is to vary the pipe diameter of each section with different pressuring rating to check if further improvements in cost per kilowatt can be achieved. Improvements are often possible, for example, if the diameter of the lowest pressure section is increased as this enables the most cost-effective reduction in head loss. Pipe losses, power outputs and cost per kilowatt of different solutions are continually compared by the user until no further improvements can be made. A example screen print is shown in Appendix **10.3**) This program assumes that a sufficient variety of pressure ratings and diameters are available on local markets and that details of these have been stored with an appropriate unit cost before the analysis is carried out. A further important assumption is that the user is aware of available turbine-generator combinations and the head requirement of each for optimum performance as this will also have a bearing on the final cost per kilowatt of the scheme.

6.2.2 Application of SELECT_PIPE to scheme design in Nepal

The implementation methods, developed during the research and described in Maher 2000a, were applied to a new site in the village of Kushadevi, Nepal. This project has been described in detail in Smith 2000b and Smith 2000c. SELECT_PIPE was used to design the penstock. The pipe combination that was implemented is shown in Table 6-3.

Section length (m)	Pressure rating (bar)	Outside diameter (mm)	Inside diameter (mm)	Price ($/m)	Head loss (m)
130	2.5	140	132	3.78	0.99
100	4	125	113	4.55	1.62
100	6	125	107	6.54	2.11
100	10	125	125	9.86	4.01

Table 6-3 Optimized penstock design at Kushadevi, Nepal

The gross head at the site is 80 m and the total cost of this penstock was US$2590, which gives a cost per kilowatt of US$590 for the penstock when supplying the rated output of 4.4 kW. The total head loss was 8.73 m. This compares very favourably with the standard approach, using a non-optimized design. If a 10 bar pipe of 125 mm was used throughout the system, this would have given a head loss of 17.3 m and resulted in a cost per kilowatt of US$1134. The optimized design is approximately 50% of the cost per kilowatt of this non-optimized solution.

6.2.3 Spreadsheet model for distribution system design: PICO_CABLES

Electricity utilities use planning tools for the design of new grid-connected supplies [e.g. Blanchard 1996, Willis 1996, Green 1999]. A comparison was made to assess the level of similarity of this process to the design of pico hydro mini-grids, in order to determine whether existing tools could be adapted. In Appendix 10.4, the design criteria and constraints for grid-connected systems are summarised and comments are made about the relevance to off-grid electrification up to 5 kW. The comparison emphasizes the difference in priorities that affect the planning of the two types of system. The conclusion from this study was that adoption of new approaches at the planning stages would benefit pico hydro mini-grids, as those currently used for grid-connected systems are not suitable.

As a result, a second spreadsheet model was developed to analyse voltages and to allow rapid comparison between different designs of mini distribution grids connected to pico hydro generators. The PICO_CABLES spreadsheet is divided into similar sections as SELECT_PIPE. The procedure for use is as follows:

1) The user indexes each branch of the system with an identifying number from a hand drawn or CAD drawn layout of a distribution system.
2) Site data is entered (design power, generator voltage, total load, power factor) as well as details of locally available cables (cost, conductor material and cross-sectional area) and poles (average cost per metre assuming insulated and non-insulated conductors).
3) Spur details are entered (index number, length, number of consumers, number of consumers in adjoining branches).
4) Voltage drop equations are verified for successive branches on each spur so that the correct relationship is maintained and maximum voltage drops are calculated.
5) A cable reference is entered from those listed in the data table for each spur and branch.
6) A visual check is made of the voltage drops to ensure that the limit has not been exceeded.
7) A pole variable is altered depending on whether an insulated or non-insulated cable has been selected assuming that the cost of pole (and pole furniture) varies.
8) Copying and pasting the table, once configured for a particular system, allows different cable combinations to be compared.

Assumptions and Simplifications

In order to allow the distribution system to be modelled satisfactorily whilst minimizing the user inputs required, the following assumptions and simplifications were made:

- The rated power of the generator is entirely consumed by the system. This assumes a diversity factor of 1, in other words the maximum allowable current is continuously drawn by each consumer.
- The generator current at rated output, is divided by the total number of consumers. Each consumer therefore, draws an equal current. This is a reasonable assumption if each consumer has an equally sized load limiter connected. (A 6% power loss in the distribution system is also assumed).
- When there is more than one consumer between nodes, they are assumed to be equally spaced. This is usually a closer approximation of the load distribution than assuming that all the loads are gathered at the second node.
- Inductance losses, reactive power flows and increased cable length between nodes due to sag have been ignored.
- Volt drops in service cables have been ignored as these are negligible for small loads, which are typically less than 100W per house. In practice this is usually case since cables are oversized for strength.

Method used for calculating volt drops

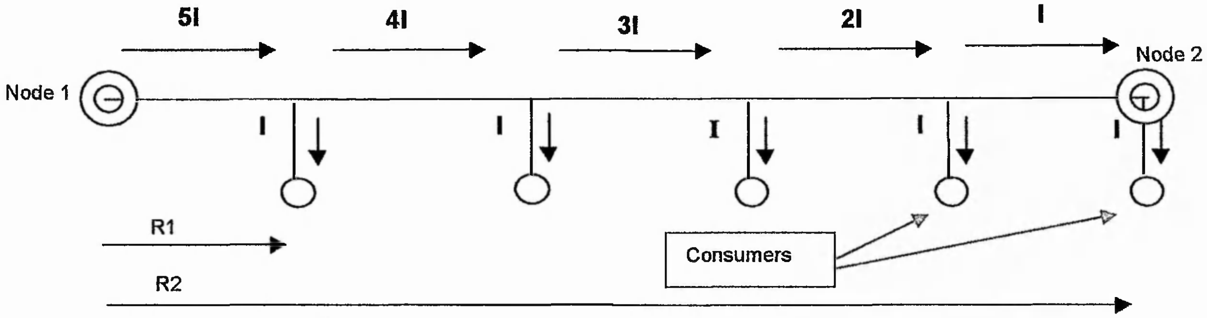


Figure 6-2 Schematic diagram of a section of the distribution system

As equal consumer spacing between two nodes is assumed, the total voltage drop at Node 2 can be calculated as follows:

$$\text{Volt drop} = (5+4+3+2+1)\ I\ R1$$

where resistance R1 = cable length (i.e. 2 x distance between houses) x cable resistance per metre

I = current per consumer = max generator current / total number of consumers

If there are subsequent sections with more houses attached at Node 2, then the number of additional houses multiplied by I R2 is added to the above value. Resistance R2 is calculated using the cable length of the whole section.

6.2.4 Application of PICO_CABLES to scheme design in Nepal

The model was used to compare distribution system designs at a demonstration site in Nepal. The final layout of the distribution system is given in Appendix 10.4. Three options for the choice of conductors were explored and minimum diameters used to allow volt drops of up to 10% at the extremities. A summary of the results, given in Table 6-4, indicates that the most cost-effective solution using locally available materials was a combination of insulated copper and non-insulated aluminum conductors. This is a saving of 30% compared with an all copper system. This scheme was implemented, following the specified design, in 1999.

Possible solutions	Length of ACSR	Length of copper	Total cost
ACSR only	4,100m	---	US$1,924
Copper only	---	4,100m	US$2,261
Mixed conductors	650m	3,450m	US$1,595

Table 6-4 Comparison of cable solutions identified using PICO_CABLES

6.3 Drawbacks with spreadsheet methods

The use of spreadsheets demonstrates how the application of computer tools can inform design decisions and allow objective comparisons to be made between different solutions. However, the shortcomings with these methods are given below.

Shortcomings of the penstock spreadsheet:

- There may be a large number of pipe combinations that could be used to achieve an acceptable head loss. Finding the optimum solution can be time consuming, particularly if the head requirements of the available turbines are also considered as a design parameter. A method is required to design the penstock using the head requirements of the turbine. This will ensure optimum system performance in addition to consideration of variable pressure rating and diameter for lowest cost of pipe. The option of automatic selection of suitable pipe combinations from the details of those stored would significantly enhance the method and time taken to reach an optimized solution.

Shortcomings of the distribution spreadsheet:

- User interaction in formula cells is required to sum the voltage drops along the correct branches according to the proposed distribution layout. As a result, there is considerable scope for errors that may be difficult to locate giving rise to misleading results.

6.4 Development of new software: Off-grid Hydro Planner (OHPlan)

The spreadsheet design tools described were a reasonable attempt at allowing discreet component data to be selected for evaluation of the system losses. However, it became apparent that for the computer tools to be of more widespread benefit to engineers and developers, a number of issues would need to be addressed:

- A lower degree of user interaction was required improving ease of use, reducing likelihood of errors and enabling solutions to be more rapidly identified
- Storing and retrieval of component data is better suited to a database package such as MS Access
- Optimization routines for component selection require a significant amount of bespoke programming
- A graphical representation of the distribution system was ideally required in order to clarify node relationships for correct summing of voltage drops

Comparisons were made of programming languages which could be most easily used to fulfill the requirements. Visual Basic was selected as the most appropriate choice. Programming of optimization algorithms was possible and limited experience with the language had been gained though the development of macro functions for the MS Excel spreadsheets described earlier. Visual Basic is well tailored to the production of 'front end' applications for databases such as MS Access and has a strong graphics capability [Halvorson 1998, Wright 1995].

The bespoke software developed is called Off-grid Hydro Planner (OHPlan) and was written using Visual Basic 6.1 Professional. This program has several important functions that do not feature in any of the software reviewed in the previous chapter. Detailed records of the principle scheme components (turbines, generators, pipes and cables) are stored in individual database modules. These databases are designed to be easily user edited so that a record of equipment which is locally available is kept up to date. Tailored program modules then formulate optimised scheme designs after browsing the records for the most suitable equipment. The program is therefore capable of assisting in scheme design, while working to the constraints and preferences defined by the scheme designer. This flexibility is not available in any of the previously available software. The program can be operated independently of any other applications on systems running Microsoft Windows 98 and above. It has been designed in a similar way to conventional Windows-based programs in order to build on user familiarity with existing interface structures, such as pull-down menus.

The main functions of OHPlan are as follows:

1. Storage of survey details and scheme designs
2. Optimized turbine and generator selection from locally available equipment
3. Optimized penstock design from locally available pipes
4. Optimized distribution system sizing from locally available cables

A flow diagram (Figure 6-3) illustrates how the different program elements interact. An outline of the format, method and operation for each program module has been described.

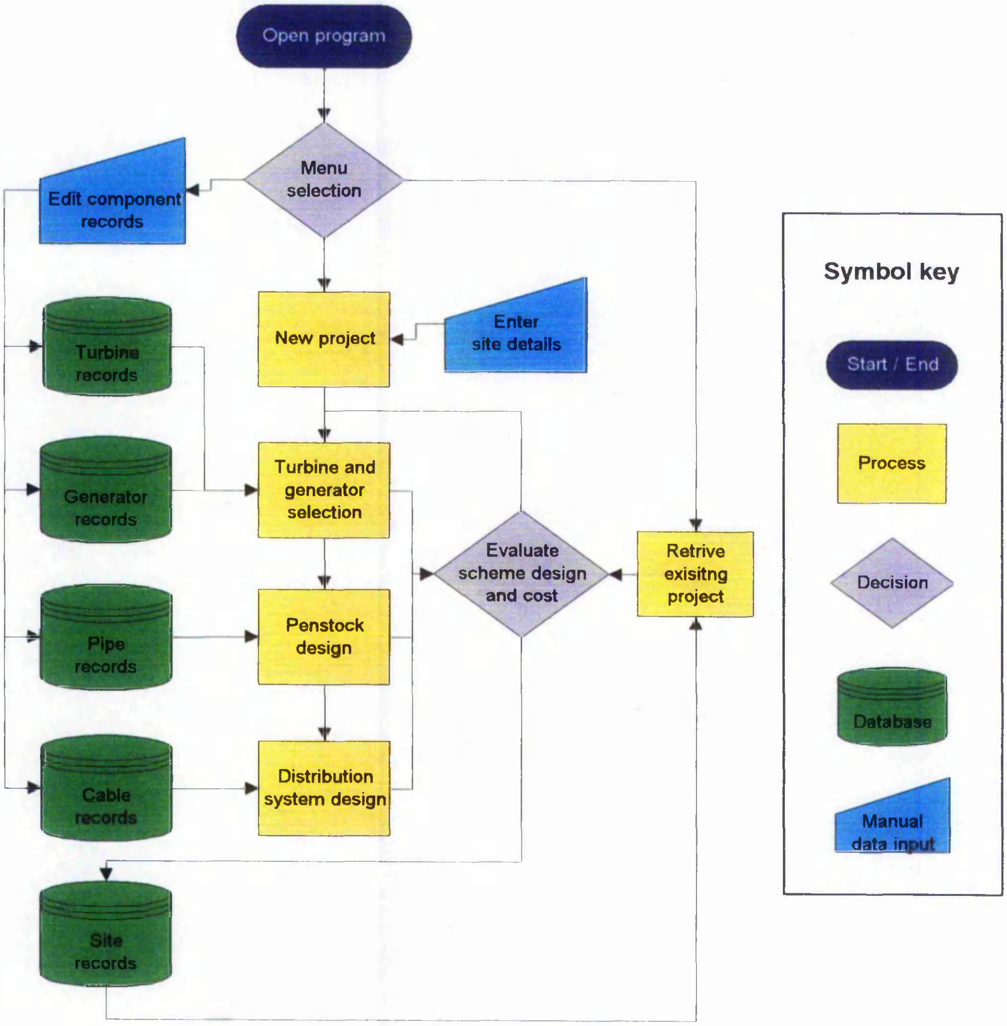
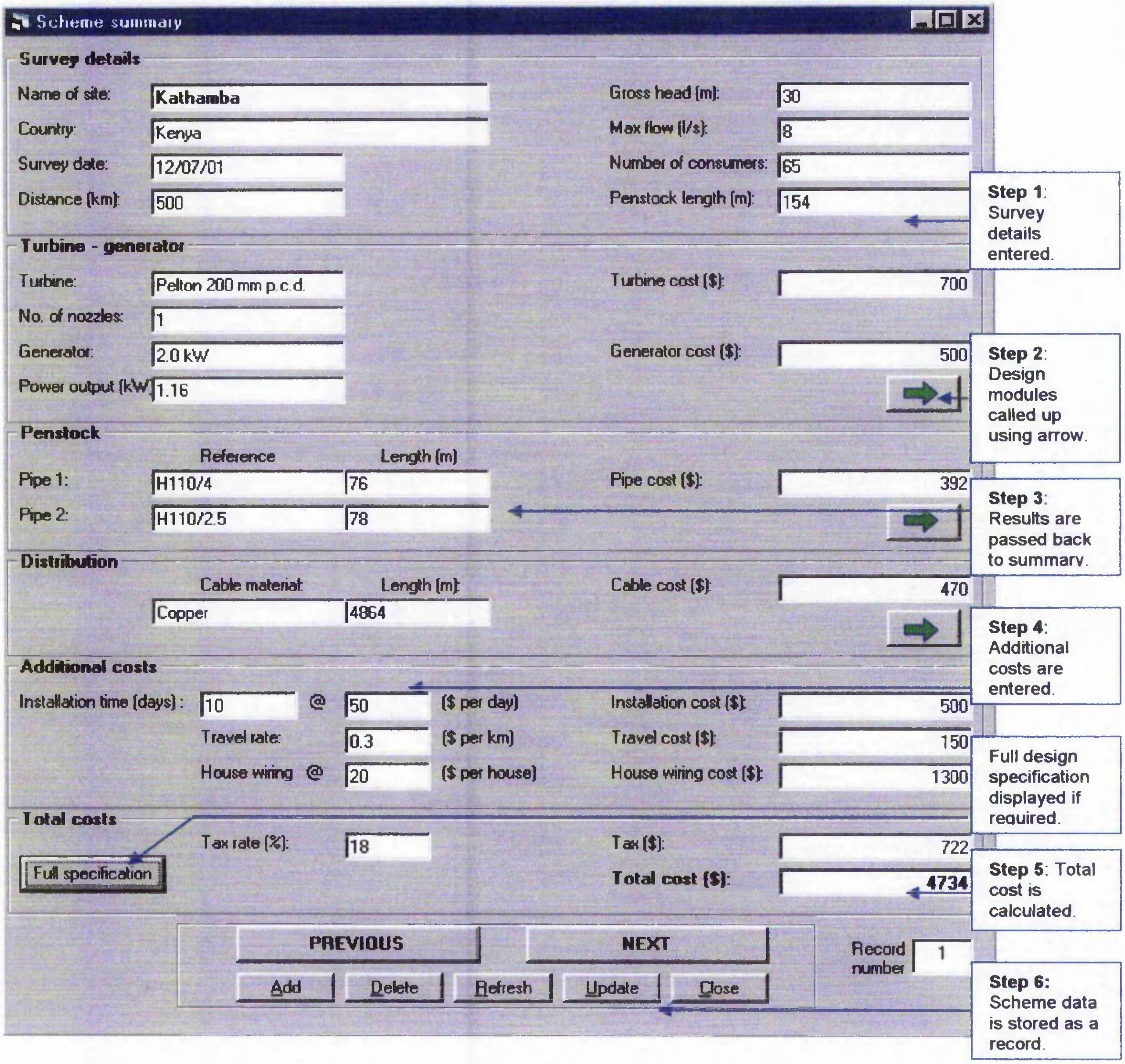


Figure 6-3 Flow diagram illustrating structure of Off-grid Hydro Planner

6.5 Storage of site information

The user enters relevant site information into the survey details window (Figure 6-4).



Survey details

Name of site: **Kathamba**

Country: Kenya

Survey date: 12/07/01

Distance (km): 500

Gross head (m): 30

Max flow (l/s): 8

Number of consumers: 65

Penstock length (m): 154

Turbine - generator

Turbine: Pelton 200 mm p.c.d.

No. of nozzles: 1

Generator: 2.0 kW

Power output (kW) 1.16

Turbine cost ($): 700

Generator cost ($): 500

Penstock

	Reference	Length (m)
Pipe 1:	H110/4	76
Pipe 2:	H110/2.5	78

Pipe cost ($): 392

Distribution

Cable material:	Length (m):
Copper	4864

Cable cost ($): 470

Additional costs

Installation time (days): 10 @ 50 ($ per day)

Travel rate: 0.3 ($ per km)

House wiring @ 20 ($ per house)

Installation cost ($): 500

Travel cost ($): 150

House wiring cost ($): 1300

Total costs

Tax rate (%): 18

Tax ($): 722

Total cost ($): 4734

Record number 1

Step 1: Survey details entered.

Step 2: Design modules called up using arrow.

Step 3: Results are passed back to summary.

Step 4: Additional costs are entered.

Full design specification displayed if required.

Step 5: Total cost is calculated.

Step 6: Scheme data is stored as a record.

Figure 6-4 Screen print of 'Scheme summary' record

This includes gross head, design flow rate, penstock length, consumer numbers in addition to the name by which the site record can be identified. The details are subsequently passed to the program modules where they are required to determine the scheme design. Entering site information just once maintains the consistency of the data throughout the program and avoids unnecessary duplication. A site record is created and stored in an MS Access database file, which is maintained when the program is closed. Component details are added to the record once a program module has been completed. The user is able to recall and update existing scheme details or begin a new record.

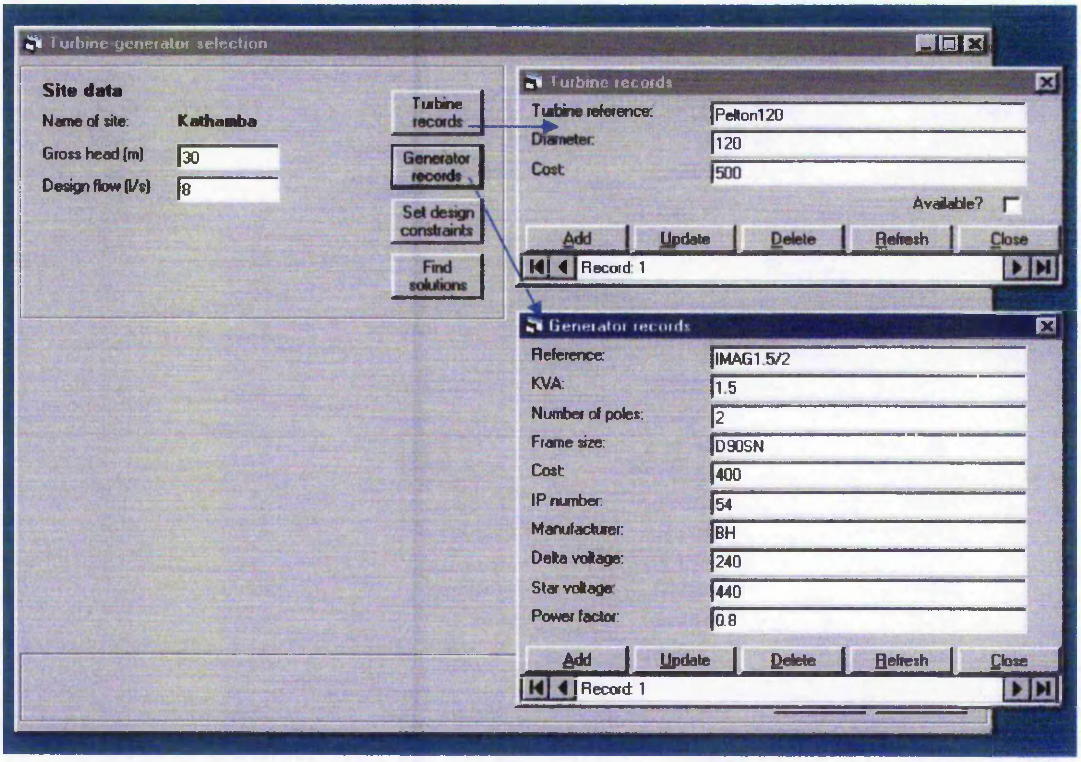
6.6 *Turbine-generator selection*

Research of pico hydro schemes in Nepal indicates that there is a high incidence of inappropriate matching of turbine-generators to the site conditions which results in power outputs below the rated value. 'One-off' designs for pico hydro units are also incompatible with reducing cost per kilowatt of schemes, since significant savings can be achieved through standardization of turbine-generator units. Based on survey information provided by the user, this program module selects the two most appropriate turbine-generator combinations.

6.6.1 User guidelines

Required steps for turbine-generator selection using the program module are as follows:

Step 1 When the program module has been loaded, either via the scheme summary window or through the 'tools' menu, scheme details will appear if a particular site has been selected as illustrated in Figure 6-5. Otherwise, gross head and design flow can be typed into the blank fields.



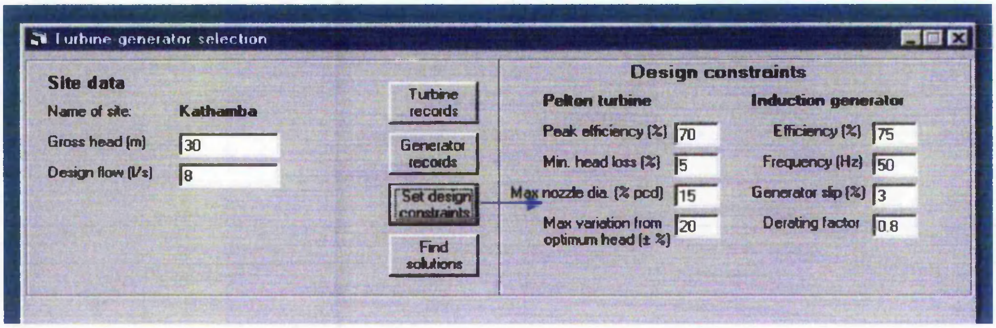
Site data
Name of site: **Kathamba**
Gross head (m) 30
Design flow (l/s) 8

Turbine reference: Pelton120
Diameter: 120
Cost 500
Available? ☐
Record: 1

Reference: IMAG1.5/2
KVA: 1.5
Number of poles: 2
Frame size: D90SN
Cost 400
IP number: 54
Manufacturer: BH
Delta voltage: 240
Star voltage: 440
Power factor: 0.8
Record: 1

Figure 6-5 Editing stored details of available turbines and generators

Step 2 Clicking 'Turbine records' or 'Generator records' loads a 'front end' to the appropriate database file allowing the user to scroll through the records. These should be updated to match locally available equipment, as the component selections are based on this information.



Site data

Name of site: **Kathamba**

Gross head (m) 30

Design flow (l/s) 8

Design constraints

Pelton turbine

Peak efficiency (%) 70

Min. head loss (%) 5

Max nozzle dia. (% pcd) 15

Max variation from optimum head (± %) 20

Induction generator

Efficiency (%) 75

Frequency (Hz) 50

Generator slip (%) 3

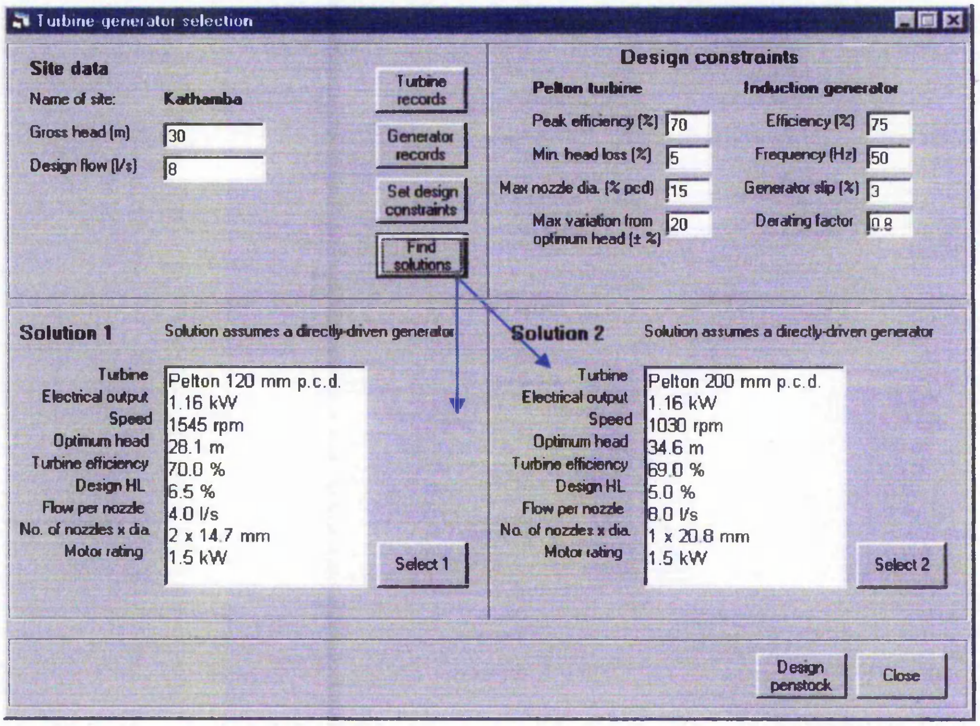
Derating factor 0.8

Figure 6-6 Design constraints are set before turbine-generator combination is selected

Step 3 Design constraints for turbine-generator units can be adjusted from the default values shown in Figure 6-6. An explanation of these is given in Section 6.6.2.

Step 4 With direct drive turbine-generators, three Pelton runner diameters and three generator speeds can provide combinations that can be approximately matched to sites with heads from 25 m to 200 m. However, the database can be expanded with further turbine details, if these are available locally, providing the possibility of more accurate matching at a greater range of sites. The 'Find solutions' button allows the combination of turbine and generator the most closely matched to the head available to be identified. A second solution is also provided since the number of nozzles will vary depending on the design flow and the maximum ratio of jet to runner diameter. A single nozzle turbine may be preferable due to lower cost and simplicity of installation even if it is slightly less efficient. An example of this is illustrated by the two solutions shown in Figure 6-7.

In this example, a 120mm p.c.d. runner is the best match for the gross head available of 30 m since, with a head loss of 6.5%, the turbine is operating at peak efficiency when directly driving a 4 pole generator. However, due to the small bucket size with a 120mm turbine, the maximum jet and nozzle diameter is limited to 120 x 15% or 18mm. This limits the flow to 6 litres per second, when 8 litres per second is the required design flow. Therefore a second nozzle is required. Solution 2 is a 200mm p.c.d. Pelton runner driving a 6 pole generator. Since the buckets are bigger, the design flow can be achieved with a single nozzle. There is a small efficiency penalty but this has negligible effect on the power as the design head is now slightly higher (28.5m instead of 28.1m). The lower head loss requirement of 5% maximum will slightly increase the cost of the penstock. This was the turbine-generator combination that was selected and implemented at the site in Kenya described in Appendix 10.



Site data

Name of site: **Kathamba**
Gross head (m) 30
Design flow (l/s) 8

Design constraints

Pelton turbine		**Induction generator**	
Peak efficiency (%)	70	Efficiency (%)	75
Min. head loss (%)	5	Frequency (Hz)	50
Max nozzle dia. (% pcd)	15	Generator slip (%)	3
Max variation from optimum head (± %)	20	Derating factor	0.8

Solution 1 Solution assumes a directly-driven generator

Turbine	Pelton 120 mm p.c.d.
Electrical output	1.16 kW
Speed	1545 rpm
Optimum head	28.1 m
Turbine efficiency	70.0 %
Design HL	6.5 %
Flow per nozzle	4.0 l/s
No. of nozzles x dia.	2 x 14.7 mm
Motor rating	1.5 kW

Solution 2 Solution assumes a directly-driven generator

Turbine	Pelton 200 mm p.c.d.
Electrical output	1.16 kW
Speed	1030 rpm
Optimum head	34.6 m
Turbine efficiency	69.0 %
Design HL	5.0 %
Flow per nozzle	8.0 l/s
No. of nozzles x dia.	1 x 20.8 mm
Motor rating	1.5 kW

Figure 6-7 The two turbine-generator combinations which most closely match the site conditions are identified

Step 5 The preferred solution is selected and the details of the design are passed to the appropriate scheme record. The scheme record is displayed for verification. Any previous solution will be overwritten once the changes have been accepted. However, several scheme designs for one site could be stored by modifying the site name and storing as a new record (e.g. Kathamba(2) etc.) Head loss requirements for the preferred turbine are passed to the penstock design module.

6.6.2 Design constraints for Pelton turbines

Peak efficiency – This allows comparison of how a turbine will perform at a particular site with efficiency under ideal conditions. The default value for peak efficiency is the value determined by testing of Nottingham Trent University Pelton turbine runners. An explanation of how the efficiency is calculated for each design iteration is given in Appendix 10.6 The peak value may be adjusted for different turbines and the shape of the characteristic is maintained.

Min. head loss – This is the minimum head loss acceptable in the penstock. Analysis has shown that cost per kilowatt of the penstock increases sharply if a head loss below 5% is selected (see Section 3.3.3). This figure is therefore set at this value. If the optimum head of the selected turbine is more than 95% of the gross head available, then a head loss of 5% will be assumed and the turbine efficiency recalculated based on the new lower value.

Max. nozzle dia. (% p.c.d.) – Each design of Pelton turbine bucket has a different maximum jet diameter associated with it. If the jet diameter is too large, then a proportion of the water will either miss the bucket completely or interact with the bucket in a negative way causing efficiency loss. The maximum jet diameter is usually expressed as a proportion of the runner pitch circle diameter. For the NTU Pelton buckets the ratio proportion is 15% of the p.c.d. If a tapered nozzle design is used, it is assumed that the nozzle diameter is the same as the jet diameter as the difference is negligible for pico hydro Pelton turbines

Max. variation from optimum head (± %) - The performance of each Pelton turbine and induction generator combination is tested under the site conditions. Turbines which have an optimum head outside of the range given are rejected. A default value of 20% has been selected since, for most Pelton turbines, a variation of up to 20% of the optimum value will result in a drop in efficiency of 3% or less. This is thought to be a worthwhile trade-off given the cost benefits of standardized design to match a wide range of sites. By experimenting with this value it is possible to see the effect on efficiency and power output of operating outside of this range to enable more accurate prediction of scheme performance once installed if the most appropriate turbine diameter is not available.

6.6.3 Design constraints for induction generators

Efficiency (%) – This is the peak value expected for operation as a generator and is required to calculate the electrical power output. Values range from 75% for 1.1kW generators to over 90% for some machines of 10kW and above.

Frequency (Hz) – This is set according to country requirements. It is important since operating speed of induction machines directly affects the frequency. The operating speed of a stand-alone induction machine is controlled by the amount of excitation capacitance that is connected across the windings. Frequency variations of up to 10% above the nominal value (e.g. up to 55 Hz instead for a 50 Hz supply) can be tolerated by most appliances. This enables available turbines to be closely matched to the site conditions by fine-tuning the operating speed of a directly driven induction generator.

Generator slip (%) – This may vary between 3% and 5% depending on the origin and power rating of the induction machine. Generator slip tends to be smaller than motor slip and will have the opposite sign.

De-rating factor – The power rating of induction machines must be scaled down when using three-phase motors as single-phase generators for stand-alone applications. The selected default value of 0.8 is a typical de-rating factor used for selecting an induction motor as a generator.

6.6.4 Design methodology and novelty of approach

The turbine-generator selection procedure is illustrated by the flow diagram in Figure 6-8. Through an iterative optimisation process, the 'best fit' turbine-generator combination for a particular site is selected from the product details stored in the component records. The ideal operating conditions of each combination of turbine runner and generator are compared with the available head at the site to find the two closest matches. This enables the best practical solutions to be quickly identified and represents a considerable improvement over current, often more heuristic approaches which have been demonstrated to be less than satisfactory in a high proportion of installations. The ability to quickly provide the developer with two suitable combinations of Pelton turbine and induction generator given particular site characteristics together with an accurate estimate of system efficiency and power output represents a significant step forwards in terms of improving the consistency with which cost-effective pico hydro schemes can be designed. A particular advantage is the high degree of flexibility and customization which is possible. By adjusting the default values of the design criteria the user is able to allow hardware availability, performance variations between different turbine runners and local preferences of turbine configuration to be reflected in the final design.

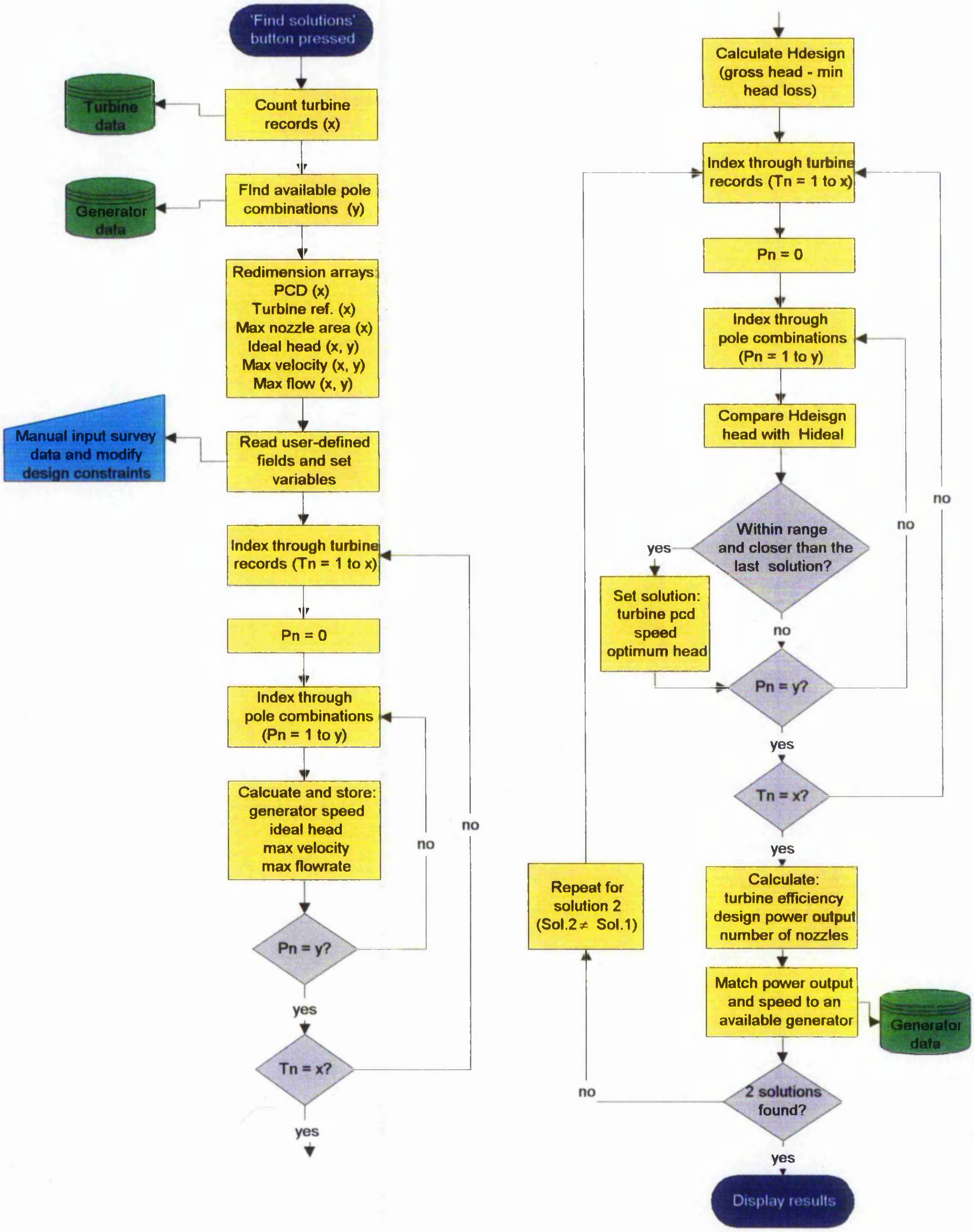
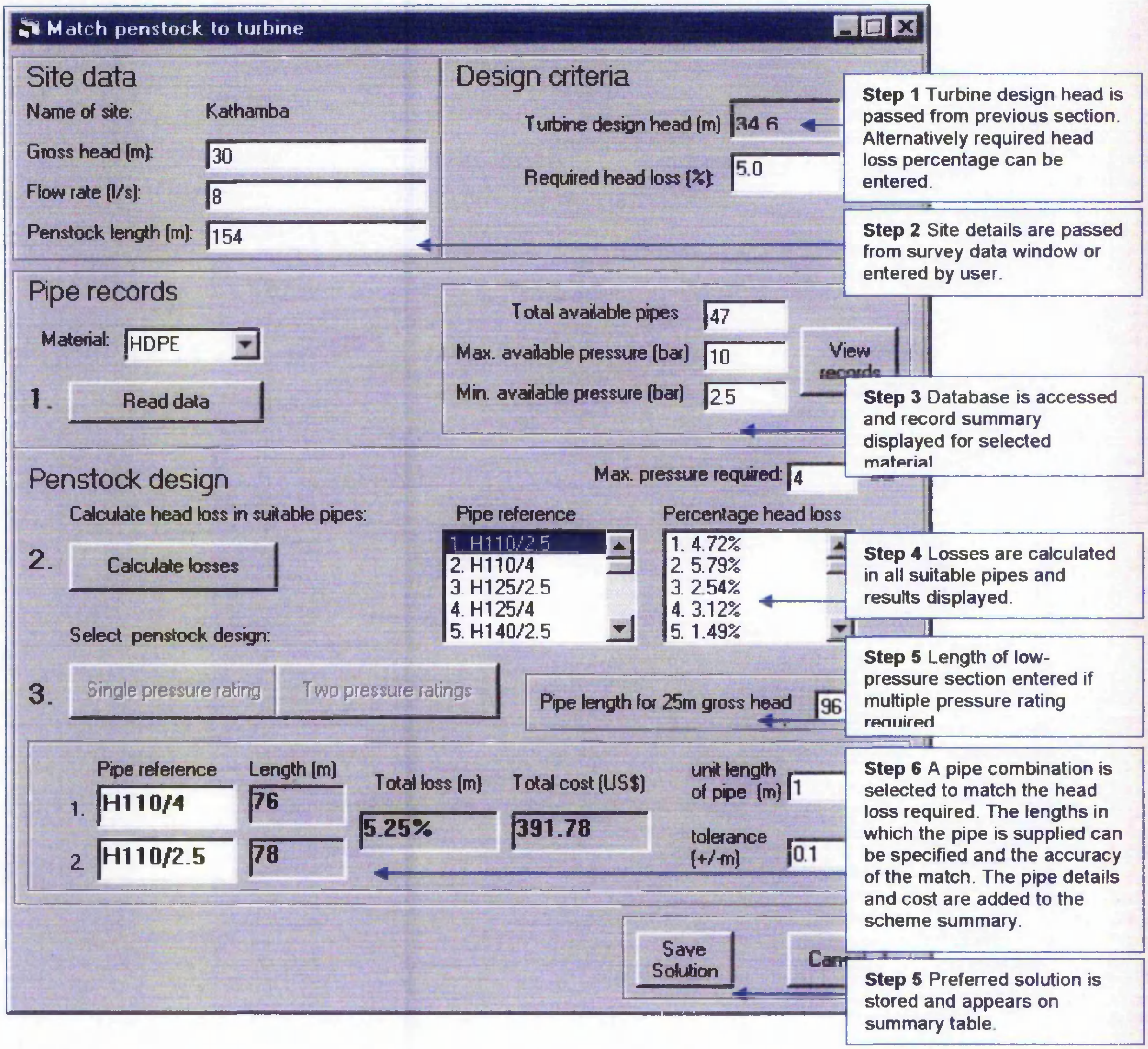


Figure 6-8 Flow diagram of turbine-generator selection procedure

6.7 *Penstock design*

An appropriate penstock selection is critical to meeting power generation expectations and research has demonstrated that this is often the most costly single element of pico hydro schemes. The most cost-effective design will have a variable pressure rating and be sized to give the head requirements of the turbine with a head loss of between 5 % and 33 % of the gross head. Since identification of the optimum design is difficult to identify quickly, even if the losses are calculated using spreadsheets, a program module has been developed which allows automatic pipe selection. An example screen print is shown in Figure 6-9.

6.7.1 User guidelines



Name of site: Kathamba

Gross head (m): 30

Flow rate (l/s): 8

Penstock length (m): 154

Turbine design head (m) 34.6

Required head loss (%): 5.0

Material: HDPE

Total available pipes 47

Max. available pressure (bar) 10

Min. available pressure (bar) 2.5

Max. pressure required: 4

Pipe reference	Percentage head loss
1. H110/2.5	1. 4.72%
2. H110/4	2. 5.79%
3. H125/2.5	3. 2.54%
4. H125/4	4. 3.12%
5. H140/2.5	5. 1.49%

Pipe length for 25m gross head 96

	Pipe reference	Length (m)
1.	H110/4	76
2	H110/2.5	78

Total loss (m) 5.25%

Total cost (US$) 391.78

unit length of pipe (m) 1

tolerance (+/-m) 0.1

Step 1 Turbine design head is passed from previous section. Alternatively required head loss percentage can be entered.

Step 2 Site details are passed from survey data window or entered by user.

Step 3 Database is accessed and record summary displayed for selected material

Step 4 Losses are calculated in all suitable pipes and results displayed.

Step 5 Length of low-pressure section entered if multiple pressure rating required

Step 6 A pipe combination is selected to match the head loss required. The lengths in which the pipe is supplied can be specified and the accuracy of the match. The pipe details and cost are added to the scheme summary.

Step 5 Preferred solution is stored and appears on summary table.

Figure 6-9 Screen print of penstock selection module with user guidelines

6.7.2 Design methodology and novelty of approach

This program module has been designed to provide an optimised penstock solution given the ideal turbine operating head and locally available pipe details stored in the component database.

Pipe of the specified material are sorted into an array by algorithm which selects those of suitable pressure rating. Accurate head loss estimation using a clear user interface panel is the first key innovation in this program module. Head losses are calculated using the Haaland formula for each pipe selected using the design flow, the required length and friction coefficient of the material. The Haaland formula is the best recommended method yet produced using an algebraic formula [Massey 1997]. The Visual Basic procedure called to calculate the head loss is given in Appendix 10.7.1 If the loss is found to be less than 33% of the gross head, the result is displayed in a list which the user can browse. A selection may be made at this stage if the simplest design of penstock with a uniform pressure rating and diameter throughout the length is preferred. This may be the case where pipe availability is limited or the cost saving with a more varied design is deemed to be not justified by the additional complexity of installation.

The optimum operating head of the selected turbine is passed from the turbine module so that the penstock design can be optimised according to the net head required. This is achieved by selecting those pipe diameters which give the closest match above and below the design head loss. A new head loss is calculated for a penstock made up of an equal length of the two selected diameters. The lengths of each pipe are then modified to adjust the loss until the design head loss is achieved within a pre-defined range. The lengths of pipe added and subtracted can be adjusted to enable the developer to make use of standard lengths which are available in the market place. Only pipes of the same pressure rating and material will be combined and it is assuming that a coupling will be available to connect the two diameters. If the design head of the turbine is greater than the gross head then a default design head loss of 5% is assumed in order to ensure that the penstock is still cost-effective.

Further cost reduction through the use of a lower pressure pipe for the upstream penstock section is obtained if local availability allows. The largest of the two pipe diameters will always be selected for pressure rating reduction as this allows the greatest cost saving. The user defines the pipe length to the lower pressure rating boundary; e.g. 25 m gross head for 2.5 bar pipe which will then restrict its maximum length.

This novel approach taken to penstock selection and design, demonstrated in rudimentary manner as an MS Excel program, allows the solution to be driven by either turbine performance, cost or complexity of installation depending on local preferences and pipe availability. It also enables rapid experimentation, for example variation to the flow rate or penstock length, and is particularly conducive to helping the new developer towards a greater understanding of the importance of careful penstock design with regard to scheme cost and power output.

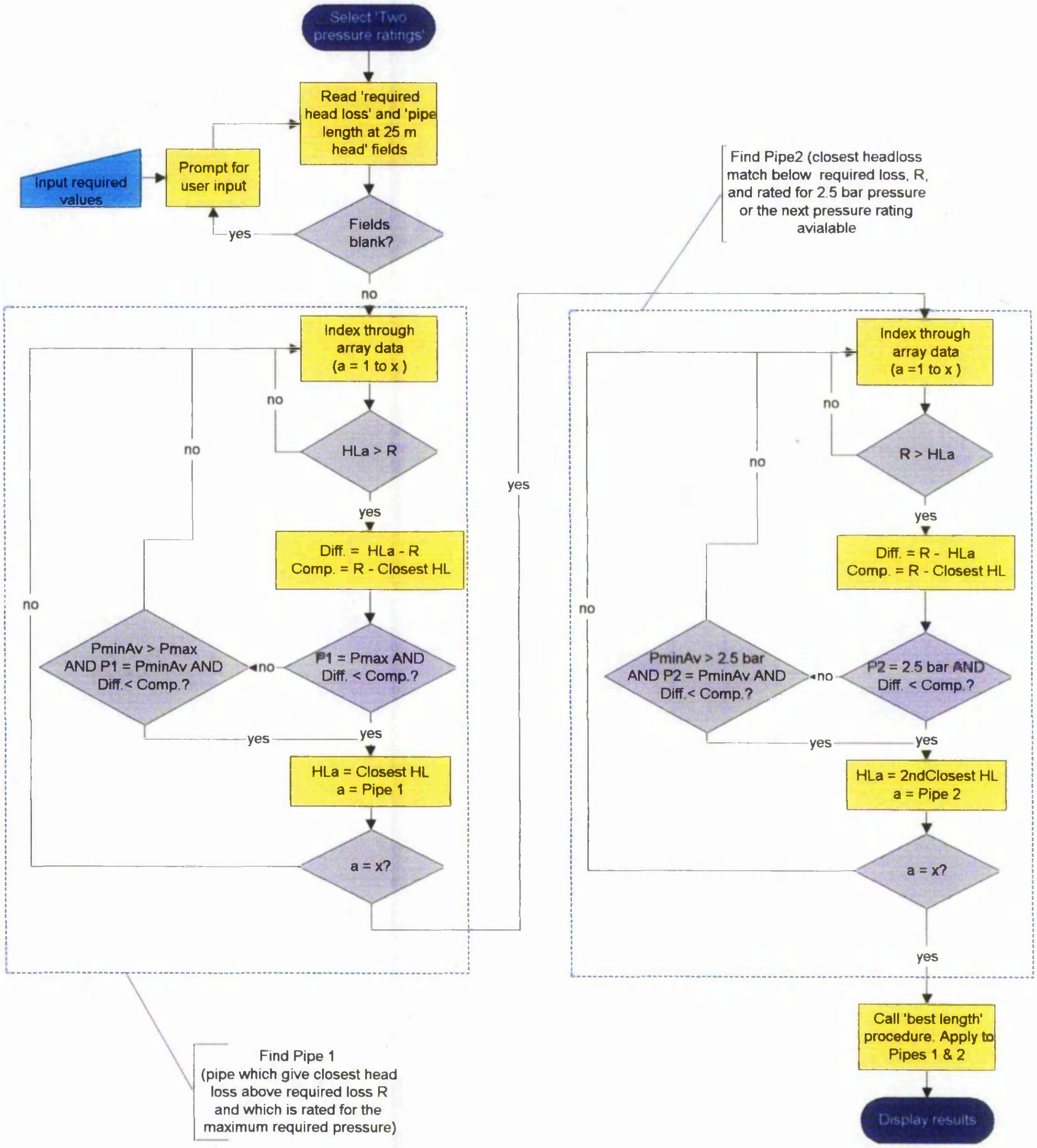


Figure 6-10 Flow diagram of procedure for selection of optimum pipe diameters assuming a penstock design of variable pressure rating.

A flow diagram has been constructed (Figure 6-10) to illustrate how the optimum pipe diameters for a particular site are selected. A second flow diagram illustrating the iterative procedure for calculating the required length of each pipe section is given in Appendix 10.7.3.

6.8 Optimized distribution cable selection

The aim of this module is to allow the developer to easily design a mini distribution grid by automatically selecting the cables for each section. The cables are selected in order to maximise the volt drop whilst maintaining the voltage within the required limits at the extremities. A plan of the site, showing locations of the generator and all consumers, is required together with a cable layout indicating the pattern of connection. This may be a hand drawn plan or one using GPS data and a CAD package. The layout may be planned intuitively or using ViPOR to minimise the cable lengths as described in Section 6.1. The layout is translated into a simplified tree structure that can be drawn and interpreted by the program. At the present time, the program is able to create separate spurs of distribution with branches off graphically as pictured in Figure 6-11, but only able to define the volt drops and cables required in the main spur sections. Hence a different distribution network is shown to illustrate cable selection in Figure 6-13.

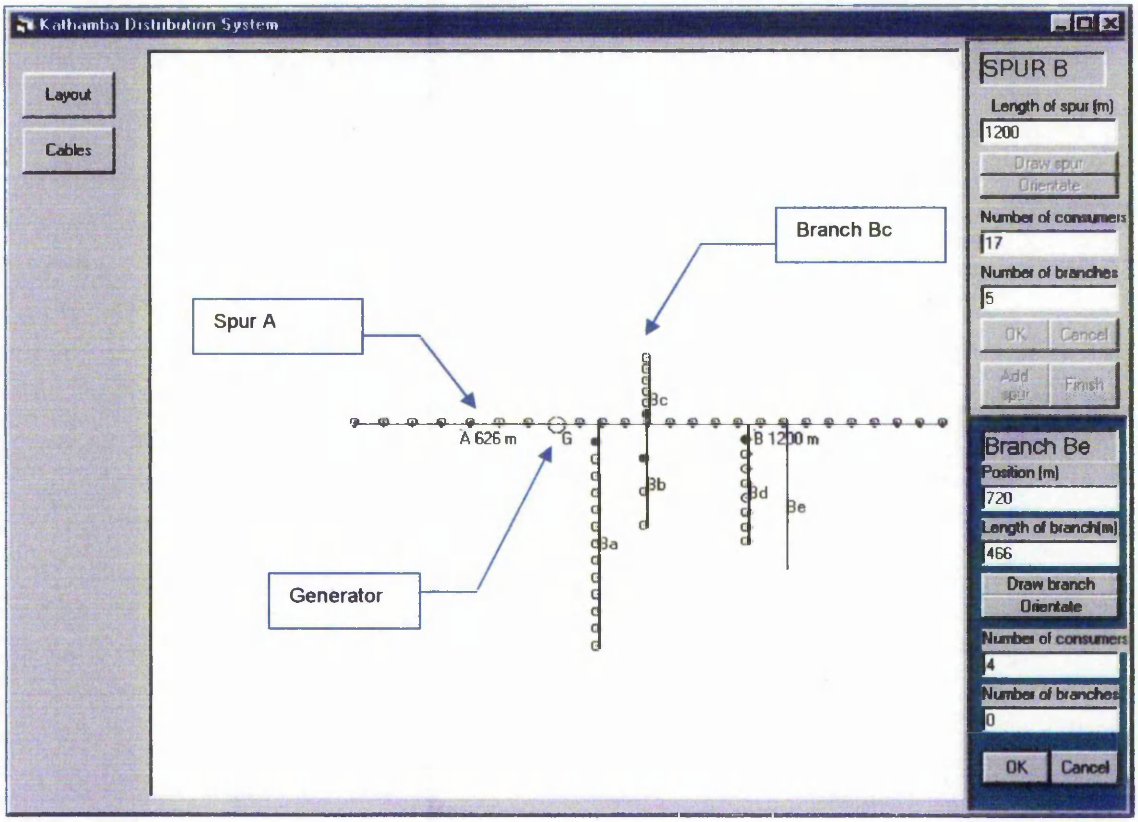
6.8.1 User guidelines

The procedure for use is as follows:

Step 1 The cable selection module can be accessed from 'Scheme data' or from the 'Tools' menu. The window appears with the name of the site across the top. When the 'Layout' command button is clicked, a prompt is given for the distance of the furthest consumer so that the drawing area can be scaled.

Step 2 Each main conductor line from the generator, which appears as a circle in the middle of the screen, is referred to as a spur. The lengths and number of consumers per spur are added and the user is able to change the orientation of the spur in 90° intervals. A maximum of four spurs can be added.

Step 3 Cables not directly connected to the generator are referred to as branches. Branches are defined in a similar way to spurs; by length, orientation and number of consumers. The position of the branch must also be entered. This is the distance, when measured from the generator, where the branch should be connected.



SPUR B

Length of spur (m) 1200

Number of consumers 17

Number of branches 5

Branch Be

Position (m) 720

Length of branch(m) 466

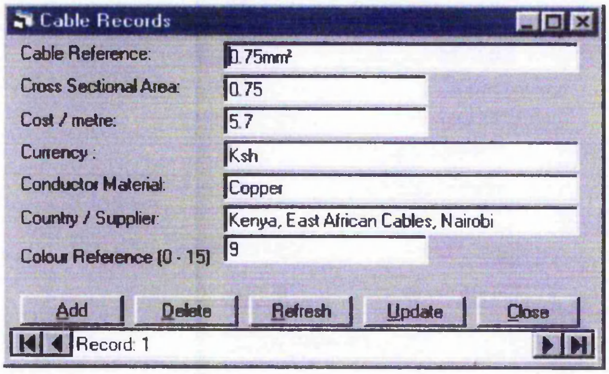
Number of consumers 4

Number of branches 0

Figure 6-11 Screen print showing representation of Kathamba distribution system

Step 4 Once a representation of the distribution system layout has been created, selecting 'Finish' closes this window. The conductors can then be sized by pressing the 'Cables' button in the left-hand column.

Step 5 As with the turbine and pipe details, key specifications of available cables are stored in an 'Access database' file. This can be reviewed and updated using the 'Cable records' menu at the top of the screen.



Cable Reference: 0.75mm²

Cross Sectional Area: 0.75

Cost / metre: 5.7

Currency : Ksh

Conductor Material: Copper

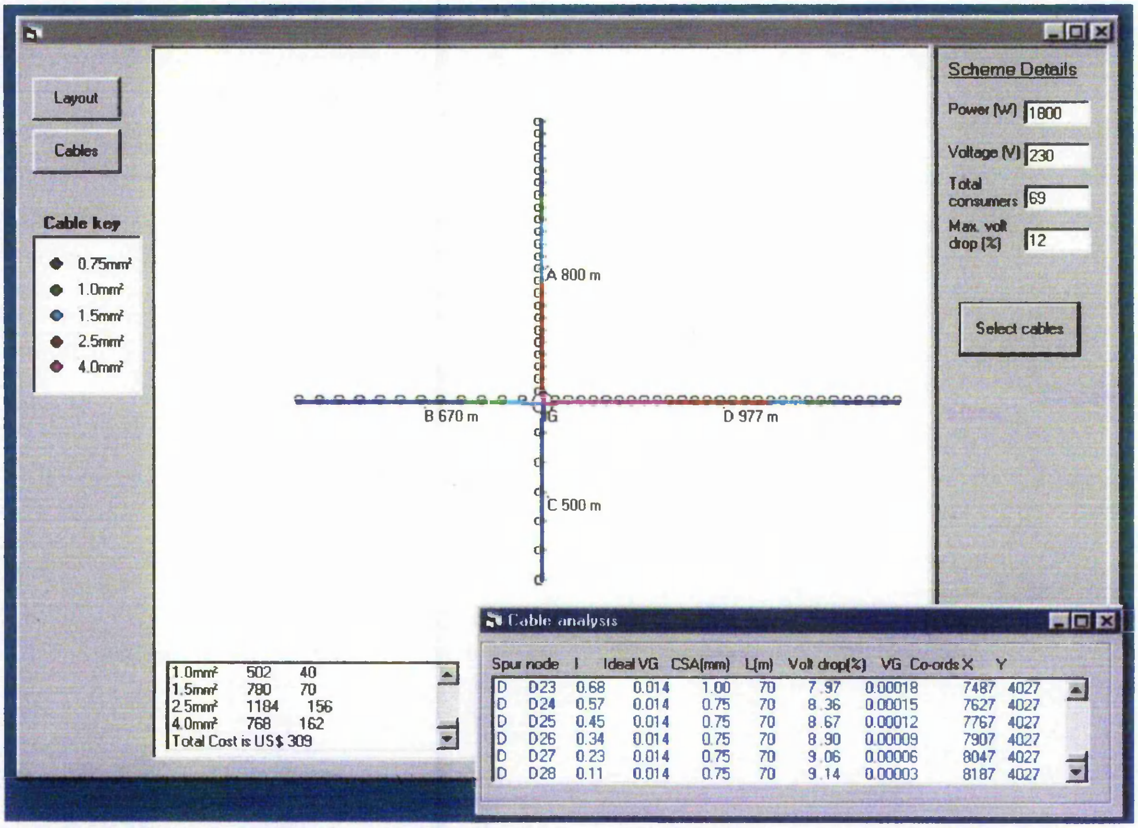
Country / Supplier: Kenya, East African Cables, Nairobi

Colour Reference (0 - 15) 9

Figure 6-12 Database window for viewing cable records

Step 6 The spur-input menu is replaced by one for the electrical variables. The power output, voltage and frequency are set to default values but can be modified by the user. If the turbine and generator have been sized previously, then the default of 5000 W will change to the new value of power output.

Step 7 The 'Size cables' button is clicked and the optimum selection is made. Sections of the distribution system appear in different colours according to the cables chosen.



Scheme Details

Power (W) 1800

Voltage (V) 230

Total consumers 69

Max. volt drop (%) 12

1.0mm²	502	40
1.5mm²	780	70
2.5mm²	1184	156
4.0mm²	768	162

Total Cost is US$ 309

Spur	node	I	Ideal VG	CSA(mm)	L(m)	Volt drop(%)	VG	Co-ords X	Y
D	D23	0.68	0.014	1.00	70	7.97	0.00018	7487	4027
D	D24	0.57	0.014	0.75	70	8.36	0.00015	7627	4027
D	D25	0.45	0.014	0.75	70	8.67	0.00012	7767	4027
D	D26	0.34	0.014	0.75	70	8.90	0.00009	7907	4027
D	D27	0.23	0.014	0.75	70	9.06	0.00006	8047	4027
D	D28	0.11	0.014	0.75	70	9.14	0.00003	8187	4027

Figure 6-13 Distribution grid showing cable selections and cost summary

6.8.2 Design methodology and novelty of approach

The distribution design module which has been developed enables the developer to generate a radially-tapered distribution system based on common voltage gradient and modular loads. This approach taken is particularly well adapted for the design of systems which supply small off-grid communities with load-limited connections of a similar size and therefore ideal for pico hydro mini-grids. The solutions developed are highly optimized in terms of the total conductor volume required and considerable cost reductions are made possible whilst ensuring that consumers at the extremities of the system still receive a supply within acceptable limits. The highly innovative method used, selects cable diameters from those locally available for each individual section based on reference to a common voltage gradient which would occur in an ideal system. The graphical illustration of the computer-generated solution is key to enabling accurate implementation. Minimum user intervention or computing experience is required in order to generate valid solutions. Manual calculation of voltage drops across even the simplest distribution system where multiple load are connected is particularly time-consuming and error prone. None of the software reviewed could adequately perform such analysis. Development of this tool therefore, represents a considerable improvement over current approaches and over the spreadsheet method described earlier. The methodology used for distribution system design is described in more detail below.

It can be shown [Jones 1993] that the minimum volume of conductor required in a distribution network can be found if the volt drop per metre is the same throughout the system. A summary of the proof is outlined below.

Assuming a main distribution spur which has several branches feeding out:

The total volume of copper in the system $C = \sum LA = \rho \sum \frac{L^2 I}{V}$

Where L = length of system

A = cross sectional area, $A = \frac{\rho L I}{V}$

$\rho =$ conductivity of copper

I = total current flowing

V = voltage drop

The expression is separated into spur and branch cables using V_1 for spur volt drop and V_2 for branch volt drop, and it is assumed that all the branches are equal so the expression becomes:

$$C = \frac{\rho}{V_1} L_1^2 I + \frac{\rho}{V_2} L_2^2 I$$

V_1/V_2 is a variable and V_1+V_2 is a constant. Differentiating and setting to zero to find where C is a minimum gives:

$$\frac{V_1^2}{V_2^2} = \frac{L_1^2}{L_2^2}$$

and hence $$\frac{V_1}{L_1} = \frac{V_2}{L_2}$$

So the volume of copper is minimum when the total volt drop is distributed equally across each part of the system, either a spur and branch, or two sections of distribution between individual consumers.

The volt drop per unit length can be described as a voltage gradient. By assuming that cable cost is proportional to conductor volume and calculating the ideal voltage gradient for a given spur, the most appropriate cables can be selected between any given points if the current along that section is known. This allows a radially tapered system with the lowest volume of copper, and hence lowest cost, to be designed whilst maintaining the supply voltage within acceptable limits at all points.

Voltage gradient can be expressed as follows:

$$\text{Voltage gradient} = \frac{\Delta V}{L}$$

Since $\Delta V = I \times R_m \times L$

ΔV = change in voltage or 'volt drop'

I = current (amps)

R_m= cable resistance per metre (ohms)

L = total length of cable (metres)

Therefore,

$$\text{Voltage gradient} = I \times R_m$$

In order to select cables from those stored in the database, similar assumptions and simplifications have been made to the spreadsheet method of volt drop calculation described earlier (Section 6.2.3).

The power available is split according to the loading on each spur and an individual spur current is calculated. Once the maximum spur current is known, an ideal cable diameter is calculated which would give the precise volt drop required if all the loads were connected at the end of the line. This ideal diameter can then be used to calculate a reference voltage gradient to which the subsequent cable selections are compared.

Nodes in the system are identified at consumer points. Co-ordinates are stored and can be accessed from a two dimensional array. Individual node data is indexed using the spur reference letter and a consumer number, established counting outwards from the generator. The current flowing to a particular node (I_x) is calculated, depending on the node position and the number of subsequent consumers, as a proportion of the maximum total current available to the spur ($I_{spurmax}$). The current at a position x (I_x), where

x = 1 to t and

t = total nodes on the spur

is calculated as follows:

$$I_x = I_{spur\max} \times \frac{t - (x-1)}{t}$$

Cable records are accessed and the resultant voltage gradient is tested using each cable diameter, by comparing with the reference value, until the most appropriate solution is identified. This will be the cable that gives the closest voltage gradient below the reference value. This process continues through each node to the end of the spur and then on the remaining spurs. Once cables have been selected to connect each node, the volt drops between nodes can be calculated and summed to give the maximum drops at the extremities of the system. This data is listed in a separate form called 'Cable analysis', which can be accessed via the 'View options' menu. It is displayed in the bottom right-hand corner of Figure 6-13.

Integer values from 0 to 15 can be used to assign a different colour to each cable in the records. A line of the appropriate colour appears on the layout to indicate the cable selected and its position. A key on the left-hand side of the layout identifies the cable. Cables lengths of a particular type are summed together and the required lengths listed with costs. This data can then be saved to the 'Summary details' window as before.

Since the voltage gradient in any spur is the product of the resistance per metre and the current flowing through that section, the cable diameter must decrease further from the generator in order for the voltage gradient to be held constant. This is demonstrated by the results of the cable selection in Figure 6-13. Larger diameter cables with a lower resistance are used near the generator where currents are highest and these gradually taper outwards with the smallest diameters used to connect the final consumers.

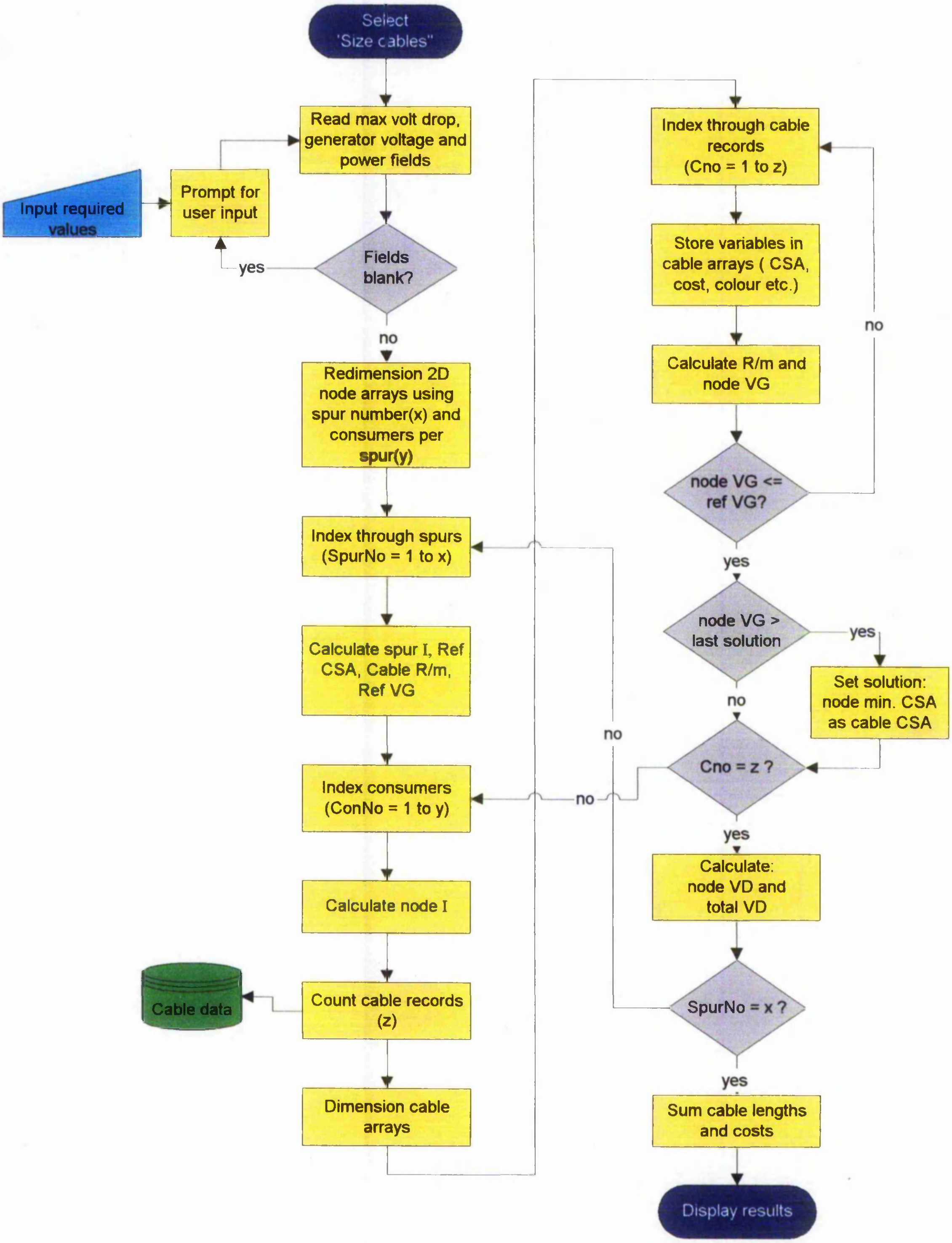


Figure 6-14 Flow diagram of procedure for optimized cable selection

7 DISCUSSION

The comparison of electrification options in chapter one concludes that, where suitable sites exist, the combination of low cost per kilowatt and high income-generating potential can make micro hydro a valuable energy option in rural areas. However, this resource remains highly unexploited due to lack of suitable turbine-generator equipment and local implementation capacity.

Chapter two explores the benefits of pico hydro, and examines the reasons for the success of schemes in Nepal and Colombia. These include reduction of manufacturing costs through standardized design, small flow requirements and therefore a large number of suitable sites, greater portability to inaccessible areas and improved affordability even amongst the poorest communities.

A systematic approach was taken to the collection and analysis of field data from existing schemes in chapter three. Detailed methods were developed in order to fully quantify the performance and cost at each scheme visited. This revealed a high degree of variability in the approaches used to implement pico hydro in Nepal and the accuracy with which they were applied. The research indicates that costs as low as US$ 2000 per kilowatt are possible at carefully designed and properly functioning schemes. However, this was rarely achieved in practice and inconsistencies were found in every area of the current implementation methods.

The remainder of the research focused on the methods to improve scheme design and enhance the viability of pico hydro. Chapter four describes how this has been achieved through development of a new turbine-generator unit which both allows a wider range of power applications and simplifies maintenance. The unit was manufactured in Nepal and installed at a new site. Universal use of low-cost load limiters and energy efficient loads enabled the connection of more than 60 houses to the 4 kW generator, a significantly greater number than previously seen in such a small scheme. The free shaft, which is a feature of the design, was used to drive a corn mill. This proved highly convenient for the many families who lived in the remote valley where the powerhouse was located. Lessons were also learnt from this installation. Lightning arrestors were insufficient and wrongly connected and shortly after commissioning, a large number of the compact fluorescent bulbs were damaged during a storm. Changes were implemented to improve the earthing and lighting protection. The arrival of the scheme also aggravated some of the existing ethnic and political divisions within the community. As a result new methods of approaching and engaging with communities during the implementation were developed. These were put into practice during the installation of the two Kenyan schemes (see Appendix 10). Further refinements to the implementation methods enabled these schemes to provide a reliable electricity supply at an even lower cost per household which enabled the beneficiaries to contribution more that 50% of the total scheme cost in cash [Maher 2002a]. Two years after commissioning both schemes continue to operate successfully. The success in Kenya was significant as there was no previous experience with the technology. Management of the schemes since commissioning has been largely from within the communities, without input from outside agencies such as non-governmental organisations. The Kenyan examples demonstrate the validity of the implementation approaches developed, and underline the suitability of pico hydro for rural electrification even amongst some of the most marginalized rural people.

Analysis of scheme data collected has revealed that the present approaches to component selection often result in disappointing performance and highly variable cost per kilowatt. The research has also highlighted the complexity of the design decisions needed to achieve an optimized scheme with available components. It was recognized during the early stages of the research that computer processing would be essential for efficient optimization since rapid comparison must be made between many possible solutions. The review of existing software concluded that although some useful tools were available, the programs identified could not provide the broad range of functionality required.

Spreadsheet methods were developed to allow more rapid comparison of the way in which various off-the-shelf cables and pipes would affect a scheme's performance. Pico hydro training course participants used the spreadsheets and their feedback allowed some degree of further refinement. However, the methods were still fairly cumbersome to apply and required a high degree of user awareness in order to select the most appropriate design, even if several solutions could be generated more rapidly. This also became apparent during observation of the participant groups as they used the programs, each group arriving at a different scheme design given the same initial set of site conditions and component choices.

'Off-grid Hydro Planner' (OHPlan) was written to allow the developer to take a more 'hands-off' approach to component selection if required and to compare the cost and performance of a computer-generated scheme design with more intuitively derived solutions.

Each of OHPlan's design module (turbine-generator, penstock and distribution system) is treated independently and has a dedicated program window, driven by its own procedures and linked to independent databases. A fully optimized approach would provide an integrated scheme design, since the specification of individual components will constrain the design of the others. However, the programming of independent procedures for each program module was a necessary evolutionary step in order to verify the solutions for each scheme component. The modular structure which has resulted also enables the key requirement of user flexibility to be met. A criticism of previous micro-hydro design software which attempted to provide all-encompassing scheme designs such as MICADO (see Section **5.2.1**) was that the user could not step easily in and out of the program for design advice relating to a single scheme element. OHPlan allows the user to quickly test one scheme element and either close the program or complete a scheme design and costing and save the results. The modular approach also enables the software to be used for partial design of related systems. The distribution cables can be sized regardless of whether the power source is a hydro turbine or a diesel generator. Equally, the penstock design module could also be used to select pipes for a water supply system.

Scheme design integration has, however, been achieved to a degree, as solutions from certain parts of the program are passed to relevant fields in other modules. For example the turbine design head is used to calculate the required head loss. Once the turbine has been selected, the design head loss is passed to the penstock window to enable the pipe diameters to be sized appropriately. Two turbine solutions with alternative diameters and nozzle arrangements are given in most instances. The design head requirements of each turbine diameter will also affect the penstock cost so both must be considered. Similarly, the electrical output of the selected turbine-generator combination is passed on to the 'Power output' field of the distribution design window, for selection of the most cost-effective cables. The cost of these will depend largely on the current carrying requirements, which again may differ between turbine-generator solutions. The data which is passed on can of course be overwritten, so the user can experiment with different scenarios.

The most appropriate turbine-generator combination for a particular head can usually be clearly defined. The penstock design module requires additional user interaction to select the pipe material and a solution with single or variable pressure rating. This option is provided since pipes with pressure rating below 6 bar are unavailable in many countries. Costs are most significantly reduced by a low-pressure section at the beginning and further increments in pressure rating would add unnecessary complexity and provide greater scope for error. A useful addition to this module would be to compare the cost of the design solution with the pipe (of suitable pressure rating) which gives a head loss closest to that required. If the additional cost is small then this may be the preferred solution in order to simplify the installation.

Design of a graphical interface which enabled the relative location of spurs, branches and nodes to be specified and referenced automatically was recognized as an essential component of the new software. This requirement in particular made the previous attempts at distribution system design using spreadsheets particularly cumbersome and error prone. Other software reviewed also failed to provide a means for achieving this, yet without accurate calculation of volt drops across a connected system, cable sizing is impossible. Although still at an early stage of development, the interface which has been designed allows very straightforward representation of the system and load positions. More complicated distribution networks must be simplified or analyzed in sections. Restricting the number of cable types used would simplify the installation. This is expected to happen in practice, particularly as purchase of short cable lengths is more expensive than complete rolls. Once a layout has been drawn and consumers positioned, very rapid comparison of different power outputs and volt drop limits on the cable cost can be made.

Since site information such as head and flow is reused by different program elements, a common entry point for survey data was established, to avoid unnecessary repetition. The scheme summary also draws the results from the different program elements together for scheme costing. It is anticipated that by providing a more accurate total cost earlier in the design process, assessing the installed price per ‘light package’ will be simplified, therefore improving the accuracy of the demand survey. Only outline details of the specified components are provided in the ‘Summary’ window. Complete details can be called up under ‘Full specification’ for purchasing.

Off-Grid Hydro Planner fulfils the need for bespoke software to improve component selection on new pico hydro schemes. Since the design principles of pico hydro are identical to those of larger projects, it is anticipated that the software will also be of use to developers of projects up to 15 kW. This is approximately the economic limit for using induction generators for off-grid applications. Three-phase distribution is also more likely at higher power outputs, although the distribution module may still be applied to the single-phase sections of a larger three-phase system if the transmission volt drops are taken into account. Although the software is still at the development stage, a completed version will soon be made available for distribution and wider review. In order for this to take place, further error trapping procedures are required to prevent the program from 'tripping up' which it does on occasion if an unrecognized input is made or a variable omitted. This is time consuming but requires relatively straight-forward programming techniques. Several further refinements have been suggested and will be incorporated at a later date.

8 CONCLUSIONS

8.1 *Main conclusions from the research*

This research has shown how pico hydro can already be a cost-effective renewable energy option for village electrification but highlighted significant variations in the quality of current practice. A holistic approach was taken with this research, the aim of which was to develop methods to improve viability and thus enable more widespread adoption by rural communities. Innovative methods of turbine-generator design, demand assessment and scheme implementation including the use of computer programs to optimize component selection have provided the developer with the tools to implement cost-effective and sustainable pico hydro schemes consistently and across a broad range sites.

Detailed comparisons of ten schemes in Nepal showed that the installed cost of locally manufactured pico hydro schemes could be as low as $2000 but in some cases was as high as $9,000 per kilowatt. Analysis of data collected at these ten schemes established the sensitivity of the cost per kilowatt to the scheme design and selection of the key components.

In order to run a competitive yet profitable business from pico hydro the manufacturer must balance the challenges of implementing reliable and high quality schemes with the fragile economic circumstances of most rural customers. Numerous scheme designs are possible at each site but without the use of dedicated software, selection of the design which optimizes cost per kilowatt is complicated and time consuming. A key output of this research is novel computer software, which enables optimum choice of scheme components. On entering the site details, the user can quickly select the most appropriate turbine, generator, penstock pipe and distribution cable from those which are available locally. Distribution cable layout, estimates of power output and a detailed costing are provided in addition to specification of individual components.

In addition to the optimization software, a new turbine-generator unit was developed to increase the limited scope of application with existing designs. The new arrangement allows mechanical as well as AC electrical loads to be connected. A standardized dimensioning system facilitates batch manufacture and simplifies scheme design. High efficiency is maintained through the use of a modified turbine runner, which allows the use of larger diameter jets therefore enabling the range of suitable sites for each turbine diameter to be increased. Suitable turbine and generator combinations can be selected automatically by the software.

A further output of this research is the development of improved methods for implementation of the electrical system. This includes cost-effective methods for earth-safety improvements, particularly for areas where low impedance earth connections are hard to achieve, and practical methods for lightning protection. Significant increases in the number of beneficiaries which can be connected to a pico hydro generator have been made possible by the introduction of low cost load limiters combined with the use of energy efficient lighting. This has significantly decreased the per-household cost of new schemes and enabled households at virtually all income levels in a community to receive a connection. These improvements have been implemented in the field by the author and have been shown to enhance the cost-effectiveness of pico hydro.

Practical experience gained through installation work in target countries has shown that the sizing of new community-owned schemes is often difficult particularly when the number of beneficiaries is large. Methods of scheme sizing have been developed which allow realistic demand assessment through the provision of electricity in the form of 'light packages'. This both simplifies the scheme sizing and enables more inclusive schemes as households at lower income levels are also able to afford a basic connection. In addition to scheme sizing and demand assessment, strategies have been developed for community organization, including consumer agreements, tariff collection and scheme operation.

Building on research and work experience gained in Nepal and Colombia, countries with existing micro and pico hydropower capacity, this program of study has resulted in the production of a portfolio of methods which enhance the viability of pico hydro as an energy option for rural communities. Practical manuals describing turbine-generator design and scheme implementation methods were produced during the research and have been downloaded in more than 40 developing countries. In partnership with local organizations, demonstration schemes that adopt the new methods have been installed in Nepal, Kenya and Ethiopia.

8.2 Further work

The pico hydro design and implementation methods described provide the means to assist developers with new schemes. These alone however, will not result in a significant increase in the number of rural households electrified. In order for this to be achieved in the numerous developing countries where widespread potential exists, the coordinated efforts of governments, aid agencies, and development organizations are required to initiate and support programs of rural development and technology transfer. Site identification, sourcing of key components and potential manufacturers, installation of pilot schemes and training are all required.

Suggestions for further work focus on the continuing development of the 'OHPlan' software as this remains the area where considerable scope exists for further improvement and broad dissemination.

8.2.1 Turbine selection

Presently the options are restricted to directly driven Pelton turbines. Increasing the range to include pumps-as-turbines and small propeller turbines would allow medium and low head sites to be catered for, significantly broadening the scope of application. In order for the program to be fully capable of handling further turbine designs, a method for entering the turbine performance characteristic is required.

Providing a user option for indirect turbine drive would allow belt-driven crossflow turbines to be selected. For a complete design specification, a database of pulley and belt sizes is required. The option of indirect drives would allow expansion of scheme sizes as synchronous generators could then also be accommodated. Performance prediction with manually selected turbine and generators under the site conditions is desirable, as this would allow comparison and verification of the computer-selected combination.

8.2.2 Cable selection

Particular scope for further refinement exists within the distribution module, as this is the component where design permutations and programming complexity increase significantly. Initial improvements to the existing program have been outlined.

At present, the cable selection between nodes is achieved by calculation of a 'voltage gradient.' This is then compared with a reference voltage gradient for the spur. Since the voltage gradient between any two points on a particular spur should be equal, to minimize the volume of conductor required, a low cost cable selection is specified. However, there are two reasons why the total voltage drop will always be less than the design drop. Firstly, the reference gradient is calculated from an ideal cable diameter which would give the exact drop required at the extremity of the system. This ideal diameter is sized assuming that all the load is placed at the end of the line and therefore over-estimates the average current in any particular section. Secondly, the cables are only available in discrete sizes. When the voltage gradient between two points is calculated with each cable in turn, the cable closest to but *above* the reference level is selected. When combined together the resultant maximum volt drop is 25 to 30% below the design volt drop. This is easily rectified when selecting the cables by specifying a design volt drop which is above the maximum required. However, modification to the selection routine would allow a degree of automatic fine-tuning of the cables. Beginning with the node where the connection of the largest cable diameter ends and working backwards, exchanging the cable selected for the next smallest diameter, would enable incremental increases in the volt drop and further accompanying cost reductions. By comparing the maximum drop with the design value, this process could continue until the design fell within the specified limits.

The user does not have much control over constraining the design at present. A useful addition would be restriction to a particular cable type or combination, for example, insulated copper conductor only or mixed conductors as a design option. Similarly, it would be useful to limit the design to a specific number of cable diameters to reduce the complexity of the installation.

Non-insulated aluminum cables are cheaper than insulated copper equivalents. However the costs of installation are greater since higher quality poles and pole furniture is required. This additional cost should be reflected by a cost multiplier which is user defined (e.g. an additional US$0.8 per metre of ACSR used).

At present the cables can only be sized for straight spurs with evenly spaced consumers forming the nodes. Future improvements will include the ability to calculate voltage drops in spur branches, user specification of consumer positions and the option of variable consumer loads.

8.2.3 General improvements

The program format is still evolving in order to improve the ease of use and presentation of results. There is scope for further standardization of the different program modules and more efforts to link them together. For example, a standard section listing the design constraints which can be adjusted by the user, similar to that provided in the turbine-generator selection module, would improve the other sections. Consistency in the way in which the key results are provided in each section would also improve ease of use and promote more rapid user familiarity.

Closer integration of the design of the turbine-generator unit and penstock would enable a particular design principle to be applied. For example, selecting 'Design for minimum cost per kW' would not necessarily produce the same combination of turbine-generator and penstock as an option for 'Design for maximum power output'. Local circumstances such as hydro resource, power demand and ability to pay also dictate the most appropriate design. The selected combination could reflect this if such design principles could be applied.

The one potentially tedious feature, which may dissuade some developers from taking full advantage, is data entry of locally available component details. Since induction motors, cables and pipes and pumps are widely available and in standardized sizes, this data could all be entered beforehand. The provision of check boxes would enable the user to quickly flag those items which are locally available and limit the automatic selection. Local prices would, of course, still need to be specified.

Finally, the additional literature that has been produced during the research, in the form of the implementation and manufacturing manuals, could be adapted to form a comprehensive 'help' section. This would enable the user to access further information relating to such topics as turbine dimensioning or consumer wiring, and provide case study examples where the component selection techniques have been adopted. This would particularly enhance application of the program as a training tool for new pico hydro developers.

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10 APPENDICES

10.1 *Sample research data, Nepal 1998*

10.1.1 Simswara cost analysis

Description	Specification	Rs / Unit	No. of Units	Cost / Rs	Cost / $	Actual Cost / kW ($)	Cost per Household ($)	Actual Cost / kW ($) (Optimised Penstock)
Generating Equipment								
Peltric Set	1000 W	29000	1	29000	483			
IGC	1000 W	11000	0	0	0			
Ballast & Tank		1500	0	0	0			
			Total	29000	483	2148.15	30.21	834.77
Penstock								
HDPE Pipe	50mm/6kg	103	550	56567.5	943			
	38mm/10kg	96.32	50	4816	80			pipe
Joining		1500	1	1500	25			600 x 63mm
			Total	62883.5	1048	4658.04	65.50	2530.22
Distribution Cable								
Copper Cable	7/22	1000			0			
House wire (PVC)	3/20	605	23	13915	232			
			Total	13915	232	1030.74	14.49	400.55
Addtional Items								
Bell mount and trash rack		1500	1	1500	25			
Earthing Sets		1000	2	2000	33			
Lightning Arrestor	2.5 kV	1500	1	1500	25			
Main Switch		300	1	300	5			
House wiring Accessories		230	16	3680	61			
MCB for each hous	Low W	350	16	5600	93			
Tool Box		500	1	500	8			
Packing Charge		500	1	500	8			
			Total	15580	260	1154.07	16.23	448.47
			Total	121378.5	2023	8991.00	126.44	4214.02

10.1.2 Bulke cost analysis

Description	Specification	Rs / Unit	No. of Units	Cost / Rs	Cost / $	Actual Cost / kW ($)	Cost per Household ($)	Actual Cost / kW ($) (Optimised)
Generating Equipment								
Peltric Set	1500	29000	1	29000	483	619.66	30.21	619.66
Gate Valve		8000	1	8000	133			
IGC	1500	18000	1	18000	300			
Ballast & Tank		2500	1	2500	42			
			Total	57500	958	1228.63	59.90	1228.63
Penstock								
HDPE Pipe	75mm/6kg	207.52	160	33203.2	553			
Joining		1500	1	1500	25			
			Total	34703.2	578	741.52	36.15	741.52
Distribution Cable								
Copper Cable	7/18	2300	39	89700	1495			
House wire (P	3/22	185	0	0	0			Cable 7/22
			Total	89700	1495	1916.67	93.44	833.33
Addtional Items								
Intake Screen		1800	1	1800	30			
6.I. Pipe for Intake		1200	1	1200	20			
Earthing Sets		1000	2	2000	33			
Air Vent		750	1	750	13			
Main Switch		300	1	300	5			
House wiring Accessories		190	16	3040	51			
MCB for each house				0	0			
Tool Box		2500	1	2500	42			
Packing Charge		400	1	400	7			
			Total	11990	200	256.20	12.49	256.20
			Total	**193893.2**	**3232**	**4143.02**	**201.97**	**3059.68**

10.1.3 Turbine speed and efficiency measurements

No.	Rated Power	Net Head	Ideal Speed (rpm)	Ideal Speed (Rpm)	Freq.	Actual Speed	Over-speed
	(kW)	(m)	150mm p.c.d.	185mm p.c.d.	(Hz)	(rpm)	%
1	1.0	42.73	1656		67	2028	22
2	1.0	28.99	1364		57	1710	25
3	3.0	44.73		1374	49.5	1485	8
4	1.5				49.2	1476	
5	2.0	57.17		1553	52.8	1584	2
6	3.0	43.86		1360	55.9	1677	23
7	3.0	35.16		1218	47.1	1413	16
8	1.0	51.03	1810		79.8	2394	32
9	1.5	113.7	2701		49.3	1479	-45
10	3.0	54.56		1517	60.3	1809	19

Table 10-1: Variation of actual and ideal turbine speeds

10.1.4 Electrical measurements

Site	Power (kW)					Line Currents (A)		
	Rated	Measured	%	Volts	Hz	A	B	C
1	1.0	0.607	61%	176	67.6	1.23	1.29	1.32
2	1.0	0.225	23%	175	57	2.88	3.68	1.41
3	3.0	0.842	28%	172	49.5	9.35	6.17	6.41
4	1.5	0.600	40%	212	49.2	5.67	5.68	4.7
5	2.0	0.780	39%	207	52.8	10.01*	5.83*	7.97*
6	3.0	1.499	50%	198	55.9	17.51	9.26	9.4
7	3.0	0.581	19%	171.7	47.1	6.48	7.8	6.61
8	1.0	0.352	35%	208	79.8			
9	1.5	1.954	130%	193.8	49.3			
10	3.0	1.340	45%	205	60.3	7.23	5.4	5.54

Table 10-2 Electrical measurements taken at the schemes visited

10.1.5 Summary of forebay and reservoir details at sample sites

Site	Dimensions (m)	Capacity	Storage Time (hrs)	Flow In (l/s)	Intake	Construction	Settling Basin	Flushing facility
1	7 x 3.5 x 1.5	37 m^3	4-5	1	diverted stream + pipe	stone and mud	no	no
2	1 x 1 x 0.5	0.5 m^3	0	4 (at spring)	diverted stream	concrete	no	no
3	14 x 8 x 2.0	224 m^3	12	2.2	200m canal	concrete and stone	yes	no
4	11 x 4 x 2	88 m^3	12		tailrace from no.3	stone and cement	woven basket	
5	6 x 4 x 2	48 m^3	5 + 2		diverted stream	concrete	yes	no
6	2.4 x 1.5 x 1.8	6.6 m^3	4		irrigation canal	earth	intake pool	no
7	2 x 8 x 2	32 m^3	5 + 2 minimum		200m canal	earth	no	no
8	10 x 4 x 2	80 m^3	5 (12 in Monsoon)		stream and small pipe	Concrete dam	yes	bunged pipe
9	3 x 3 x 1.5	13.5 m^3	24 hr op. Possible		spring source	stone and concrete dam	yes	bunged pipe
10	7 x 3 x 1.8	38 m^3	4		stream and small pipe	Concrete dam	yes	bunged pipe

Table 10-3 Summary of forebay and reservoir details

10.1.6 Details of earth connections at sample sites

Site	Description of Earth Connection
1	Not known
2	No Earth
3	3 m coil of copper wire buried below lightning conductor outside powerhouse
4	No Earth
5	One straight copper wire 3m deep underneath first pole
6	Buried 1.2 m underneath lightning conductor which is 5 m high
7	One straight copper wire buried 3m below 2 lightning conductors (outside p/h and in village)
8	12" sq. copper plate buried 2m deep
9	12" sq. copper plate buried 2.5 m below the first pole outside the power house.
10	Not known

Table 10-4 Survey of earth connection techniques.

10.2 Results of modelling site conditions at Nepal schemes

Site	Design Output Power	HDPE Penstock Internal Diameter (mm) with Pipe Length (m) in Columns						Predicted Flow Rate	Real Gross Head	Head Loss in each Penstock Section (m)	
	kW	38	50	63	75	90	100	l/s	m	1	2
1	1.06	10	170					3.88	64	17.12	4.15
2	1.06	50	550					3.19	75	33.54	12.31
3	3.04						120	7.54	46	1.27	
4	1.51				***				60		
5	2.01				160			6.73	63	5.83	
6	3.04						110	7.46	45	1.14	
7	3.04						100	6.68	36	0.84	
8	1.06			250				4.20	60	8.97	
9	1.51				552			7.27	137	23.34	
10	3.04					250		8.33	60	5.44	

Table 10-5 Summary of penstock conditions based on survey data (1)

Site	Net Head	Head Loss	Predicted Output Power	Measured Output Power	Estimated Efficiency	Design Head	Design Flow Rate
	m	%	W	W	%	Metres	l/s
1	42.73	33	732	607	37	55	4.4
2	29.15	61	410	225	25	55	4.4
3	44.73	3	1489	842	25	72	9.6
4				600		63	5.4
5	57.17	9	1699	780	21	64	7.1
6	43.86	3	1445	1499	47	72	9.6
7	35.16	2	1037	581	21	72	9.6
8	51.03	15	946	352	17	55	4.4
9	113.7	17	3647	1954	24	63	5.4
10	54.56	9	2005	1340	30	72	9.6

Table 10-6 Summary of penstock conditions based on survey data (2)

10.2.1 Distribution system analysis - Bulke

Name of Site	**Bulke**	
District	**Sankuwa Sabha**	
Assumed Power Factor	1	
Nominal Voltage (V)	230	
Measured Voltage	207	
Rated Power (W)	2000	
Measured Power (W)	780	780
Total Loads (W)	90	1440
Cable Type	7,18	7,22
Resistivity (Ohms / km)	2.08	6.11
Length of system (m)	3574	
Multiplying Factor	1	

Point	**Distance (Metres)**	**Adjusted Distance (m)**	**Cumulative Distance (m)**	**Lighting Load (W)**	**Adjusted Load (780 W)**	**Design Load (2000W)**	**Design Current @ 230v (A)**	**Actual Current @ 207v (A)**	**Resistance of Cable (ohms)**	**Design Voltage Drop (v)**	**Actual Voltage Drop (v)**	**Design Voltage Drop %**	**Actual Voltage Drop %**
Spur A													
1	250	250	250	360	195	500	2.17	0.94	1.04	2.26	0.98	0.98	0.47
2	33	33	283	270	146	375	1.65	0.71	0.14	0.23	0.10	0.10	0.05
3	43	43	326	180	98	250	1.10	0.47	0.18	0.20	0.08	0.09	0.04
4	5	5	331	90	49	125	0.55	0.24	0.02	0.01	0.00	0.00	0.00
											Σ	1.17	**0.56**
Spur B													
5	141	141	141	90	49	125	0.54	0.24	0.59	0.32	0.14	0.14	0.07
											Σ	0.14	**0.07**
Main Line													
6	75	75	75	990	536	1375	5.98	2.59	0.31	1.87	0.81	0.81	0.39
7	190	190	265	900	488	1250	5.48	2.35	0.79	4.33	1.85	1.88	0.90
											Σ	2.69	**1.29**
Spur C													
8	195	195	460	360	195	500	2.23	0.93	0.81	1.81	0.75	0.79	0.36
9	79	79	539	270	146	375	1.69	0.70	0.33	0.56	0.23	0.24	0.11
10	115	115	654	180	98	250	1.13	0.46	0.48	0.54	0.22	0.23	0.47
11	20	20	674	90	49	125	0.57	0.23	0.08	0.05	0.02	0.02	0.12
											Σ	3.98	**2.35**
Main Line													
12	105	105	370	450	244	625	2.79	1.19	0.44	1.22	0.52	0.53	0.25
13	97	97	467	360	195	500	2.25	0.96	0.40	0.91	0.39	0.39	0.19
14	411	411	878	270	146	375	1.69	0.72	1.71	2.89	1.23	1.26	0.59
15	23	23	901	180	98	250	1.14	0.48	0.10	0.11	0.05	0.05	0.02
16	5	5	906	90	49	125	0.57	0.24	0.02	0.01	0.01	0.01	0.00
Σ		1787									Σ	4.93	**2.34**

10.2.2 Optimization of cable sizing - Bulke

Adjusted Load (780W)	Resistance of Cable (ohms)	Design Current @ 230v (A) (Optimised)	Actual Current @ 207v (A) (Optimised)	Design Voltage Drop (v) (Optimised)	Actual Voltage Drop (v) (Optimised)	Design Voltage Drop % (Optimised)	Actual Voltage Drop % (Optimised)	Power Loss in Cable (Design) W	Power Loss in Cable (Actual) W	Power Loss in Cable (Optimised: Design) W	Power Loss in Cable (Optimised; Actual) W
195	3.06	2.17	0.94	6.64	2.88	2.89	1.39	4.9149	0.923	14.44	2.71
146	0.40	1.65	0.72	0.67	0.29	0.29	0.14	0.3722	0.069	1.10	0.21
98	0.53	1.10	0.48	0.58	0.25	0.25	0.12	0.216	0.04	0.64	0.12
49	0.06	0.55	0.24	0.03	0.01	0.01	0.01	0.0063	0.001	0.02	0.00
					Σ	3.44	**1.66**				
49	1.72	0.54	0.24	0.94	0.41	0.41	0.20	0.1733	0.033	0.51	0.10
					Σ	0.41	**0.20**				
536	0.92	5.98	2.59	5.48	2.37	2.38	1.15	11.151	2.094	32.76	6.15
488	2.32	5.49	2.38	12.75	5.53	5.54	2.67	23.729	4.35	70.02	13.18
					Σ	7.93	**3.82**				
195	2.38	2.25	1.02	5.36	2.43	2.33	1.17	4.0489	0.702	12.08	2.48
146	0.97	1.71	0.77	1.65	0.75	0.72	0.36	0.9378	0.159	2.81	0.58
98	1.41	1.14	0.52	1.60	0.73	0.70	0.35	0.6098	0.102	1.83	0.38
49	0.24	0.57	0.26	0.14	0.06	0.06	0.03	0.0266	0.004	0.08	0.02
					Σ	11.73	**5.74**				
244	1.28	2.81	1.22	3.61	1.57	1.57	0.76	3.4065	0.622	10.16	1.92
195	1.19	2.27	0.99	2.69	1.17	1.17	0.57	2.0362	0.369	6.09	1.16
146	5.02	1.71	0.74	8.59	3.74	3.73	1.81	4.8928	0.884	14.68	2.79
98	0.28	1.16	0.51	0.33	0.14	0.14	0.07	0.1249	0.022	0.38	0.07
49	0.06	0.58	0.25	0.04	0.02	0.02	0.01	0.0068	0.001	0.02	0.00
					Σ	14.55	**7.03**	**56.65**	**10.38**	**167.61**	**31.86**

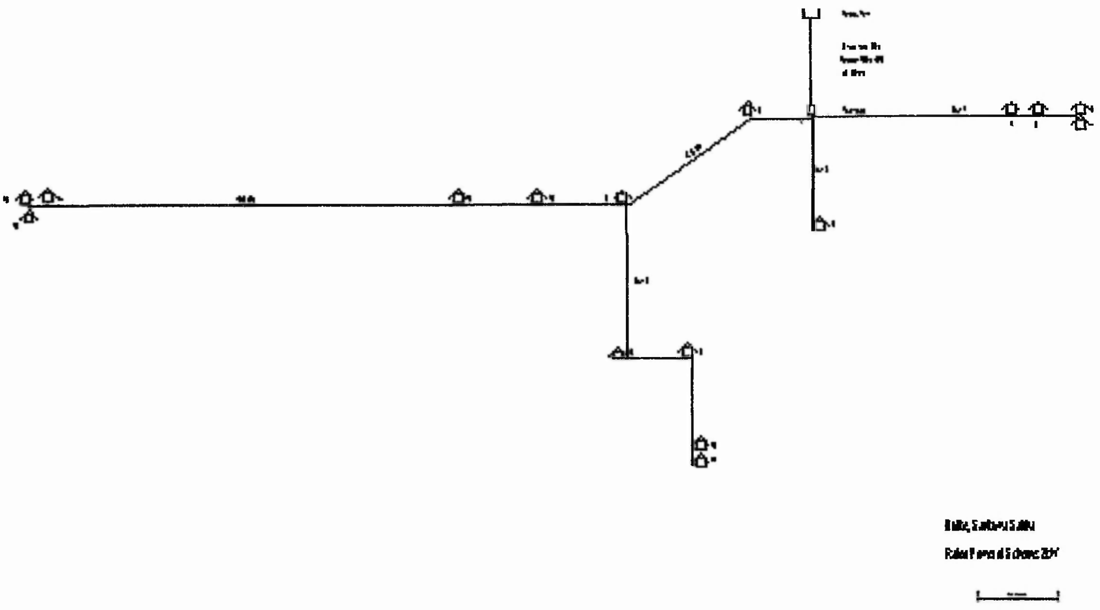


Figure 10-1 Distribution system layout at Bulke

10.2.3 Comparison of inductive with resistive volt drop in closely spaced conductors with a small overall diameter.

For example, considering a cable with a nominal cross sectional area of 6mm^2 made up of seven individual copper strands.

Overall physical diameter = 3 x strand diameter = $3\times\sqrt{\dfrac{4\times 6mm^2}{7\times\pi}}$ = 3.13mm

Therefore, overall physical conductor area = $\dfrac{\pi\times 3.13^2}{4}$ = 7.71mm^2

The equation for the reactance, X, of a conductor is

$$X = 2.\pi.f\left[19+46.\ln\left(\frac{s}{d}\right)\right].10^{-5} \quad \text{ohms / km}$$

where

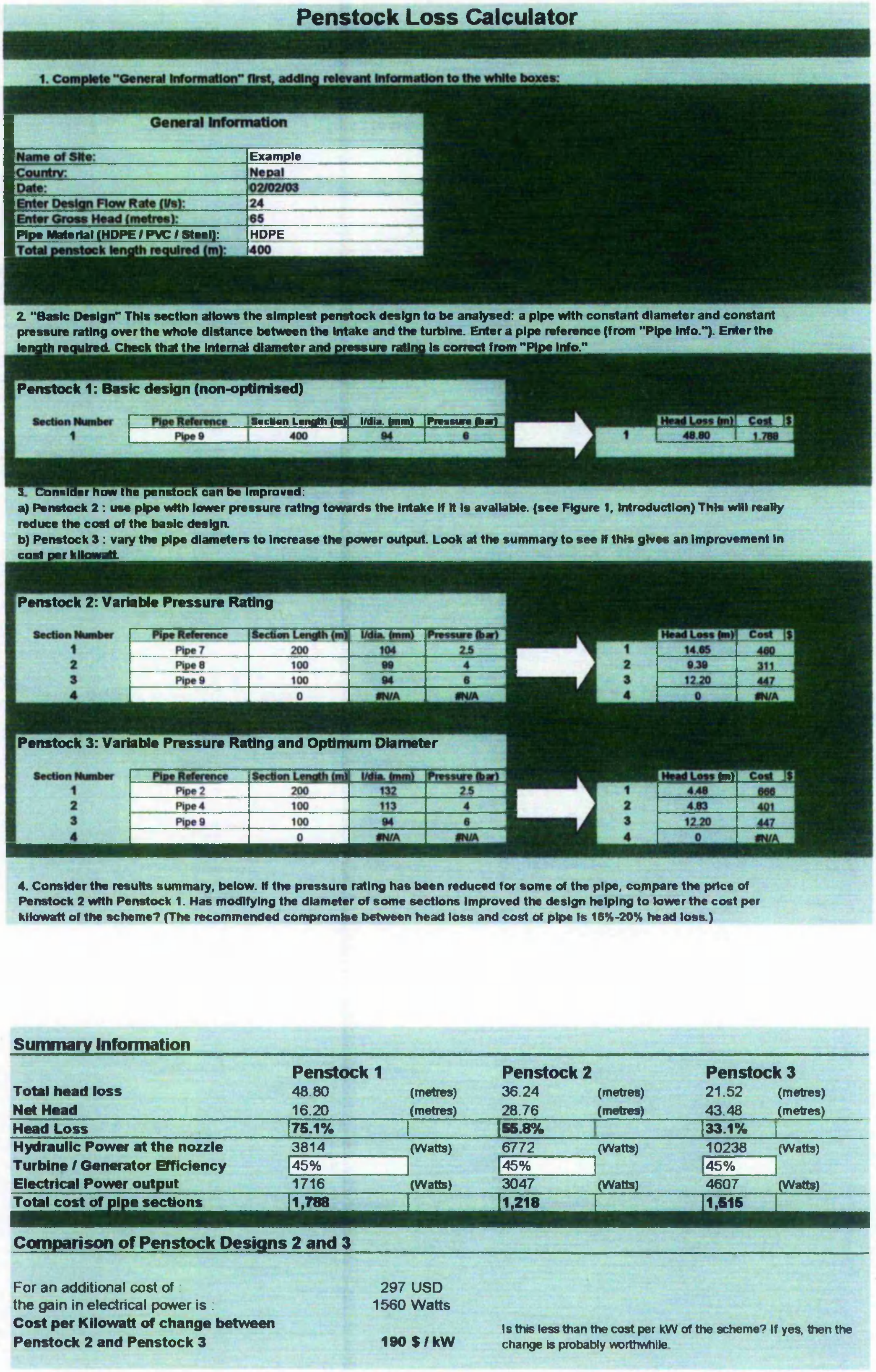
f = line frequency (Hz)

s = equivalent conductor spacing (m)

d = overall physical diameter (m)

for a 50 Hz, single-phase system with 6mm^2 insulated copper conductors and spacing of 10mm (i.e. twisted or taped together) the reactance = 0.227 ohms per kilometre. This compares with a resistance of 2.833 ohms per kilometre. The inductive volt drop is therefore equivalent to just 8% of the resistive volt drop and can be neglected when sizing the conductors.

10.3 Select_Pipe penstock design spreadsheet



Penstock Loss Calculator

1. Complete "General Information" first, adding relevant information to the white boxes:

General Information

Name of Site:	Example
Country:	Nepal
Date:	02/02/03
Enter Design Flow Rate (l/s):	24
Enter Gross Head (metres):	65
Pipe Material (HDPE / PVC / Steel):	HDPE
Total penstock length required (m):	400

2. "Basic Design" This section allows the simplest penstock design to be analysed: a pipe with constant diameter and constant pressure rating over the whole distance between the intake and the turbine. Enter a pipe reference (from "Pipe Info."). Enter the length required. Check that the internal diameter and pressure rating is correct from "Pipe Info."

Penstock 1: Basic design (non-optimised)

Section Number	Pipe Reference	Section Length (m)	I/dia. (mm)	Pressure (bar)		Head Loss (m)	Cost $
1	Pipe 9	400	94	6	1	48.80	1,788

3. Consider how the penstock can be improved:

a) Penstock 2 : use pipe with lower pressure rating towards the intake if it is available. (see Figure 1, introduction) This will really reduce the cost of the basic design.

b) Penstock 3 : vary the pipe diameters to increase the power output. Look at the summary to see if this gives an improvement in cost per kilowatt.

Penstock 2: Variable Pressure Rating

Section Number	Pipe Reference	Section Length (m)	I/dia. (mm)	Pressure (bar)		Head Loss (m)	Cost $
1	Pipe 7	200	104	2.5	1	14.65	460
2	Pipe 8	100	99	4	2	9.39	311
3	Pipe 9	100	94	6	3	12.20	447
4		0	#N/A	#N/A	4	0	#N/A

Penstock 3: Variable Pressure Rating and Optimum Diameter

Section Number	Pipe Reference	Section Length (m)	I/dia. (mm)	Pressure (bar)		Head Loss (m)	Cost $
1	Pipe 2	200	132	2.5	1	4.48	666
2	Pipe 4	100	113	4	2	4.83	401
3	Pipe 9	100	94	6	3	12.20	447
4		0	#N/A	#N/A	4	0	#N/A

4. Consider the results summary, below. If the pressure rating has been reduced for some of the pipe, compare the price of Penstock 2 with Penstock 1. Has modifying the diameter of some sections improved the design helping to lower the cost per kilowatt of the scheme? (The recommended compromise between head loss and cost of pipe is 15%-20% head loss.)

Summary Information

	Penstock 1		Penstock 2		Penstock 3	
Total head loss	48.80	(metres)	36.24	(metres)	21.52	(metres)
Net Head	16.20	(metres)	28.76	(metres)	43.48	(metres)
Head Loss	75.1%		55.8%		33.1%	
Hydraulic Power at the nozzle	3814	(Watts)	6772	(Watts)	10238	(Watts)
Turbine / Generator Efficiency	45%		45%		45%	
Electrical Power output	1716	(Watts)	3047	(Watts)	4607	(Watts)
Total cost of pipe sections	1,788		1,218		1,515	

Comparison of Penstock Designs 2 and 3

For an additional cost of :	297 USD	
the gain in electrical power is :	1560 Watts	
Cost per Kilowatt of change between Penstock 2 and Penstock 3	**190 $ / kW**	Is this less than the cost per kW of the scheme? If yes, then the change is probably worthwhile.

Figure 10-2 Screen print from Select_Pipe penstock design program

10.3.1 The Henri Darcy formula for friction head loss in pipes

$$h_f = \frac{\Delta p}{\rho g} = \frac{4 f l \bar{u}^2}{d 2 g}$$

where
h_f = head loss due to friction (m)
f = friction factor
l = pipe length (m)
u = mean velocity (m/s)
d = pipe diamter (m)
g = acceleration due to gravity (m/s^2)

The friction factor f is a coefficient that is a function both of Reynolds number and the relative roughness k/d, the ratio of surface roughness to pipe diameter [Massey 1997].

If the flow was laminar head loss would not depend on surface roughness and would be mainly affected by Reynolds number. However flow in pipes is usually turbulent and as the turbulence increases, corresponding to higher values of Reynolds number, the effect of Reynolds number reduces until f becomes independent of Re and is purely influenced by k/d. So, h_f is proportional to u^2 in Darcy's formula for fully developed turbulent flow as all other parameters are unchanging. Since the flow rate Q = u x A, $h_f \propto Q^2$ for a pipe of constant diameter.

10.4 Design methods for distribution systems

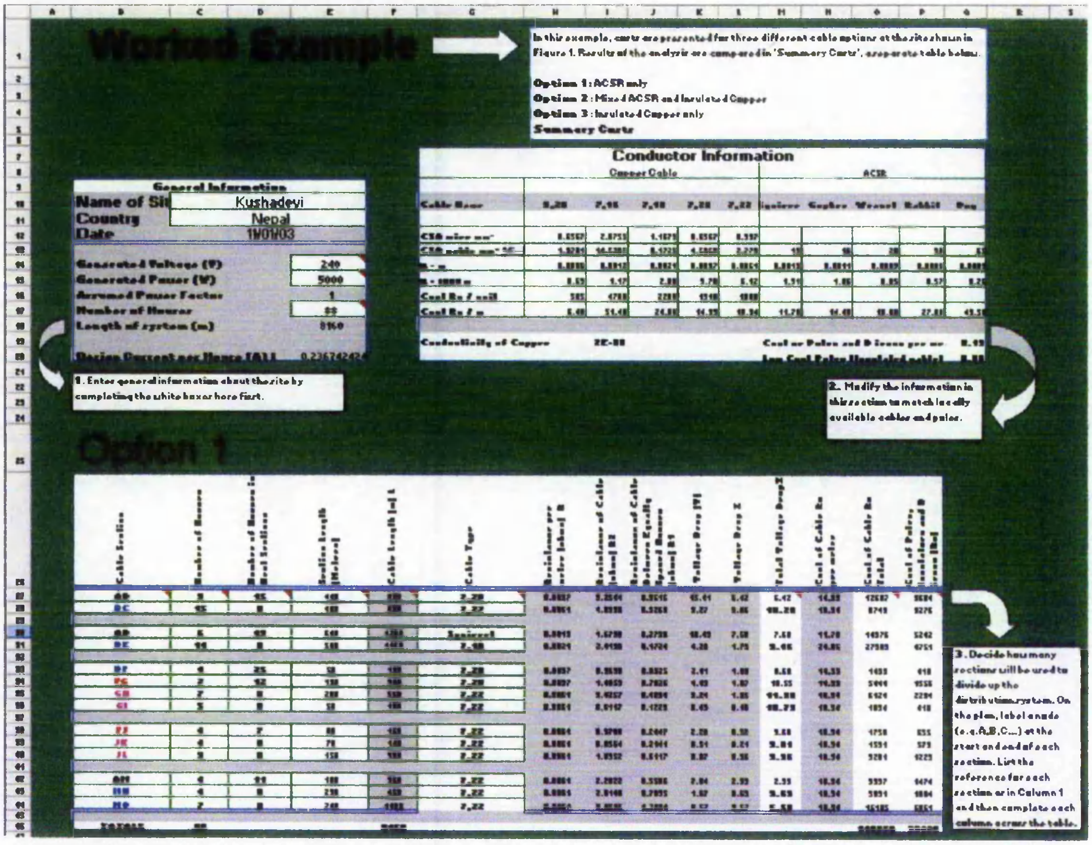
Design Criteria	Grid-connected Village Electrification	Off-grid Village Electrification up to 5kW
Layout pattern	Each load connected using the least amount of cable required	Each load connected using the least amount of cable required
Line size	Allows volt drops that fall within acceptable limits. For 11kV voltage drops are +/- 3%	Allows volt drops that fall within acceptable limits. More flexibility therefore more scope for minimisation.
Problem size	Need to decide boundary of area for design analysis	Boundary layer determined by economic limits and power/consumer ratio.
Number of substations	Determined by area boundary and load density	N/A
Tapering of conductors	Necessary to optimise economically, depends on load density, layout and meshing.	Necessary to optimise economically, depends on load density, layout and meshing.
Type of consumers	Industrial or domestic, single phase or 3 phase power supplied	Single phase power to most consumers. (If 3-phase, then to one load only but can be ignored for this study).
Future load forecasts	Predict likely increase in demand from load history.	Future loads usually ignored in favour of most economical scheme
Voltage levels	Economics of transformers v's cable costs	Voltage level usually fixed at the generator at mains voltage.
Load density	Important because affects extend of meshing and transformer numbers	N/A
Extent of meshing	Meshing reduces power losses economically where load density is high. Radial loops can be completed at relatively small cost which is more than offset by reduced losses for particular cable diameters.	Rarely applies because of small number of consumers. Requires further analysis to determine when it becomes cost-effective. Rings in houses reduces losses because loads come on at different times. Should argue against using rings for these – faults can go undetected, isolation is more difficult.

Table 10-7 Comparison of criteria used to assess the design of grid-connected and off-grid systems

Design Constraints	Grid-connected Village Electrification	Off-grid Village Electrification up to 5kW
Location of existing feeder trunks	Important	N/A
Location of existing transformers	Important	N/A
Size of key elements and limits of upgrading	Important	N/A
Physical obstructions	Affects layout	Affects layout
Economic distance to transmit with transformer	Depends on load density	N/A
Underground or overhead conductors	Underground cables much more expensive than small overhead systems in rural areas and are therefore infrequently used.	Underground cables much more expensive than small overhead systems in rural areas and are therefore infrequently used.
Terrain type	Cost of extending feeders. Little effect on LV distribution	N/A
Available equipment	Supplied by utility	Local materials substituted when necessary. Basic material requirements. Design could be modified due to lightning particularly if no arrestors available
Type of area	Eg. Urban, rural affects load density,	Less effect because small-scale and usually rural.
Power house location	N/A	May be some flexibility (e.g by building a canal) but usually highly constrained.

Table 10-8 Design constraints affecting the two types of system

10.5 'Pico Cables' distribution design spreadsheet



Worked Example

In this example, costs are presented for three different cable options at the site shown in Figure 1. Results of the analysis are compared in 'Summary Costs', a separate table below.

Option 1: ACSR only
Option 2: Mixed ACSR and Insulated Copper
Option 3: Insulated Copper only
Summary Costs

Conductor Information

Copper Cable

ACSR

General Information

Name of Sit	Kushadevi
Country	Nepal
Date	1W01W03
Generated Voltage (V)	240
Generated Power (W)	5000
Assumed Power Factor	1
Number of Houses	88
Length of system (m)	8160
Design Current per House (A)	0.236742424

1. Enter general information about the site by completing the white boxes here first.

2. Modify the information in this section to match locally available cables and poles.

Option 1

3. Decide how many sections will be used to divide up the distribution system. On the plan, label a node (e.g. A,B,C...) at the start and end of each section. List the reference for each section as in Column 1 and then complete each column across the table.

Figure 10-3 Screen-print from 'Pico Cables' spreadsheet volt drop analysis

10.5.1 Distribution system layout plan for Kushadevi, Nepal

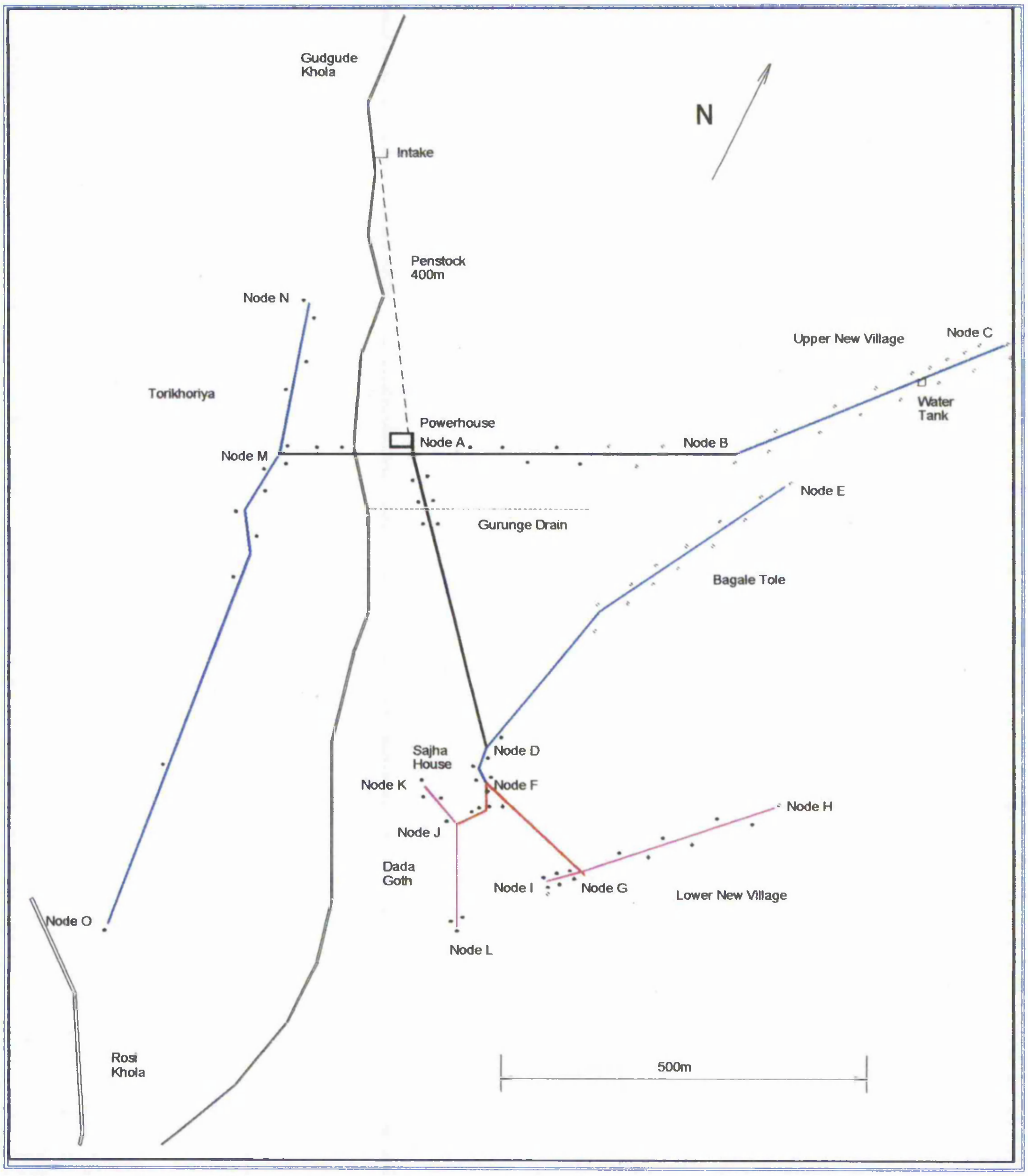
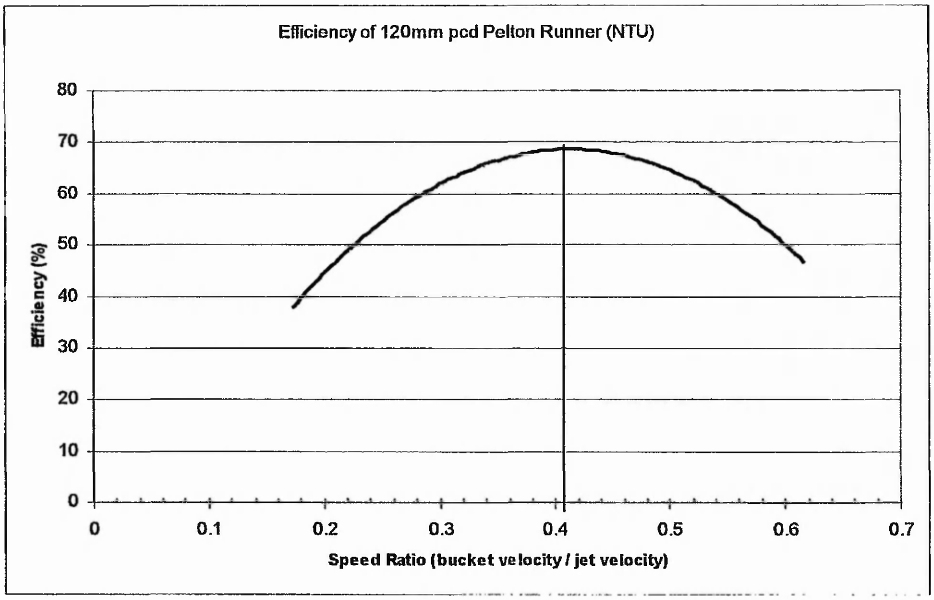


Figure 10-4 Kushadevi distribution system, optimized using spreadsheet volt drop analysis

10.6 Optimum head and turbine efficiency.

A performance characteristic for a Pelton runner design developed at NTU is shown in the Figure below:

Figure 10-5 NTU Pelton turbine characteristic showing optimum speed ratio



Maximum efficiency occurs when the ratio of bucket to jet velocity is at an optimum value. For Pelton turbines with diameters greater than 250mm, the optimum speed ratio is commonly around 0.45. However, performance tests carried out on the runners developed by NTU have identified that the ratio for optimum performance is approximately 0.41 as illustrated above. This was used to calculate the optimum head as follows:

$$V_{jet} = \sqrt{2gH} \qquad (1)$$

$$U_{bucket} = \frac{pcd}{2} \times \frac{2\pi N}{60} \qquad (2)$$

where:
H is net head (m)
pcd is effective diameter of runner (m)
N is speed (rpm) of turbine (or generator as only directly coupled designs are considered)

For optimum efficiency: $U_{bucket} = 0.41 \times V_{jet}$

Substituting 1 and 2 above and multiplying out the constants gives approximately:

$$N = \frac{35 \times \sqrt{H_{opt}}}{pcd}$$

Therefore rearranging, the ideal head for a particular runner and generator speed is given by:

$$H_{opt} = (\frac{pcd \times N}{35})^2$$

10.7 Program samples from Off-grid Hydro Planner

Samples of the Visual Basic 6.0 code have been included to illustrate the methods used for component selection in OHPlan. Comments are given in blue.

10.7.1 Procedure for calculating head loss

The procedure for calculating head loss using the Haaland formula is as follows:

```
'global variables corresponding to survey data and user inputs are defined

    Global sngPipeLoss As Single
    Global snggrosshead As Single
    Global sngflow As Single
    Global sngpenstocklength As Single

Public Function headloss(snggrosshead As Single, sngflow As Single, sngpenstocklength As
Single, sngroughness As Single, sngpipedia As Single)

' local variable are defined
    Dim sngVelocity As Double
    Dim sngFlowm As Single
    Dim sngdiameterm As Single
    Dim sngReynolds As Single
    Dim sngF As Single

    Const PI = 3.14159265358979

        sngFlowm = sngflow / 1000
        sngdiameterm = sngpipedia / 1000


'flow velocity is calculated

             sngVelocity = sngFlowm / (PI * (sngdiameterm ^ 2) / 4)

'Reynolds number is calculated

              sngReynolds = sngVelocity * 0.1 / (1.14 * 10 ^ -6)

'loss is calculated for a particular pipe specification.

             sngF = (1 / (-3.6 * (Log((6.9 / sngReynolds) + (sngroughness * 10 ^ -3 / (3.71 *
             sngdiameterm)) ^ 1.11) / Log(10#))) ^ 2)

             sngPipeLoss = (4 * sngF / sngdiameterm) * ((sngVelocity ^ 2) / (2 * 9.81)) *
             sngpenstocklength

End Function
```

10.7.2 Procedure for selecting the closest diameter matches

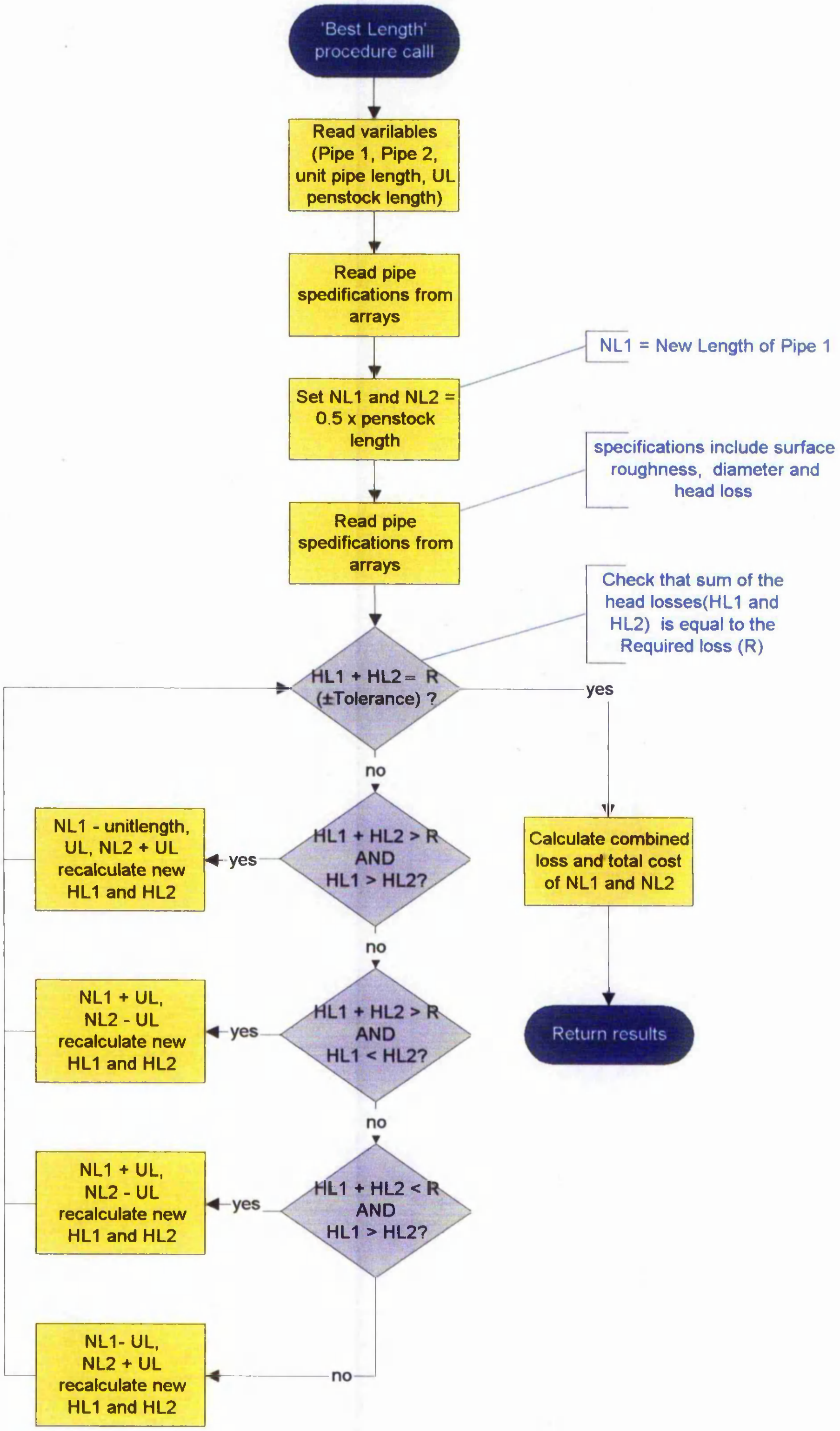
This procedure is designed to select the two pipe diameters which give a head loss either side of the ideal value.

```
Private Sub cmdautoselect_Click()

'display reference number of pipe which gives closest value of head loss to
lblreqheadloss.caption in txtpipe1.text

            ReDim difference(totalpipes)
             ReDim Preserve refarray(totalpipes)
              varclosest = lossarray(1)

    For checkall = 1 To totalpipes

     difference(checkall) = Sqr((sngreqloss - lossarray(checkall)) ^ 2)
     sngcomparison = Sqr((sngreqloss - varclosest) ^ 2)

         If difference(checkall) <= sngcomparison Then
         varclosest = lossarray(checkall)
         pipe1index = checkall
         txtpipe1.Text = refarray(pipe1index)

         End If
    Next


    'after finding the closest match to the required head loss (varclosest)
    'the pipe which gives the closest loss of the opposite sign (varoppsign)is required

    'if loss from varclosest < reqloss then varoppsign
    'must be first pipe with bigger loss than reqloss
    'otherwise first pipe with smaller loss

    Dim check2 As Integer

    If lossarray(pipe1index) < sngreqloss Then
    difference(1) = sngreqloss - lossarray(1)

     For check2 = 2 To totalpipes

            difference(check2) = sngreqloss - lossarray(check2)

            'interested only when this is negative as this means a loss greater than reqloss
            sngcomparison = -1 * (sngreqloss - varclosest)

            'this will definately be negative

          If difference(check2) < sngcomparison And difference(check2) > difference(check2 - 1)
Then

           'if this is true, then difference must be negative
           'doesn't give the closest result just any negative result

           pipe2index = check2
           txtpipe2.Text = refarray(pipe2index)

           End If
```

```
   Next


  ElseIf lossarray(pipe1index) > sngreqloss Then

     difference(1) = sngreqloss - lossarray(1)

      For check2 = 2 To totalpipes

      difference(check2) = sngreqloss - lossarray(check2)
'interested only when this is positive as this means a loss smaller than reqloss

       sngcomparison = Sqr((sngreqloss - varclosest) ^ 2) 'will definitely be positive

      'comparison is formed from difference between required head loss and closest pipe
match.
      '2nd pipe found,must be larger than this to prevent selection of the same diameter again.

          If difference(check2) > sngcomparison And difference(check2) <
Sqr((difference(check2 - 1)) ^ 2) Then

          'if this is true, then difference must be positive

          pipe2index = check2
          txtpipe2.Text = refarray(pipe2index)

          End If

       Next

  Else
  msg = "A pipe combination with matches the required head loss could not be found."
  title = "Pipe Combinations"
  style = vbOK
  Response = MsgBox(msg, style, title)
  txtpipe2.Text = "0"
 End If

 'procedure require to identify which pipes were selected for diameter and roughness data
 'could use index number or could compare loss results to find a match.


 End Sub
```

10.7.3 Flow chart of 'Best length' procedure

This procedure was developed to find the appropriate length of two pipes which will give the precise head loss required.



10.7.4 Procedure for cable selection

This procedure is designed to size cables for connection of all nodes on a spur according to the maximum allowable volt drop as defined by the user:

```
Private Sub cmdGetVD_Click()

 frmdisttables.lstCableSelections.Clear

 Datcablerecs.Recordset.MoveLast
 TotalCables = Datcablerecs.Recordset.RecordCount

 genP = txtgenpower.Text
 TotalCons = txtTotalCons.Text

    Dim addconsumers As Integer
    Dim Conindex As Integer
    Dim Conposition As Integer

    ReDim spurI(intspurno)
    ReDim minCSA(intspurno)
    ReDim refCSA(intspurno)
    ReDim sngspurVD(intspurno)
    ReDim sngspurVDpercent(intspurno)
    ReDim CableRef(TotalCables)
    ReDim CableCost(TotalCables)
    ReDim cableCSAarray(TotalCables)
    ReDim VoltGradref(intspurno)
    ReDim CableColour(TotalCables)

    'Dimension node arrays as 2D to allow reference to consumer number and spur

    ReDim NodeI(intspurno, TotalCons)
    ReDim NodeminCSA(intspurno, TotalCons)
    ReDim NodeVG(intspurno, TotalCons)
    ReDim NodeMaxVG(intspurno, TotalCons)
    ReDim NodeVD(intspurno, TotalCons)
    ReDim NodeTotVD(intspurno, TotalCons)
    ReDim NodeVDpercent(intspurno, TotalCons)
    ReDim NodeRef(intspurno, TotalCons)
    ReDim NodeColour(intspurno, TotalCons)

' read user defined fields and calculate consumer current assuming loads are equal and
limited.

    genV = txtGenVolts.Text
    genI = genP / genV
    ConI = genI / TotalCons

'loop through spurs and calculate reference voltage gradient for design voltage drop at end of
spur
'this is based on the ideal cable diameter with a fixed resistance per metre

    For Spurindex = 0 To intspurno

            spurI(Spurindex) = (intspurcons(Spurindex) / TotalCons) * genI
            refCSA(Spurindex) = (1.7 / (txtmaxVD.Text * genV)) * spurI(Spurindex) * 2 *
intspurlength(Spurindex)
            cableRperm = 1.7 * 10 ^ -8 / (refCSA(Spurindex) * 10 ^ -6)
            VoltGradref(Spurindex) = spurI(Spurindex) * cableRperm
```

```
    'loop through consumers and store node current and node reference

        For Conindex = 1 To intspurcons(Spurindex)

            NodeMaxVG(Spurindex, Conindex) = 0

                If Conindex = 0 Then
                Conposition = 1
                Else:
                Conposition = Conindex
                End If

            NodeI(Spurindex, Conindex) = spurI(Spurindex) * (intspurcons(Spurindex) - (Conindex
- 1)) / intspurcons(Spurindex)
            NodeRef(Spurindex, Conindex) = Chr(65 + Spurindex) & Conposition

            newX = NodeX(Spurindex, 0, Conindex)
            newY = NodeY(Spurindex, 0, Conindex)

    'indexes through cable records, storing details in relevant arrays and identifying optimum
diameter for a closely matched voltage gradient


            Datcablerecs.Recordset.MoveFirst

        For cableindex = 1 To TotalCables

                cableCSAarray(cableindex) = Datcablerecs.Recordset.Fields("Cross Sectional
Area").Value
                CableRef(cableindex) = Datcablerecs.Recordset.Fields("Cable Reference").Value
                CableCost(cableindex) = Datcablerecs.Recordset.Fields("Cost / metre").Value
                CableColour(cableindex) = Datcablerecs.Recordset.Fields("Colour Reference (0-
15)").Value

                   cableRperm = 1.7 * 10 ^ -8 / (cableCSAarray(cableindex) * 10 ^ -6)

                   NodeVG(Spurindex, Conindex) = NodeI(Spurindex, Conindex) * cableRperm

                       If NodeVG(Spurindex, Conindex) <= VoltGradref(Spurindex) And
NodeVG(Spurindex, Conindex) > NodeMaxVG(Spurindex, Conindex) Then

                        NodeMaxVG(Spurindex, Conindex) = NodeVG(Spurindex, Conindex)
                        NodeminCSA(Spurindex, Conindex) = cableCSAarray(cableindex)
                        cableRperm = 1.7 * 10 ^ -8 / (NodeminCSA(Spurindex, Conindex) * 10 ^ -6)
                        NodeVD(Spurindex, Conindex) = NodeI(Spurindex, Conindex) * cableRperm *
2 * SpacingArray(Spurindex)
                        NodeColour(Spurindex, Conindex) = CableColour(cableindex)

                      ' calculate total voltage drop on spur

                            If Conindex > 0 Then
                            NodeTotVD(Spurindex, Conindex) = NodeVD(Spurindex, Conindex) +
NodeTotVD(Spurindex, Conindex - 1)
                            Else
                            NodeTotVD(Spurindex, Conindex) = NodeVD(Spurindex, Conindex)
                            End If
                       End If
                If Not Datcablerecs.Recordset.EOF Then Datcablerecs.Recordset.MoveNext
```

```
             If Conindex = 1 Then

             CurrentX = picsiteplan.ScaleWidth / 2
             CurrentY = picsiteplan.ScaleHeight / 2
             Else
             CurrentX = NodeX(Spurindex, 0, Conindex - 1)
             CurrentY = NodeY(Spurindex, 0, Conindex - 1)
             End If
     ' calculate percentage volt drop and draw cable of correct colour to current node

            NodeVDpercent(Spurindex, Conindex) = (NodeTotVD(Spurindex, Conindex) /
genV) * 100
             picsiteplan.Line (CurrentX, CurrentY)-(newX, newY),
QBColor(NodeColour(Spurindex, Conindex))
             picsiteplan.DrawWidth = 3
        Next
      Next
  Conindex = 0
  Next

   ' list results of volt drop analysis node by node, into data sheet (frmdisttables)

   frmdisttables.Frame1.Visible = True

   For Spurindex = 0 To intspurno
        For Conindex = 1 To intspurcons(Spurindex)
         frmdisttables.lstCableSelections.ForeColor = QBColor(NodeColour(Spurindex,
Conindex))
          frmdisttables.lstCableSelections.AddItem strSpurRef(Spurindex) _
          & "     " & NodeRef(Spurindex, Conindex) _
          & "     " & Format(NodeI(Spurindex, Conindex), "#0.00") _
          & "       " & Format(VoltGradref(Spurindex), "#0.000") _
          & "        " & Format(NodeminCSA(Spurindex, Conindex), "#0.00") _
          & "       " & 2 * Format(SpacingArray(Spurindex), "###") _
          & "        " & Format(NodeVDpercent(Spurindex, Conindex), "#0 .00") _
          & "      " & Format(NodeVG(Spurindex, Conindex), "#0.000") _
          & "        " & NodeX(Spurindex, 0, Conindex) & "   " & NodeY(Spurindex, 0,
Conindex)
        Next
   Next

' dimension additional variables required for summary of cable selection (length and cost) and
positional data required for cable key

Dim TotalCost As Single
Dim CableNo As Integer
Dim KeycoX As Integer
Dim KeycoY As Integer
ReDim SelCSA(TotalCables)
ReDim SelL(TotalCables)
For cableindex = 1 To TotalCables

   For Spurindex = 0 To intspurno

      For Conindex = 1 To intspurcons(Spurindex)

          If cableCSAarray(cableindex) = NodeminCSA(Spurindex, Conindex) And
SelCSA(cableindex) = 0 Then
          SelCSA(cableindex) = cableCSAarray(cableindex)
          SelL(cableindex) = SpacingArray(Spurindex)
```

```
        CableNo = CableNo + 1
        ElseIf cableCSAarray(cableindex) = NodeminCSA(Spurindex, Conindex) And
SelCSA(cableindex) <> 0 Then
        SelL(cableindex) = SpacingArray(Spurindex) + SelL(cableindex)
        End If

    Next
  Next
Next

' procedure to display colour-coded key of cables selected
picCableKey.Cls

For cableindex = 1 To TotalCables

    If SelCSA(cableindex) <> 0 Then
        lstCableSummary.AddItem CableRef(cableindex) _
        & "      " & 2 * Format(SelL(cableindex), "###") _
        & "      " & 2 * Format((SelL(cableindex) * CableCost(cableindex)), "###")
    TotalCost = TotalCost + (SelL(cableindex) * CableCost(cableindex))

    KeycoX = picCableKey.ScaleWidth / 5
    KeycoY = picCableKey.ScaleHeight / (CableNo + 1) + KeycoY
    picCableKey.FillColor = QBColor(CableColour(cableindex))
    picCableKey.Circle (KeycoX, KeycoY), 60
    picCableKey.PSet (KeycoX * 2, KeycoY - 100), BackColor
    picCableKey.Print CableRef(cableindex)
    End If
Next
lstCableSummary.ForeColor = QBColor(0)
lstCableSummary.AddItem "Total Cost is  " & Format(TotalCost, "###")

End Sub
```

10.8 Journal papers arising from the research

Pico Hydro Power for Rural Electrification in Developing Countries

(International Journal of Ambient Energy, Vol. 19, No. 3, July 1998)

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Synopsis

Pico hydro power is a renewable energy which has the potential to provide millions of rural people world-wide with a cheap, sustainable source of electricity. The development of new, cost-reducing approaches towards local manufacture and implementation in developing countries has increased the accessibility of this technology to large numbers of people. The new approaches have been investigated and some of the present constraints to wider adoption of this technology have been analysed.

Introduction

Hydro power schemes are classified according to power output and head range. Pico hydro is the smallest classification of power output, having a maximum output of 5 kW. The emphasis of this study is pico hydro for medium to high head sites (10m to 200m).

The biggest markets for pico hydro power of this type, exist in developing countries which have large rural populations living in hilly or mountainous areas. It is extremely difficult for most utilities to cover the costs of electricity production and distribution in these areas, let alone to obtain an adequate return on investment [1].

Pico hydro power is, in many cases, an ideal solution to solving the problems of rural energy needs. The number of potential sites which can provide flows and heads of suitable size for pico hydro, is very large and the small flows required don't have a large impact on water required for other purposes such as irrigation. The small size of the generating equipment eases the problems of transportation to remote areas, particularly in regions where roads are scarce. The civil works can be simplified with pico hydro, which makes tasks such as the installation of a plastic penstock pipe or positioning the intake, easily achievable by local people [2].

The initial capital costs of large hydro power schemes are high. In many cases there are also negative environmental effects. Pico hydro, in contrast, has low initial capital costs and is environmentally benign making it suitable for widespread adoption in many countries where rural populations are isolated from an electricity supply network.

In addition, hydro power is a technology which is widely understood in the developing world. Local manufacture and assembly is possible which removes dependency on foreign organisations, allows local people to be employed, and reduces the production costs. In contrast, solar power, wind power and diesel generators usually rely heavily on imported technology and are prohibitively expensive for the majority of rural people with subsistence lifestyles.

Typical Operation and Components of a Pico Hydro Scheme.

A flow of water (between 2 l/s and 10 l/s) is taken from a spring or a mountain stream and directed to a forebay tank by means of an earth-lined channel, a polyethylene pipe or sometimes a combination of both. A penstock made from HDPE (High Density Polythene) pipe conveys the water over a vertical distance of between twenty and one hundred metres from an intake in the forebay to the powerhouse. A single jet of water is directed through a nozzle to a Pelton turbine which directly drives an induction generator. An electronic load controller is used to regulate the voltage and frequency of the supply. Distribution is by means of overhead, insulated copper cables on bamboo poles [3].

Comparison of Present Approaches

The design approach and standards adopted by implementation agencies when tackling micro hydro projects (up to 100kW) tended, in the past, to be based on scaled down versions of those for large projects [1]. The added cost which resulted, hindered the development of micro hydro power despite its inherent advantages for rural electrification in developing countries. As a result, new approaches have been developed in order to take advantage of the unique design and implementation opportunities presented by schemes of less than 100 kW. Examples of the new approaches have been described in 'Micro Hydropower Sourcebook' [Inversin 1986, 4] and 'Micro Hydro Design Manual' [Harvey 1993, 5].

Successful commissioning of an increasing number of schemes below 5 kW in Nepal and Columbia have demonstrated that additional changes in approach to the design and implementation can have major additional benefits for pico hydro[6,7].

The approaches to the design and implementation of small schemes in Sri Lanka and Nepal have been compared in terms of cost per installed kilowatt in Figures 1 and 2.

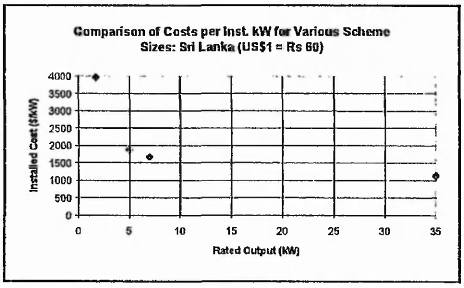

Figure 1

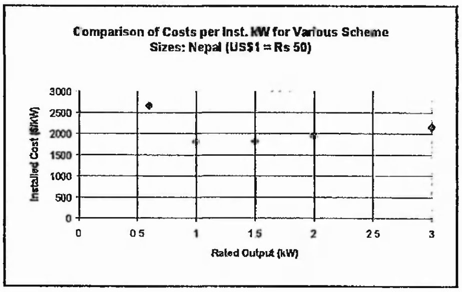

Figure 2

The total costs of each scheme comprised of the turbine, generator and load controller, penstock, distribution cables, house wiring, building materials and other accessories. Labour was provided free of charge by the beneficiaries [8,9].

Figure 1 compares the cost of four schemes of different rated outputs which have been commissioned in Sri Lanka. A similar design and implementation approach was adopted for each. The rising costs per installed kW as the schemes become smaller in size, are a result of the economies of scale associated with larger projects. The cost of the survey, design and installation varies little with the rated output and hence larger schemes are more favourable[3]. In contrast to this, Figure 2 highlights the substantially lower costs / kW for pico-hydro projects achieved by manufacturers in Nepal. This has been made possible by the development of a standardised design of pico hydro system known as a "Peltric Set" at Kathmandu Metal Industries (Figure 3) The standardised units, which can be bought "off-the-shelf" for a variety of head and flow combinations allow batch production methods and a subsequent reduction in cost. In addition, the site surveys are conducted by trained users and agents operating on behalf of the manufacturer. The installation is carried out in a similar way. Users and agents can receive training at the workshop in Kathmandu[2]. This 'DIY' approach to the survey and installation, allows a further significant reduction in overall cost.

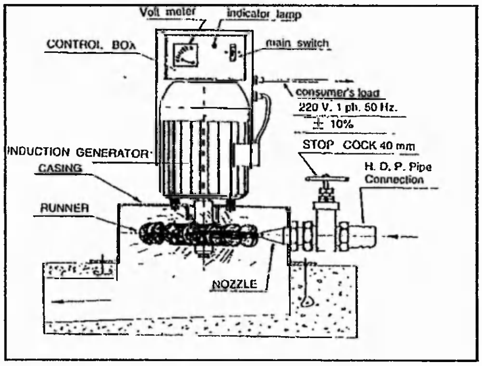

Figure 3: The 'Peltric Set'

Advantages of "Off-The-Shelf" Pico Hydro Power

1) In remote regions where hydro power is used to form an isolated energy supply, maximum efficiency is less important than reliability and cost per kilowatt. A standardised design can provide satisfactory operation over a range of heads and flows whilst permitting batch production rather than one off designs, thereby significantly reducing costs [3].

2) The small size of the turbine and generator allow a pico hydro unit to be carried almost anywhere [2].

3) Standardised design allows a greater sense of familiarity with the technology to develop in areas where several units are installed. This improves the understanding of the operation amongst members of the local population and facilitates improved implementation of future schemes on a local level.

The Potential for Pico hydro Power.

Every country which has streams and rivers has potential for pico hydro power. Hillside locations where springs occur are particularly suited to medium and high head schemes.

Most areas where irrigation is employed for farming have pico hydro potential. The flows required can be as little as 1-2 l/s and are therefore, in most cases, less than those which are used for irrigation. Countries such as Columbia, Peru, Nepal, India, Sri Lanka, China, Fiji and Ethiopia all have large unconnected rural populations and have large potential for pico hydro power [1,10].

Constraints on further Market Development

Despite the numerous advantages of pico-hydro units which can be bought off-the-shelf, there are three main issues which are hindering large scale adoption of this technology.

1) The quality of schemes.
2) The affordable cost per kW output power.
3) The return on investment

Quality of Schemes

From a consumers perspective, the quality of a pico hydro scheme can be judged in terms of the quality of electricity supply and how their appliances are affected, and in terms of the reliability of the supply.

Quality of Consumer Supply

The quality of the electrical power supplied to the consumer is affected by the regulation of voltage and frequency. If the voltage and frequency aren't maintained within certain limits, the life of consumer goods is shortened or the quality of service which the device provides is reduced. Load control is required if the consumer loads are allowed to vary.

Reliability

The reliability, assuming correct installation, is reduced by inadequate maintenance. One advantage of "off-the-shelf" pico-hydro schemes is that they require very little maintenance because of their inherent simplicity. The generator bearings need to be occasionally replaced according to the manufacturers guidelines. Damaged capacitors also need to be replaced otherwise the condition of the remaining capacitors rapidly deteriorates if no load control is present. Both of the above can eventually lead to complete system failure and an interruption to the supply. The reliability of the electricity supply is taken for granted in many developed countries. Poor reliability and inadequate back-up support from manufacturers is know to be one of the key factors which is undermining wider adoption in Nepal [8].

Affordable Cost per kW Output Power

The affordable cost depends on the availability of capital to a potential pico hydro customer. Access to government subsidies and bank loans improve the affordability to an individual. Output power is the power which the scheme can usefully provide. This may differ considerably from the rated power which is the value quoted by the manufacturer. If the output power is reduced for some reason then the cost to the consumer increases.

Poor Performance.

The performance of a pico-hydro scheme is closely related to the accuracy of the initial survey, the installation and subsequent maintenance procedures. The rated power output of 8 pico-hydro schemes in Nepal were compared with measured output during a field visit [3] in order to gauge their performance.

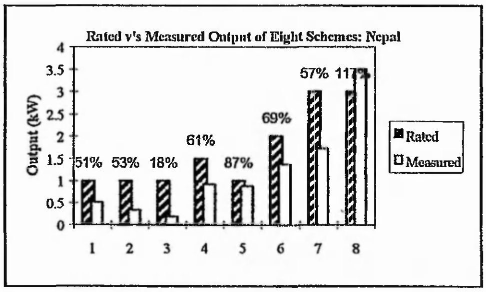

Figure 4

The results displayed in Figure 4 reveal that the measured power was below the rated power in all but one of the eight schemes. Following discussions with manufacturers and installers, factors which are known to contribute to loss of power following installation have been summarised as follows:

In a stand-alone induction generator, capacitors provide the only form of magnetising current and they must be carefully chosen to give the correct values for voltage and frequency [11] .Damaged capacitance due to over-voltage through poor power regulation, result in reduced excitation and loss of performance.

Incorrectly connected capacitance causes imbalance of generated current across the phases with subsequent power loss. [3]

Wrongly sited or sized intake, penstock or powerhouse.[12]

Incorrect nozzle alignment alters the interaction between jet and runner.[6,7]

Obstructions in the nozzle which reduce the flow.[7]

Incorrect sizing of penstock and distribution system.

The penstock typically accounts for 20% of the total scheme cost with pico hydro [13]. The diameter of the penstock needs to be carefully judged. A penstock which is too narrow will cause excessive head losses. [3] If the diameter is large, the frictional losses are reduced but price increases so an optimal compromise must be reached. Similarly, the cable which is used for the distribution systems can have large associated costs and therefore also requires optimisation because thinner (and hence cheaper) cable results in greater power losses. This area of cost reduction becomes particularly important when distribution lines are long.

Return on Investment

This is the level of benefit which the consumer associates with the electricity supply and acts as an incentive. The immediate benefits are ones of improved light and atmosphere (electric light often replaces kerosene lanterns which produce smoke as they burn) and improved social status [8]. There are countless useful applications to which pico hydro can be applied, many of which, such as battery charging [7] can generate income and improve the financial viability of the scheme as a whole. People who have never had electricity have little idea of its advantages and are therefore less willing to invest any capital they possess.

Future Development

In order to ensure that this technology achieves its full potential in countries such as Nepal, several aspects of the implementation process require further development. In particular, successful implementation on a local level is essential not only to reduce scheme costs, but also to improve understanding and confidence with the technology amongst the users.

Survey

In remote areas, the site survey can be a costly and time consuming aspect of the implementation if it is conducted by the manufacturer. This introduces unacceptably high costs to the scheme which can be avoided if necessary equipment and training are available locally. The principle tasks are accurate measurement of flow and head at the proposed site. Relatively low cost, lightweight and straightforward techniques are now available which facilitate local surveys. In particular, the 'salt dilution method' of flow measurement is well suited to village hydro schemes [5]. A known mass of salt is dissolved in the stream and the change in conductivity is recorded using a digital meter. For rapid and accurate head measurement (±5m), digital altimeters can be used for medium to high head schemes providing that the changes in atmospheric pressure are taken into account [7]. The loan of such equipment to customers and appropriate documentation could be provided by the nearest agent of a manufacturer or by the manufacturer themselves. Agents of this type presently operate in Nepal [8].

Manufacture

Through the involvement of the current pico hydro manufacturers and NGO's in countries such as Nepal and Columbia, it is hoped to encourage new manufacturers to take up 'off-the-shelf' pico hydro. This will be through the publication of a practical manual on the pico-hydro units covering standardisation, detailed design, manufacture and quality control.

Computerisation of Design Process

Computer technology has already arrived in many business organisations in countries such as Nepal [12] and its application to engineering is increasingly being realised [6]. Previous attempts have been made to develop software which would simplify aspects of the design process for micro-hydro and they have met with varying degrees of success. Software will be developed for medium to high head pico hydro schemes allowing new and existing manufacturers to optimise aspects of the design such as the distribution system and the penstock diameter according to predetermined conditions such as cost and availability. The aim is to simplify the decision making process, reduce time required for designing and costing of new schemes and pass the savings through optimum design onto the consumer. Testing and evaluation of the software by existing manufacturers will be a continuous process during its development.

Installation

An installation manual is essential if the actual performance of pico-hydro units is to be comparable with the intended performance. Careful 'DIY' installation by the purchaser is necessary for optimum performance and a reliable, safe electricity source. Modifications to the standardised scheme, such as the inclusion of meters on the controller will allow early performance evaluation and help problems to be investigated.

The Role of Other Organisations.

Organisations such as the ADBN (Agricultural Development Bank Nepal) are ideally positioned to act as promoters for pico-hydro development [8]. Although they are not yet actively promoting pico hydro, customers are informed when they come to the bank for other reasons. Since government subsidies are also available through the bank for village electrification schemes in Nepal, the bank has some control over the installation. The subsidy is paid directly to the manufacturer, but only when the scheme has been successfully implemented [8]. There are possibilities to extend this role further, ensuring that quality control and safety guidelines are adhered to by the manufacturers.

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Assessment of Pico Hydro as an Option for Off-Grid Electrification in Kenya
(International Journal of Renewable Energy 28 (2003) 1357 – 1369)

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Abstract

This paper discusses off-grid electrification options for low-income household in rural Kenya, where less than 2% of rural households are grid connected. The paper outlines the electrical load priorities of rural households and describes how these are supplied at present through centrally charged automotive batteries and solar home systems. The recent introduction of pico hydro schemes (<5kW) to Kenya is discussed, including details of the implementation of the two community schemes and the costs involved. A comparison is made between pico hydro and solar home systems and conclusions are presented on the way forward for off-grid electrification in Kenya.

Introduction

Community pico hydro (up to 5kW electrical power), a technology well established in countries such as Nepal [1], has recently been introduced to Kenya. Pico hydro has negligible environmental impact since large dams are not involved, and the schemes can be managed and maintained by a community. It is estimated that there is at least 3MW of hydro power potential in Kenya for schemes up to 5kW in size [2]. 3MW alone is sufficient to supply basic electricity to 150,000 households. This is comparable to the number of solar home systems currently installed and clearly a significant energy source for rural electrification in Kenya.

Rural electricity demand

Expansion of the local television network during the 1990's fuelled an already strong demand for electricity in rural areas of Kenya. Tens of thousands of people bought automotive type batteries to power black and white televisions. These televisions are imported from China and sell for around US$40 in Kenya. A 50Ah car battery can power a television for 3-4hrs each night over about a week before recharging is required.

Modern fluorescent lighting enables very appreciable improvements to the domestic environment with minimal power consumption [3]. Low cost energy efficient lamps are becoming widely available in developing countries. A reliable 8W CFL (Compact Fluorescent Lamp) can now be bought in Nairobi for less than US$4. These lamps improve the economics of off-grid generation since significant benefits can be obtained from power supplies which provide as little as 10W per household. Electricity systems can be scaled down as in the case of solar power or, with pico hydro the number of houses connected to a generator can be increased. Either way, on a per-consumer basis, the cost-benefit ratio markedly improves.

Despite being subsidised through a levy on electricity bills, rural households through grid extension is not widespread. By 1999, only about 61,500, less than 2%, of the 3.7 million rural households had been connected during 15 years of the national utility's program of rural electrification [4]. The current rate of new connections, at approximately 10,000 per year, is hardly keeping pace with rural population growth. Of those who do eventually receive a connection, most are upper and middle class households who can afford to make a significant contribution towards the connection costs and who do not represent the majority of the rural population.

Battery charging

The most readily available source of electricity for rural populations who are not grid-connected, is from dry cell batteries. They are widely used in Kenya and particularly useful for small loads that are used intermittently such as torches and radios. However, they are too expensive for larger loads as shown in Section 8.

Rechargeable automotive type batteries are used to supply higher power consumption loads, such as fluorescent lamps and small televisions. At least 5% of rural households use automotive batteries which they recharge at a grid-connected charging station [5]. However, the drawbacks with this approach are considerable are considerable.

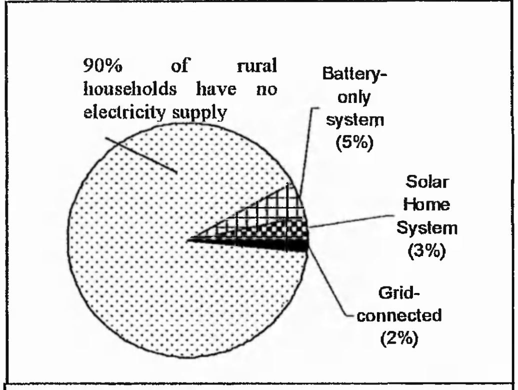

Figure 1 Rural households with electricity

A typical charge from a grid-connected charging station costs Ksh50 (US$0.64). The battery must be transported to the charging station, often over distances of several kilometers and at considerable inconvenience and additional expense. Transportation costs may easily be equal to the charging costs. Where batteries are recharged at charging stations, the power is rarely used for loads other than radios and televisions due to the high costs and inconvenience of frequent recharging.

The battery chargers are often old and inefficient and cannot provide any indication of the charging levels. The consumer pays for being connected for a fixed amount of time and is unable to verify if the battery has been fully charged. Lead acid batteries designed for vehicle use, retain charge only for short periods and are not designed for deep discharging. Most batteries are used until the load will no longer work and then may be left for several days or weeks until being recharged and continue to self-discharge even when the load is no longer connected. Leaving an automotive battery in a fully discharged state is particularly detrimental [6]. Little understanding of these limitations and almost non-existent use of charge indicators, leads to a rapid decline in performance and lifetime. As the battery performance diminishes, the frequency of charging which is required increases so the battery becomes progressively more expensive to run. This places an additional financial burden on the user. An additional drawback is that automotive batteries present an environmental hazard in areas where there is little recycling due to their high lead content.

Solar home systems

A tenfold reduction in the delivered price of energy from solar photovoltaic (PV) panels during the 1980's and 1990's [7] has encouraged significant growth in the Kenyan market. In 2000 it was estimated that cumulative sales of solar home systems (SHS) had exceeded 100,000 [8] and current annual sales of panels total approximately 20,000. The largest part of these sales is now of amorphous silicon (a-Si) panels which typically have a rated power output of 10 –12W_p (W_p= output during peak sunlight hours). Crystalline panels are a well established technology with a higher efficiency than a-Si PV and a robust design which has been proven to give useful service of 20 years or more. However, these have a higher cost per watt and are only available as panels with outputs of at least 20W_p. Efficiency is rarely an issue on which purchasing decisions are based since there is usually ample roof-area to accommodate a larger panel. Because the a-Si PV modules are available in smaller power outputs (10-12W_p) and at lower cost, they are proving very popular as part of entry level systems with households which previously would have been unable to afford a SHS. The battery is more often connected to electric lamps as well as TV and radio since the power is effectively available free of charge once the panel has been installed.

The recent success of the amorphous silicon modules in the Kenyan PV market has been tempered by a number of significant problems with the SHS's which are installed. The SHS market in Kenya is largely 'component' driven [9]; most owners of SHS's purchase the components separately rather than as a complete system. This way they can stagger the cost over a longer period and upgrade existing battery-only systems. The drawback with this approach is that poor selection of one component can drastically reduce the performance of the entire system. A particularly common problem is using an automotive battery which may have a capacity of around 50 Ah with a 12W_p panel. With a panel of this size, such a large battery will rarely become fully charged; it would require more than 50hrs of optimum conditions and no loads connected to charge from empty. Optimum conditions can only be expected for a maximum of around 7 hours per day. Furthermore, tests on commercially available solar modules in Kenya have shown that there is considerable inconsistency in the performance of the available a-Si panels with some brands falling well below the manufacturers rated power output [7]. Despite their advantages, deep discharge solar batteries are rarely used, due to higher purchase cost and lack of availability.

In addition to the technical challenges, the residents of upland areas of Kenya, such as the Aberdare and Kirinyaga districts experience three months of almost continuous cloudy weather called the Gathano season. During this time the PV panels are virtually ineffective since they barely provide enough power to cover the self-discharge within the battery.

Low cost implementation of pico hydro

Pico hydro is generally classified as water-powered generating systems which produce up to 5kW of electrical power. During the last five years, research at the Micro Hydro Centre, Nottingham Trent University, has focused on the development of low-cost implementation of pico hydro to improve the affordability for low-income households. A methodology has been developed which produces significant reductions in cost per kW when compared with more conventional approaches whilst maintaining quality, reliability and safety [10]. The key components are listed below [11]:

- Low-cost scheme survey and installation
- Low-cost civil works
- Local manufacture and use of 'off-the-shelf' components
- Compact, appropriate turbine generator sets
- Use of software for rapid scheme design
- Use of energy efficient loads and careful load management

Community pico hydro in Kenya

In December 2001, two community-owned pico hydro schemes were commissioned and the first houses connected [12]. These schemes were installed as part of a project to demonstrate that pico hydro power is a viable option for electrification of low-income households in parts of rural Kenya and other Sub-Saharan countries where suitable sites exist. Areas with considerable pico and micro hydro potential in Kenya include Mt. Kenya, Aberdare, Nyambene, Mt. Elgon, the Kisii Highlands, Cheragany hills, Kerio and Nandi escarpments [13].

The project also included training of African engineers and mechanics so as to establish local manufacturing and installation capacity. As the technology and low-cost implementation practices outlined above were being demonstrated for the first time in this region, the funding agency (European Commission) met the costs of the penstock pipe and generating equipment. However, a substantial proportion of the total scheme cost including building materials, distribution cables and house wiring components, was met by the consumers. In addition, consumers contributed free labour and trees from their 'shambas' to make distribution poles.

Scheme sizing is difficult as consumers need firm cost information in order to decide how much power they want. However, the costs are not fully known until the size of the scheme and the extent of the distribution are determined. This problem was dealt with in the following manner:

1. On completion of each site survey, a conservative estimate of the maximum power output was determined. At Kathamba, this was limited by the water flow available and at Thima, by turbine availability for the site head.
2. This design power was then divided into 10W 'light packages' to facilitate power allocation and demand assessment. One light package is enough power for one 8W CFL and a radio.
3. A community meeting was held with local residents to discuss the proposals and to gauge the level of local interest and commitment. A battery-powered fluorescent lamp was used to demonstrate how bright the light would look inside the houses.
4. The positions of the houses within 250m, 500m, 750m and 1000m of the proposed generator location were surveyed using a hand-held GPS (Global Positioning System).
5. A map was constructed and the boundary limits for the distribution decided based on connecting the nearest houses, with each assumed to be taking an average of two light packages, until all the packages had been allocated.

6. The total cost for the entire scheme was estimated and the cost per light package was calculated.
7. Further community meetings were held. An electricity association of potential consumers was formed with an elected committee to oversee the installation and management of the scheme.
8. An agreement was signed between the association and the implementing organisation.
9. Consumers within the boundary lines were invited to subscribe to 1 to 3 light packages depending on what they were able to afford, the third light package only being available if there was a surplus.
10. A schedule of work was drawn up to identify the key tasks and who was responsible for carrying them out.
11. Consumers paid their connection fee depending on how many packages they had subscribed to.
12. The scheme was installed and the houses connected.

The consumers pay a monthly tariff depending on the number of light packages which they have been allocated. This pays for the operators wages and contributes to a maintenance fund which ensures that the scheme continues to operate reliably. The tariff charged is 50 Kenyan shillings per light package. For two packages, this is US$1.3 per month (US$1=Ksh78) and approximately US$15 per year.
This approach to scheme development worked well for the Kenyan installations which are completely community owned and managed. A similar method could be used by a private entrepreneur, charging a connection fee depending on the number of light packages and then a monthly tariff based on the operating costs.

To some degree, the joint installation and ownership of the hydro schemes has had a beneficial effect on the community spirit, creating an atmosphere of unity and empowerment which may well help to catalyse further developmental activity. However, their continued success depends on good management, particularly with regard to rectifying technical problems, tariff collection, ensuring that the generator does not become overloaded (for example by consumers bypassing their load limiter), and diplomatic resolution of disputes. Clearly, the individual electricity supply provided by a solar home system, is not subject to these conditions.

Pico hydro scheme costs and components

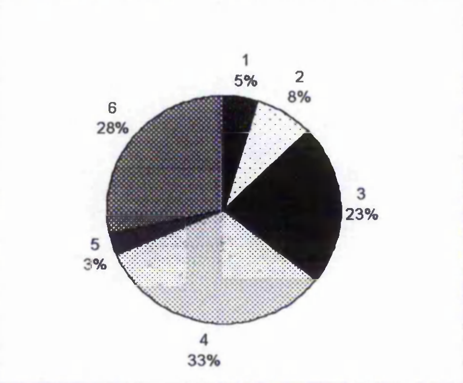

Figure 2 Kathamba 1.1kW Scheme. Total cost: US$ 5288 (65 houses)

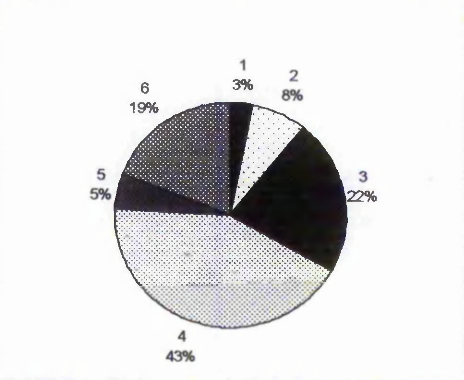

Figure 3 Thima 2.2kW Scheme. Total cost: US$ 7865 (110 houses)

Key to Scheme Components in Figure 2 and Figure 3

1	Civil works (intake and turbine house)
2	PVC penstock
3	Turbine, generator, controller and protection
4	Distribution system cable, house wiring and energy saving bulbs
5	House-wiring labour
6	Design and delivery and project management (equivalent cost of private contractor from Nairobi)

The implementation methodology developed by the Micro Hydro Centre at NTU was applied to the design and installation of the pico hydro demonstration schemes. The civil works, amounting to no more than 5% of the scheme costs, were constructed using locally available building materials to reduce transportation costs. Community labour was provided free of charge. For the intake, use was made of natural features to minimise the building work required. For example, an intake position at Thima was chosen where a natural weir existed to avoid a large and expensive concrete structure.

The turbine and generating equipment was sourced through local companies to minimise costs and ensure that local repair and replacement is possible. At Kathamba, a standardised design of directly-coupled Pelton turbine and induction generator was installed which was fabricated in Nairobi (Figure 4). This is slightly less efficient than an optimally sized turbine but considerably cheaper as standard bucket patterns could be used. At Thima, a standard centrifugal pump is used as the turbine (Figure5) . A 'monobloc' pump was selected as this comes directly connected to a motor that can be used as a generator. The pump comes from India, but was purchased through a supply outlet in Kenya. The pump impeller was turned down on a lathe to better match it to the site and thereby improve the operating efficiency.

In addition to the aspects outlined above, careful distribution and management of the power was key to making the Kenyan schemes affordable to households at all income levels. Energy efficient lamps make it possible to spread the benefits of the power to a much wider number of consumers since each bulb only consumes a few watts but gives out a bright light. Connecting more consumers, enables the cost per house to be reduced and improves affordability to low income households. Since the power output is being so widely distributed, load limiters are required in each house to prevent individual consumers from drawing too much current and overloading the generator [14]. The load limiter can be designed to allow different numbers of lamps to be connected.

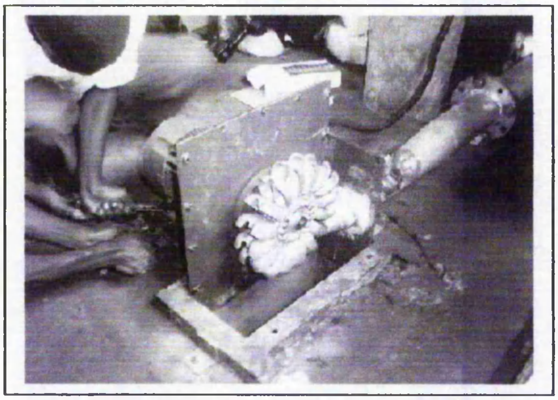

Figure 4 1.1 kW Pelton Turbine, Kathamba

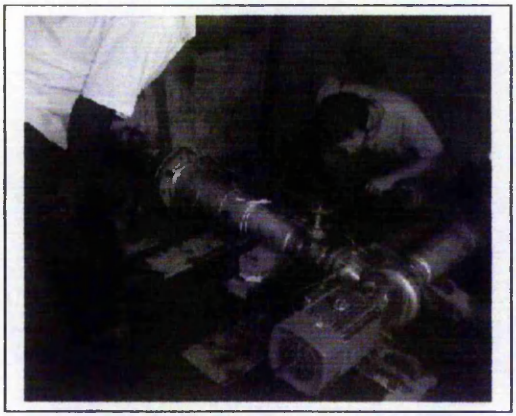

Figure 5 2.2 kW Pump as Turbine, Thima

Table 1 summarises the technical details of the schemes. The turbines are shown in Figures 4 and 5.

	Scheme A: Kathamba	**Scheme B: Thima**
Power Output (Electrical)	1.1kW	2.2kW
Number of houses connected	65 (100 x 10W light packages)	110 (200 x 10W light packages)
Penstock (PVC)	160m / 110mm diameter / Class B	90m / 160mm diameter / Class B
Type of Turbine	Pelton (200mm p.c.d.)	Pump-as-Turbine (centrifugal 'monobloc')
Type of Generator	Induction (6 pole)	Induction (2 pole)
Head (net)	28 metres	18 metres
Flow (design)	8.4 litres per second	28 litres per second
Efficiency (turbine+ generator)	48%	45%
Distance of furthest house	550 metres	800 metres

Table 1 Pico Hydro Demonstration Schemes Specifications

Cost comparison of off-grid electrification options

The following table compares installed costs of typical solar and pico hydro system in Kenya.

Type of System	Installed cost per household (US$)	Life of system (years)	Annual maintenance and operation costs (US$)	Life Cycle Cost (US$)	Energy per household over lifetime	Average Cost US$ per kWh
Amorphous Silicon – 12Wp	**200**	**10**	**35***	**480**	**271 kWh**	**1.77**
Crystalline – 20Wp	**330**	**20**	**35***	**960**	**879 kWh**	**1.09**
Pico Hydro – 16W average	**81**	**20**	**12**	**321**	**2102 kWh**	**0.15**
Auto Battery Only - 50Ah	**70**	**2**	**33**	**136**	**31.2 kWh**	**4.36**

Table 2 Cost Comparison of Off-Grid Options for Household Electrification in Kenya

Assumptions made for calculations of values in Table 2:

Solar Home Systems

- Annual maintenance costs based on battery depreciation (cost new = US$70, lifetime of 2 years). NOTE* assumed to be zero for years 1 and 2 because a new battery is installed with the system
- Measured watts per panel were used rather than manufacturers rated output for a realistic estimate of likely power output (aSi 12W_p = 10.6W measured, crystalline 20W_p = 17.2W measured [8]).
- Effective direct sunlight hours per day assumed to be 7 hours throughout the year

Pico Hydro

- power from pico hydro is continuous and used continuously
- tariff for operation and maintenance is US$1 per month for 16W supply

Battery-Only Systems

- The battery is recharged each week at a cost of Ksh50 (US$0.64) for 25Ah (50% depth of discharge). The battery capacity is assumed to be constant but in practice diminishes over its lifetime.
- Transportation costs to charging stations are ignored as many people carry their own battery. Typical costs associated with the battery transport are similar to charging costs.
- The battery voltage is 12V.

Cost of Dry Cell Batteries

A typical zinc carbon D cell (1.5V 3.0Ah) costs US$0.8. Cost per kWh = US$ 178 / kWh.
As a result, it is clear why rechargeable car batteries are the preferred choice for loads which are used regularly.

Other applications for pico hydro energy

Mobile phone companies are expanding their business into rural parts of Kenya. Users in the Kirinyaga District, where the demonstration schemes are located, can now access both main mobile networks. Despite the relatively high cost and low wages, there is tremendous demand for mobile telephone access in isolated rural areas. A mobile phone with pre-pay tariff is now available for around US$60 in Kenya. The need for regular recharging is the major drawback for people who are not grid-connected. A mobile phone needs to be charged every couple of days, depending on usage, and at an equal cost to recharging car batteries (e.g. US$0.64 per charge in Kirinyaga District). One user at Thima was charging his phone 15 times each month at this price. Now that he has received a connection to the pico hydro scheme he is charging his phone at home. Other appliances with built-in rechargeable batteries are also becoming more widespread. Already, a small workshop has been set up in the powerhouse at Kathamba where a cordless drill is recharged and loaned out to community members.

A major energy demand in rural areas of Kenya is for agro-processing services, e.g. corn milling and coffee bean pulping. Selection of a double-ended motor as a generator in the pico hydro scheme, provides a bare shaft which can be used as a mechanical drive for such machinery. In this way, a service can be provided to local households at lower cost than alternatives such as diesel milling since there are no fuel cost to consider. The intention at Thima is to connect the bare shaft (see Figure 5) to a 'posho' mill in the near future, since there is high demand for corn milling in the area.

Standard automotive battery chargers can be used in the powerhouse to charge lead-acid batteries at off-peak times. This can be a lucrative income-generating end-use, contributing to capital repayments and scheme maintenance if carried out on a commercial basis. Centralised battery charging is also a means of extending the benefit of pico hydro beyond the radius of consumers who are connected directly to the generator. There are plans to install battery-charging equipment at the powerhouse in Kathamba.

For consumers who own an automotive battery and receive a connection to a pico hydro generator, there is a strong desire to be able to charge at home, so saving money and time [15]. Battery charging is still required by those who own a television since even the smallest television will trip the load limiter on a 20W AC connection. Conventional automotive battery chargers would trip the load limiter but a charger which draws 18.5W AC is available in the UK at a cost of US$16 and tests have shown that this can fully charge an automotive battery. Connecting the charger to the battery each night would ensure that the charge levels were kept up, thus prolonging the useful life of the battery.

Conclusions

Both pico hydro and solar home systems have the potential to provide electricity supplies to many rural households in Kenya. Pico hydro, whilst much more site dependent than solar power, is presently more cost effective on a per-household basis at less than half the installed cost per household. Since the power from pico hydro is usually available continuously, the cost per kWh is less than 15% of that from the cheapest solar home system. This puts it within reach of most low-income households. The cost of solar power is likely to continue to fall but pico hydro has several other key advantages; AC power, mechanical drives, continuous power supply and home electrification without batteries. All the benefits of community pico hydro are subject to competent local management to ensure continuous operation. Sufficient promotion and improved availability of components could create a strong demand in Kenya where sites exist, even when SHS's become more cost-effective. In addition to promotional activities, further capacity building is required to ensure that pico hydro technology becomes more widespread. Programmes to support in-country manufacturing and to build local site survey, scheme design and installation experience are required.

A coordinated approach is required to enable a rapid increase in rural electrification. Firstly, communities close to existing grid lines should be ear-marked for grid electrification. Low-cost connection approaches, such as use of load limiters, should be adopted to make these supplies more affordable. Secondly, in areas where the grid will not realistically reach in the medium term, pico hydro should be developed where suitable sites exist, due to the advantages over solar power outlined above. In addition to funding further grid extension, the rural electrification levy should be used to encourage the development of pico hydro and SHS's particularly for low-income households.

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10.9 Kenya case studies

Community Pico Hydro in Sub-Saharan Africa: Case Study 1
Site: Kathamba, Kirinyaga District, Kenya

Background

This scheme was installed as part of a program implemented by The Micro Hydro Centre at Nottingham Trent University to demonstrate Pico Hydro technology in Sub Saharan Africa. The cost of the penstock, turbine and generator equipment was met by the project funders (European Commission) and all other costs were contributed by the 65 households which the scheme now supplies with electricity.

Technical Summary

This case study describes a pico hydro plant using a Pelton turbine directly-coupled to an induction generator which has an electrical output of 1.1kW. The penstock is 158m in length, 110mm diameter PVC pipe. The net head is 28m and the flow into the turbine is 8.4 l/s. The electrical output of 1.1kW corresponds to a turbine-generator efficiency of 48%. The water source is a small spring with a flow rate of at least 5l/s during 90% of the year and has never been known to run completely dry. Approximately $80m^3$ of storage has been provided at the intake to ensure that the turbine can be kept running for long periods. The generator output is regulated by means of an Induction Generator Controller to ensure that the voltage and frequency are held at the correct values during conditions of changing consumer load. Excess power is fed to a ballast load. A 2kW cooking ring was used for this. There are 65 households within a 550m radius of the turbine house and these are all being connected to the generator using a single-phase distribution system and insulated copper conductors. It is possible to do this cost-effectively since the current drawn by each house is small and restricted by a current limiter so the distribution cables are also small in diameter. Each house has a 230V supply which is sufficient for one or two energy-saving lamps and a radio. The locations of the generator and consumer houses were recorded using a GPS system so that a distribution plan could be developed. The average cost per house for all equipment and materials was around $58 and more than 50% of this cost was contributed by the consumers.

General Description of the Site

Kerugoya town lies 130km north of Nairobi on the southern foothills of Mount Kenya (Kirinyaga in Kiswahili). Kathamba is located on the eastern side of the Mukengeria River near to Gaghigi approximately 4km north of Kerugoya. Travelling time from the town is approximately 20 minutes along unmade roads. The spring, which provides the hydraulic power for the pico hydro system, flows into the Mukengeria River approximately 300m from the source. There are 65 houses within 550m of the junction between the stream and the river and two sites for new houses. The principle source of income in this region is through farming and the crops grown include tea, coffee, maize and fruits.

Community Participation

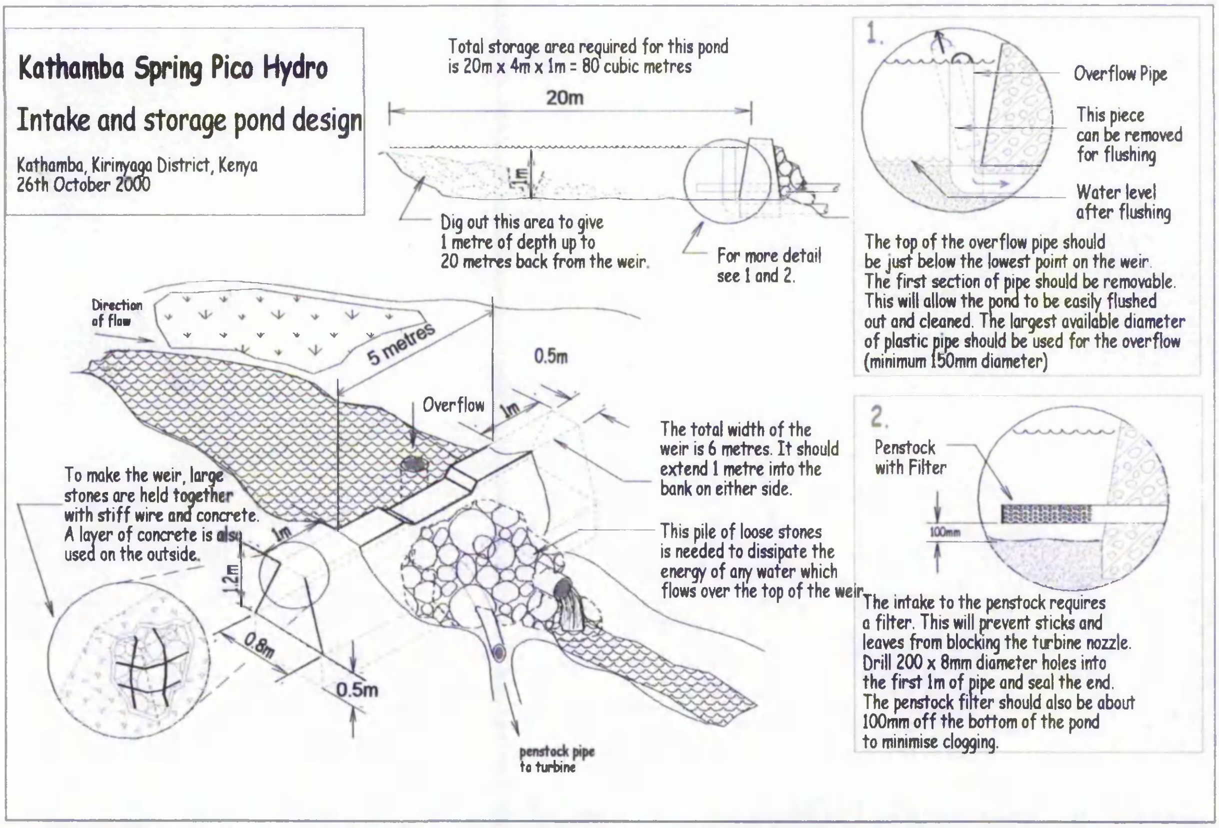
One of the principle elements which lead to the successful implementation of this project was community participation. This was necessary both to lower the installation cost and to foster a sense of local ownership. Once it was established that there was sufficient hydro potential at this site, the first community meeting was held to discuss the project concept. A Community Electricity Association was formed and a committee elected to manage the installation of the project and oversee the operation of the scheme. A written agreement was subsequently signed between the community and the implementing partners. It was agreed that all labour for the project was to be provided by the community in addition to the building materials required for the intake and the turbine house. The consumers also were required to pay a connection fee once the turbine was commissioned. This covered the costs of the distribution cables, house-wiring and energy saving light bulbs. The community association was also required to register with the local government office and to open a bank account in order to save the local contributions towards the project costs.

Community members assembled to begin the installation

Intake and Storage Pond

The design flow for this scheme was just over 8 litres per second. This flow will normally be available throughout most of the year although during the driest periods when it can fall to 3 l/s. A small concrete weir was designed which would provide sufficient depth of water to ensure that the penstock is fully submerged at all times. The natural storage area behind this weir was also enlarged by widening of the banks to 4 –5 meters width and 20m length. This provides sufficient storage to supply the extra flow required for 4 hours of evening lighting during the driest part of the year when the shortfall is at a maximum of 5.5 l/s.

5.5 x 60 x 60 x 4 hours = 79,200 litres storage capacity required (79.2 m^3).
Storage provided = 4m wide x 20m length x 1m depth = $80m^3$



Kathamba Spring Pico Hydro
Intake and storage pond design
Kathamba, Kirinyaga District, Kenya
26th October 2000

Total storage area required for this pond is 20m x 4m x 1m = 80 cubic metres

Dig out this area to give 1 metre of depth up to 20 metres back from the weir.

For more detail see 1 and 2.

To make the weir, large stones are held together with stiff wire and concrete. A layer of concrete is also used on the outside.

The total width of the weir is 6 metres. It should extend 1 metre into the bank on either side.

This pile of loose stones is needed to dissipate the energy of any water which flows over the top of the weir.

The top of the overflow pipe should be just below the lowest point on the weir. The first section of pipe should be removable. This will allow the pond to be easily flushed out and cleaned. The largest available diameter of plastic pipe should be used for the overflow (minimum 150mm diameter)

The intake to the penstock requires a filter. This will prevent sticks and leaves from blocking the turbine nozzle. Drill 200 x 8mm diameter holes into the first 1m of pipe and seal the end. The penstock filter should also be about 100mm off the bottom of the pond to minimise clogging.

Preparing foundations for the weir

A wire mesh gabion filled with stones and clay

Shuttering in place during application of cement layer to seal the weir

Completed intake with storage pond

Penstock

The penstock pipe conveys water from the intake to the turbine and provides the pressure required at the nozzle. The length required was 158 metres. This was the shortest measured distance between the intake and the turbine. PVC pipe with a diameter of 110mm was selected. This gave 2m head loss with a flow of 8 l/s and provided a net head of 28m. Class B PVC (6bar pressure rating) although a lower pressure rating could have been used if available. The increased wall thickness however improves the reliability and lifetime of the penstock. A trench was dug from the intake to the turbine house so that the pipe could be buried to anchor it in place and to protect it from damage by the sun.

Digging the penstock trench

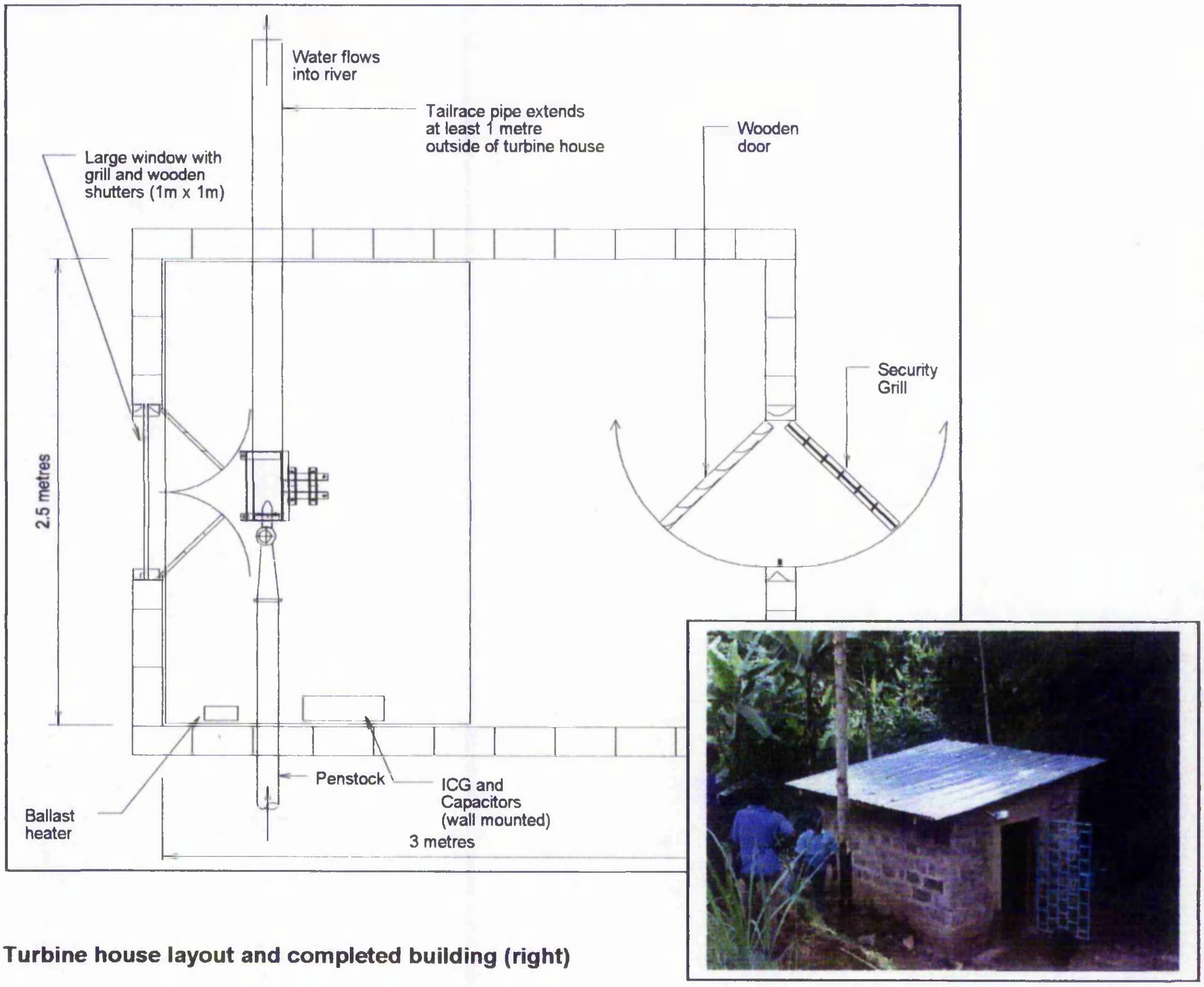
Laying the pipe from the intake to the turbine house.

Turbine house.

The location for the turbine house was chosen to give the maximum available head whilst still being high enough away from the river at the bottom of the valley to avoid flooding during the rains. The building was constructed using local stone and timber to minimise material and transportation costs. The farmer who owned the land where the powerhouse was constructed was given a free light as a concession by the local community in return for the land which was used.

Collecting hardcore for the foundations

Digging out the footing for the walls.



Turbine house layout and completed building (right)

Turbine

A Pelton turbine runner was used to convert the hydraulic power into rotating mechanical power. This was connected directly to an induction generator and housed inside a metal casing.

The Pelton runner is defined in terms of its p.c.d. (pitch circle diameter). Runner p.c.d.'s of 120mm, 160mm and 200mm were available. Different sizes of runner operate best with different combinations of head and flow. The runner had to rotate at the correct speed to drive the induction generator. The speed range of these is limited because electricity at 50 Hz is required for the electrical loads connected in the system. For this site, a 6 pole generator coupled to a 200mm p.c.d runner is suitable. This is shown by the following equations:

The operating speed of a six pole induction generator is given by the following:

$$\text{rpm} = \frac{120 \times frequency}{6} \times (\ 1+ \%\ \text{generator slip}\ )$$

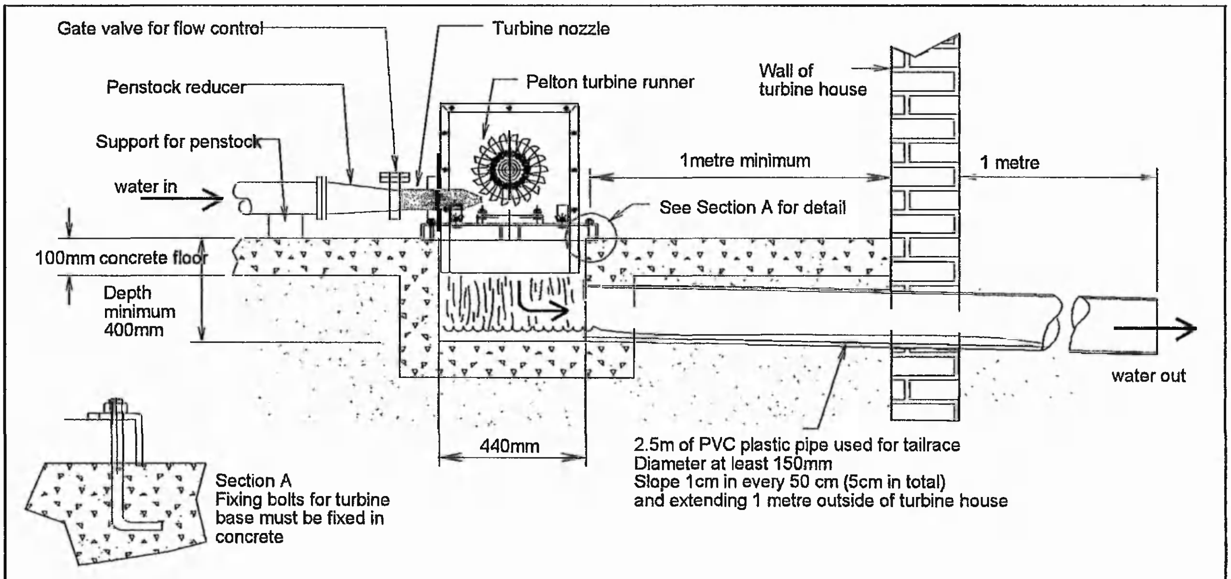
Assuming a typical slip of 3% then the speed (rpm) = (120 x 50 / 6) x 1.03 = 1030 rpm

The equation for selecting the correct turbine runner for this speed and 28m net head is as follows:

$$\text{Ideal p.c.d} = \frac{38\sqrt{H_{net}}}{rpm} = \frac{38 \times \sqrt{28}}{1030} = 195mm$$

The design flow for this turbine is 8.4 l/s (0.0084 m^3/s)

$$\text{Jet Diameter} = \sqrt{\frac{Flow}{3.43 \times \sqrt{H_{net}}}} = 22\text{mm}$$



Section view through turbine house

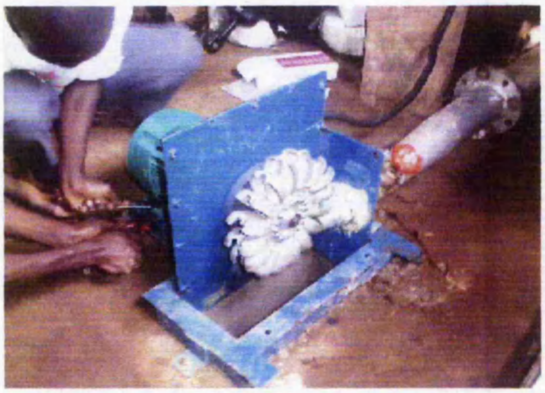
Local Manufacture

Turbine components were fabricated by Kenyan Electrical Distributors who received training during a 2 week course for African manufacturers of pico hydro equipment held by the Micro Hydro Centre near Nairobi in February 2001. Another Kenyan firm, Rodson Electronics, who also participated in the training, fabricated the load controller, the enclosure and made the internal connections to the capacitors and protection equipment.

Generator

An IP55 1.5 kW 3-phase induction motor with 240V delta connection was selected for use as the generator. As shown above, the required number of poles was 6. In addition, the IP rating for the selected motor was IP55 to ensure maximum protection from entry of water and dust inside the machine.

The connection of capacitors to the motor is required in order for it to operate as a generator. By connecting the capacitors in a C-2C arrangement it is possible to produce single-phase power efficiently from a 3-phase induction motor.



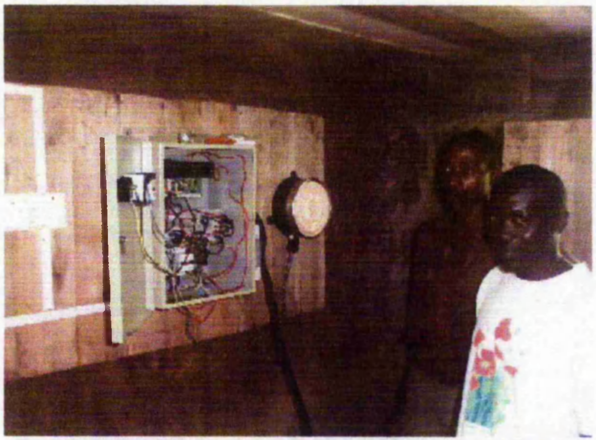
200mm p.c.d. Pelton turbine and nozzle

1.1 kW induction generator (6 pole)

An IGC (Induction Generator Controller) ensures that the voltage and frequency of the electricity produced remain constant by sending excess power to a ballast heater during times of changing consumer load. A 2kW electric cooker is used as a ballast at this site. The controller and capacitors are housed together in a lockable enclosure. In addition to these components, an RCD (Residual Current Device) is connected for consumer safety and a motor protection switch is used to protect the generator windings from overheating due to excessively high currents.

Operator Training

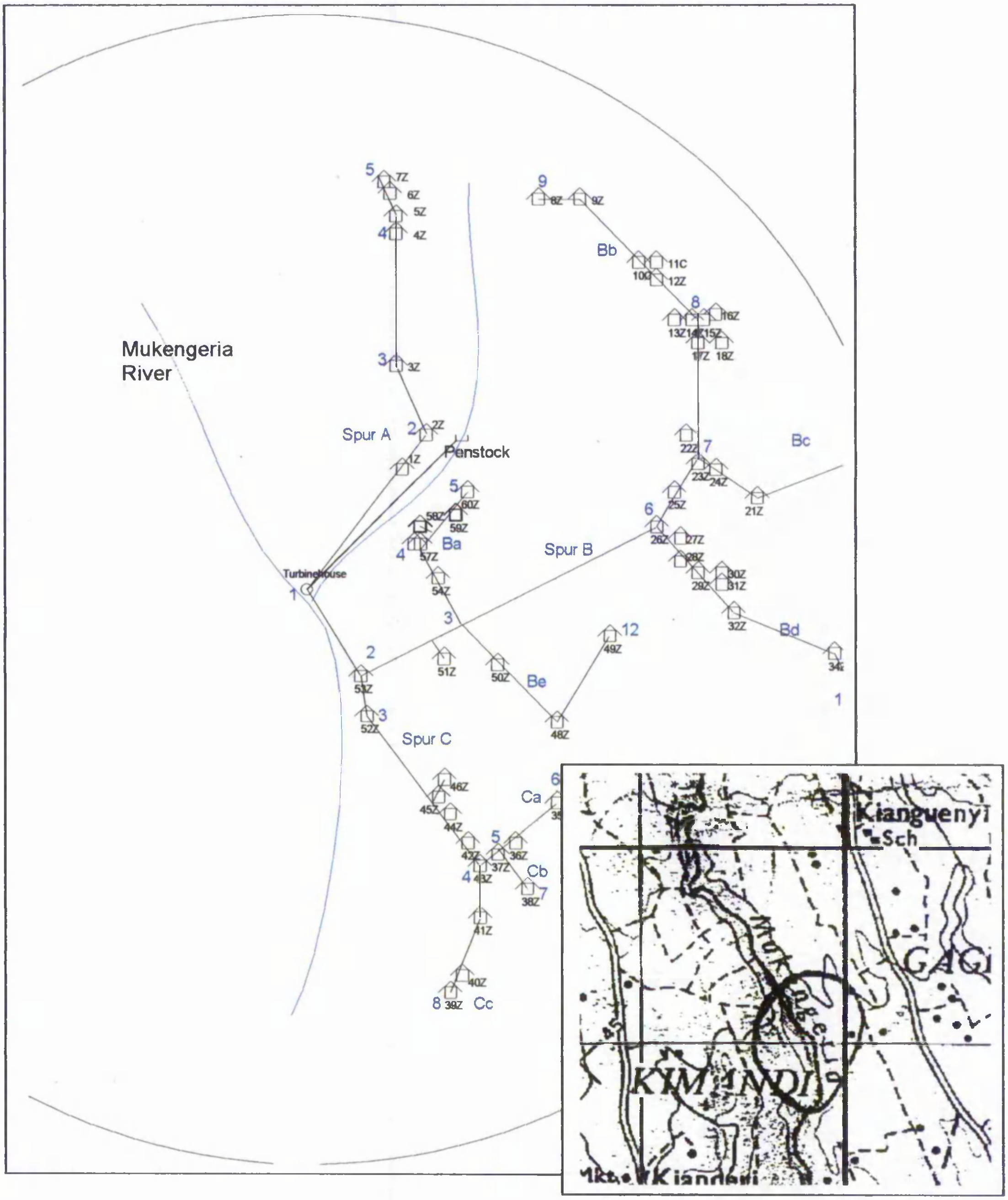
Sufficient training for key individuals was essential to ensure that the scheme will continue to be operated and maintained successfully in the future. Local electricians were involved from the beginning of the turbine and generator installation. They were given on-the-job training to ensure that they could locate faults and replace damaged components. This was particularly important as these are the first schemes of their kind in Kenya. The training was back up with comprehensive documentation including complete circuit diagrams and a maintenance schedule. The new internet facility in Kerugoya town (1hr walk from the site) provides a route to a further source of technical back-up; the operators are now able to request advice directly from pico hydro specialists in Nairobi or the UK if a problem arises which cannot be solved locally. The consumers are charged a fixed monthly tariff depending on whether they have two lamps or one. This is used to pay the operators wages and to contribute to a maintenance fund to replace worn components and keep the scheme operating.



Trained pico hydro installers and operators, Peter Kinyua Mbui and David Kinyua with the IGC enclosure and ballast.

The Distribution System

The plan below shows the position of the consumers relative to the generator. The large circle represents a radius of 500m from the turbine house. The location of the houses was recorded using a widely available and relatively low-cost hand-held GPS system. This allowed the length of cable required to reach all the houses to be accurately calculated and then sized to ensure that even consumers at the furthest points in the system received a supply which was within an acceptable voltage range without excessive cost. This was important as the entire cost of the distribution system and house-wiring was met by the electricity consumers. Local trees were used for distribution poles after basic treatment to reduce damage by termites and weathering. The installation of the distribution system initially required a considerable degree of co-ordination to collect, treat and erect a sufficient number of poles. Guidance was given on the required pole height, methods of treatment, the d buried depth and the spacing. Every consumer contributed one or two poles to the scheme.



The first few houses were connected under supervision from the project implementers, particularly with regard to pole positioning, cable tensioning and service wire connection. The final phase of the project, to connect the remaining houses, continued under the direction of the local electricians and committee members without the need for much external support. The immediate prospect of electric lighting and connection of small electrical loads such as radios and, in some cases, mobile phone chargers, rapidly encouraged the payment of the remaining connection fees. This allowed the final cables and house wiring components to be purchased. In addition, the electricians were paid on a per consumer basis for the house wiring and therefore were keen to keep up the pace of installation of the final poles and conductors.

The first house is connected to the generator

This picture on the right was taken through the front door of a house in Kathamba a few minutes after the first energy saving lamps had been installed and the generator switched on. Despite only drawing 8 watts of power, these lamps give out a bright light. This is particularly apparent in homes that have only previously been lit with kerosene lanterns.

After months of anticipation, the lights were finally switched on (6th November 2001).

Project Costs

A cost breakdown for the scheme components is given in the table below. The hydro potential at this site was limited by the small flow. Due to the limited power available and the relatively large number of consumers living nearby, the power per house is sufficient only for one or two lamps and a radio. This however, had the advantage that the cost of the distribution was divided amongst more people and so households at all income levels were able to benefit. Consumers paid for a 1 lamp or 2 lamp connection depending on how much they were able to afford.

Scheme Components	Cost (US$)
1. Civil works (intake and turbine house)	250
2. PVC penstock	425
3. Turbine, Generator, Controller and Protection	1,200
4. Distribution system, house wiring and energy saving bulbs (65 houses / 100 bulbs)	1,750
5. Labour costs (electrical wiring:200 shillings per house, other labour provided at no cost)	163
Total	**$3,788**

The total cost was $58 per house. This is particularly reasonable when compared to a lead acid battery which, when bought new, not only costs more but requires regular charging, provides DC power only and has a useful life of 2 years or less. A solar home system, providing a similar amount of power as the pico hydro has the same disadvantages as a battery only system and would have cost at least 5 times more per house.

Community Pico Hydro in Sub-Saharan Africa: Case Study 2
Site: Thima, Kirinyaga District, Kenya

Background

This was the second of two schemes installed as part of a program implemented by The Micro Hydro Centre at Nottingham Trent University to demonstrate Pico Hydro technology in Sub Saharan Africa. The cost of the penstock, turbine and generator equipment was met by the project funders (European Commission) and all other costs were contributed by the 110 households which the scheme supplies with electricity.

Technical Summary

This case study describes a pico hydro plant using a 'pump-as-turbine' directly-coupled to an induction motor as generator which has an electrical output of 2.2kW. The penstock consists of 90 metres of 160mm diameter PVC pipe. The net head is 18m and the flow into the turbine is 28l/s. The electrical output of 2.2kW corresponds to a turbine-generator efficiency of 45%. The water source is the Rutui River which has a flow rate of more than 100l/s during 90% of the year. The minimum flow, measured after an unusually long period of dry weather, was 84 l/s. The generator output is regulated by means of an Induction Generator Controller to ensure that the voltage and frequency are held at the correct values during conditions of changing consumer load. Excess power is fed to a ballast load. Two 1.8kW cooking rings connected in parallel have been used for this. There are around 160 households within a 900m radius of the turbine house and 110 of these are being connected to the generator using a single-phase distribution system with insulated copper conductors. Each house has a 230V supply which is sufficient for one or two energy-saving lamps and a radio. It was not possible to connect all the houses due the proximity of some to the grid lines which supply a tea factory and a local church. Areas in the vicinity of the grid lines were avoided to prevent risk of conflict with the national utility. The locations of the generator and consumer houses were recorded using a GPS system so that a distribution plan could be developed. The average cost per house for all equipment and materials was $58 and more than 50% of this cost was contributed by the consumers. In addition the consumers contributed their labour free of charge and trees from their *shambas* (farms) to make distribution poles.

Site Description

Kerugoya town lies 130km north of Nairobi on the southern foothills of Mount Kenya. Thima is approximately 4km north-west of Kerugoya. Traveling time from the town to the site is around 15 minutes with a vehicle. The powerhouse can be reached after a further 10 minute walk down into the steep valley along which the Rutui River flows. This river, which provides the hydro power potential, is formed at the conference of the Kangaita River and a smaller tributary 500m upstream from the turbine. There are approximately 160 houses within the vicinity, the furthest of which is 900m from the turbine house.

Community Organisation

The local community at Thima were organised and motivated from the outset. They had previously formed an association and collected money so that a transformer could be purchased because grid lines run nearby to a tea factory. This is the only way of receiving a connection to the grid in many rural parts of Kenya. In many African countries it is quite normal that grid lines pass over or very close to houses but they often have little hope of ever being connected. The relatively small power demand is simply not sufficient for them to provide a good return on investment for the utility. Unfortunately the group did not manage to raise sufficient funds for the transformer so they were unable to get grid connected. However, this group provided a good basis to form an association for the implementation and management of this project once the local hydro potential had been recognized.

Community members outside the turbine house at Thima

Intake

The design flow for this scheme was 28 litres per second. The lowest recorded flow, using the salt-gulp method of flow measurement, was 84 l/s. This was taken after a particularly prolonged dry period caused by the failure of two consecutive rainy seasons so there is a good degree of certainty that the design flow to the turbine will always be available. For pico hydro schemes, the use of natural features and semi-permanent structures is favored to avoid the high costs of civil works often associated with larger hydro projects.

Galvanized wire mesh prevents debris from pool entering the penstock at the intake

Boulders have been used to form a deep around the intake. Soil bags seal the gaps.

At this site, use was made of a natural division in the river to provide a more easily controlled flow of water to the intake. Maize sacks filled with clay soil were used to re-enforce the channel leading to the intake and boulders were positioned to form a pool with sufficient depth to ensure that the penstock is kept full. The edges around the boulders were sealed with more stones and soil sacks. A flushing pipe was also added to enable the pool to be drained quickly. The intake was formed from low-pressure PVC pipe fittings and 5mm galvanized wire mesh rolled into a sealed tube. This acts as a filter to prevent any debris from entering the penstock and fouling the turbine. Two filters are used to ensure that a sufficient flow rate was always maintained. A wooden fence at the entrance to the channel reduces the risk of large sticks and leaves entering the channel to the intake. These are swept away by the main river flow instead.

Penstock

A community effort transformed the landscape of the riverbank within a few of hours to provide a platform at the correct level to support the first section of the penstock. Soil bags were used to secure the pipe in position and cover it to prevent sunlight damage. Locally fabricated metal posts, set into concrete, secure a suspended section of the pipe as it descends over a steep rocky slope parallel to the waterfall. A clamp lined with rubber was welded to the top of the posts and bolted around the pipe sockets where risk of a rupture was greatest.

The penstock level is marked out with string up to the proposed intake position.

A few hours later, a stone platform has been constructed to support the pipe.

The length of penstock required at this site was 90m to gain 20m of head. Class B (6bar) PVC pipe with a nominal diameter of 160mm was selected. This gives a head loss of about 2 meters with a flow rate of 28 l/s, so the net head at the turbine is 18m. This pipe was manufactured in 6metre lengths with each length joined to the next by means of a socket at one end. No PVC cement was required at the sockets, as a rubber 'O' ring was fitted which gives a pressure tight seal. One disadvantage of PVC pipe is that it is quite rigid and therefore potentially more difficult to install at a site where the landscape is uneven and rocky as in this case. Two 45° elbows were used to obtain the correct slope for the pipe down the steepest section. Other sections were carefully molded around a former after heating over a fire to give more gentle radius bends where required. A large wheel hub, securely anchored in the centre, provided a suitable shaped former. During this process it is important to fill the centre of the pipe with hot sand (plugged with maize sacks) to ensure that it does not buckle. Softening the pipe is easier over embers because the heat supplied is more even. Nevertheless, it is still important to keep the pipe moving during heating by constant rotation to prevent the plastic from burning.

Sockets enable the 6m pipe lengths to be fitted together. An 'O' ring fits in the socket recess and provides a pressure tight seal.

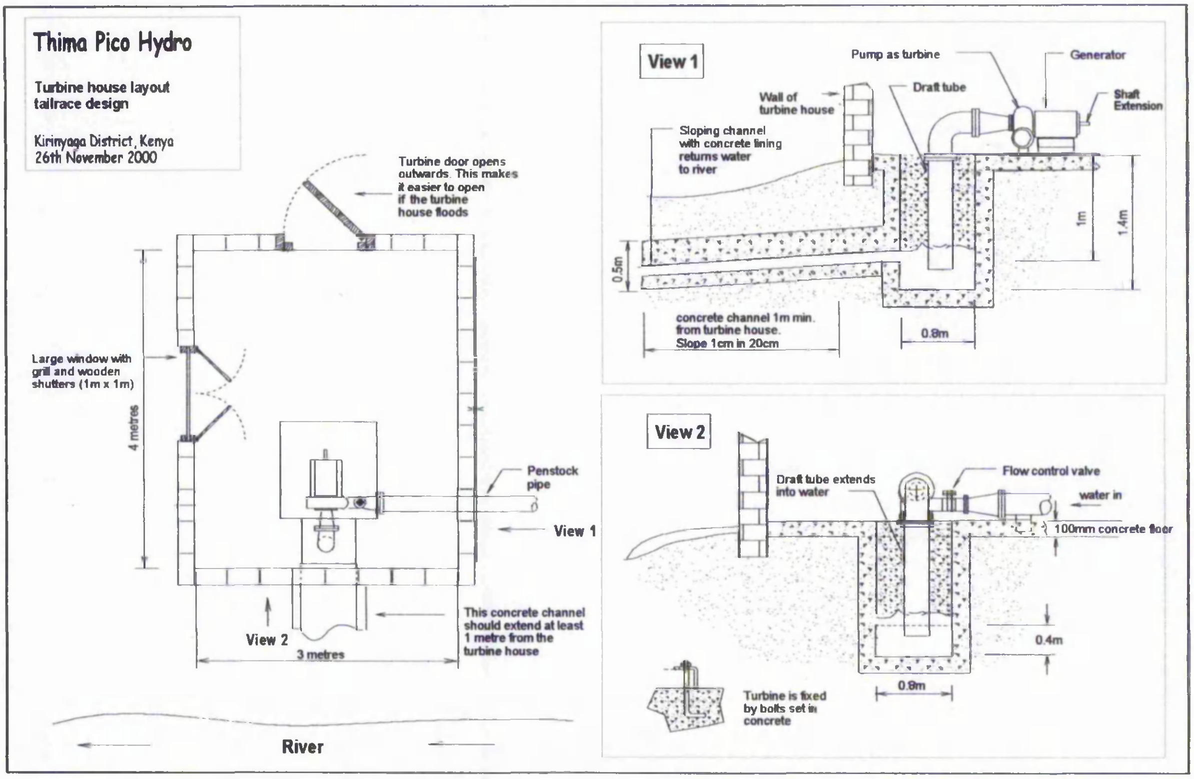
Since PVC is quite rigid, 45° elbows joints were cemented in at two points to enable the penstock to follow the shortest path to the turbine house.

Small bends were made by heating sections and then shaping around a former. Embers rather than flames (as above) should be used to avoid the risk of melting the pipe completely.

The entire penstock was supported by soil bags wherever possible and covered to prevent damage by sunlight.

Turbine House

This building houses the pump-as-turbine and generator equipment and ensures that the water is returned directly to the river. It is built above flood level but otherwise close to the riverbank. The location was chosen to maximise the available head whilst minimising the penstock length. A draft tube was added to the outlet of the pump to obtain and extra 1metre of head. Extra floor area was added to the building since the intention is to use the fan end of the generator shaft to drive a *posho* (maize) mill. Double-ended generators such as this can sometimes be requested from the supplier or otherwise a shaft extension can be fabricated in a workshop and welded in position.



This scheme was installed in 10 days at a cost of $2,600 (excluding distribution and house wiring).

The induction motor as generator produces 2.2kW but a shaft extension provides a 3kW drive for mechanical loads.

Pump-as-Turbine

Since the head at this site was not sufficient for a Pelton turbine, another low-cost and robust solution was selected. Standard centrifugal pumps can be used as turbine generator units if carefully matched to the site. In this case a 'mono-bloc' type was used which is supplied with a directly-coupled induction motor. The pump impeller becomes the turbine runner and the motor is used as an induction generator. The difficulty lies in predicting precisely how a particular pump will perform as a turbine at a given site. Performance prediction equations can be used to select a particular machine if the site conditions are known. The Indian manufacturer Kirloskar Brothers supplied the pump used for this project since they have a sales outlet in Nairobi. To calculate the power output from this pump when it is used as a turbine, it is necessary to look at the pump best efficiency data which was obtained from the manufacturer. The following equations can then be used which take into account the speed increase necessary when operating the pump connected directly to an induction motor which is used as a generator.

$$Q_t = \frac{N_t}{N_p} \times \frac{Q_{bep}}{\eta_{\max}^{0.8}} \qquad H_t = \left(\frac{N_t}{N_p}\right)^2 \times \frac{H_{bep}}{\eta_{\max}^{1.2}}$$

Where:

Q_t = Flow rate using pump as turbine (litres per second)

H_t = Head using pump as turbine (metres)

Q_{bep} = Flow rate at best efficiency point (litres per second)

H_{bep} = Head at best efficiency point (metres)

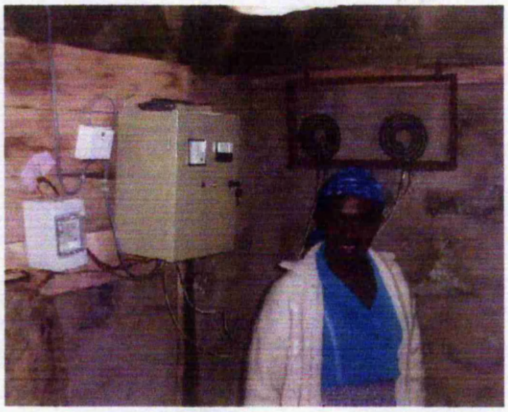
η_{max}= maximum efficiency (%)

N_t = Speed of turbine (rpm)

N_p = Speed of pump (rpm)

Using data for a Kiloskar 515+ pump, Q_t= 26.9 and H_t= 18m which matches the site conditions and allows for approximately 2 metres of head loss in the penstock. A stuffing box type seal was also specified rather than a mechanical seal as replacement parts for the mechanical seal are more difficult to obtain. A bronze impeller was selected instead of cast iron because of improved corrosion resistance.

A draft tube increases the head by 1m whilst ensuring that the turbine remains above flood level.



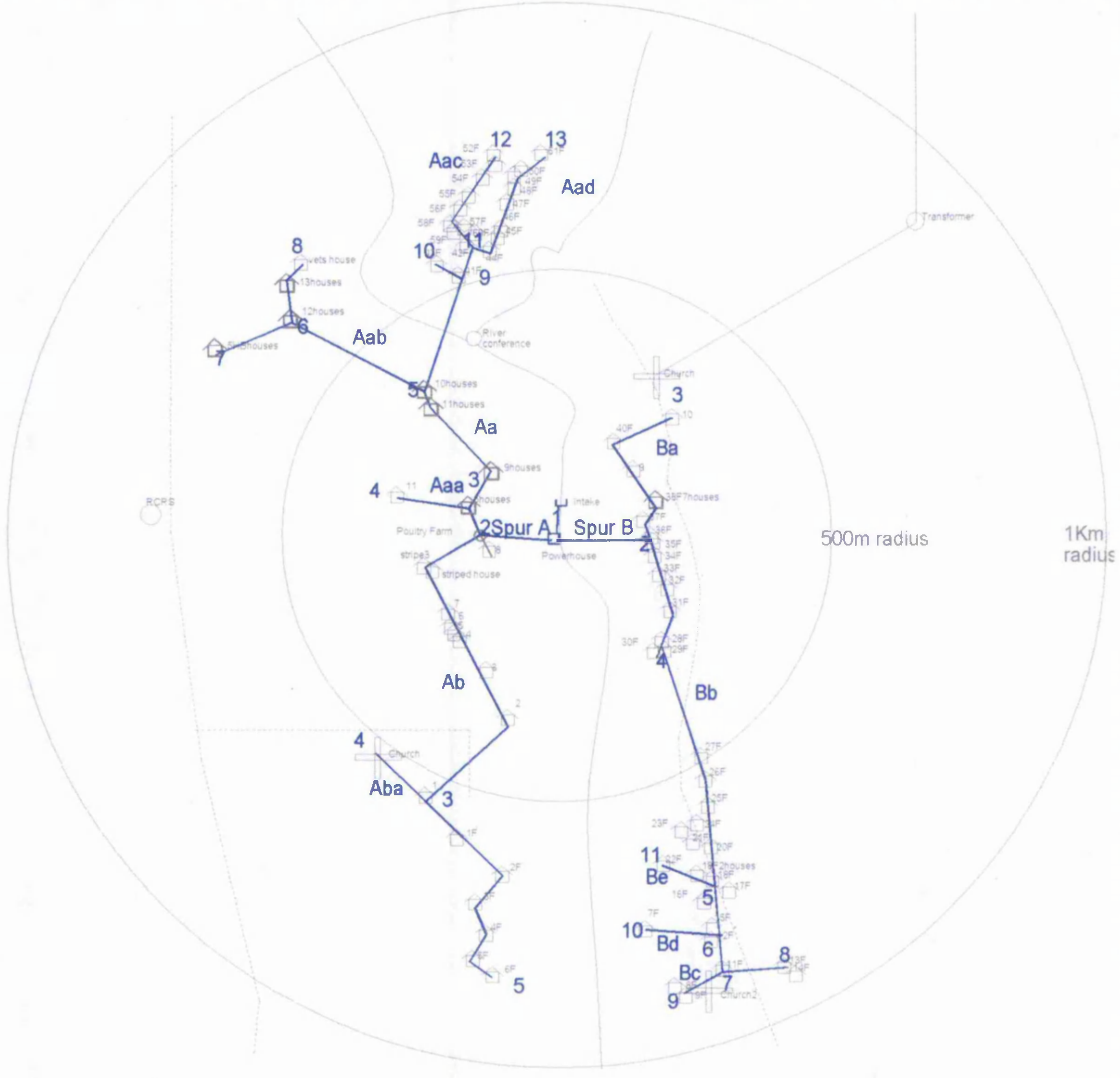
Two 1.8kW cooking rings have been used as a ballast load. An RCD (left) improves consumer safety by minimising the risk of dangerous electric shocks.

Generator

The KDS 515+ pump is fitted with a 3.7kW (5h.p.) induction motor. This produces 2.2kW of electrical power when driven by the turbine (pump impeller). The motor voltage was specified from the manufacture to be 260V rather than 240V and the winding insulation Class F rather than Class B which is standard on machines of this size. Both of these measures help to prolong the life of the windings by ensure that they operate at a much lower temperature than their rated temperature. A 3kW induction generator controller (IGC) provides voltage and frequency regulation by diverting excess power to a ballast load (two 1.8kW cooking rings). A residual current device (RCD) with 30mA tripping current maximises consumer safety by disconnecting the generator if an earth fault develops, either because of a faulty appliance or due to someone accidentally touching a live wire.

Distribution System Planning Using GPS Data

The locations of the houses shown on the plan were recorded with a relatively inexpensive GPS unit (Global Positioning System). This uses satellite technology to triangulate a precise position by 'tuning in' to 3 or more satellites (accuracy of +/-15m). The position is then referenced and stored. Downloading these points to a CAD (Computer Aided Design) program allows a map of the site to be generated. Using the CAD system, the routes for the distribution cables was worked out and drawn in to ensure that all the consumers were connected. A spreadsheet program was used tp determine the minimum cable diameters which could be used whilst still ensuring that all consumers would receive a connection with an acceptable voltage, no matter if their house lies at the end of the cable furthest from the generator. This helped to keep the connection costs for the consumers as low as possible.



Consumer houses were surveyed using a GPS unit. Using this data a map was drawn and the network planned out. Houses which are not connected have not been shown.

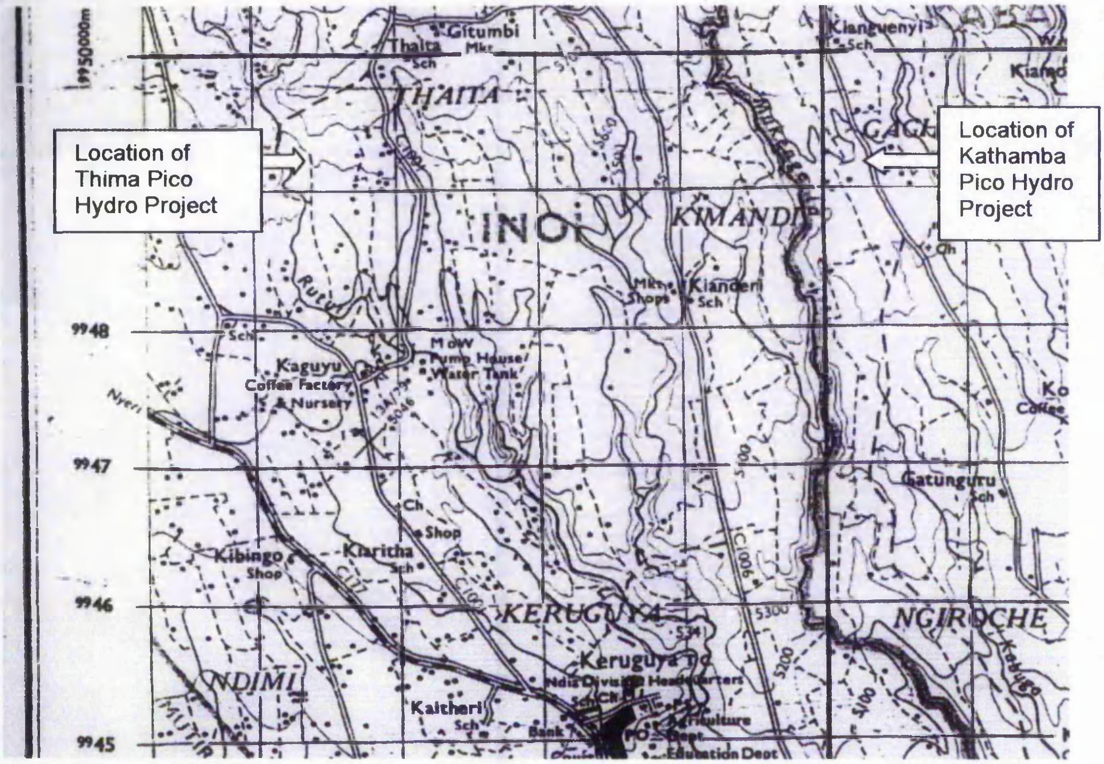
Project Costs

A cost breakdown for the scheme components is given in the table below.

Scheme Components	Cost (US$)
1. Civil works (turbine house)	250
2. PVC penstock	600
3. Turbine, Generator, Controller and Protection	1,750
4. Distribution system, house wiring and energy saving bulbs (110 houses / 200 bulbs)	3,365
5. Labour costs (electrical wiring:200 shillings per house, other labour provided at no cost)	400
Total	**$6,365**

The total scheme cost averages $58 per house. This makes pico hydro very cost-effective when compared to a lead acid battery which, when bought new, not only costs more but requires regular charging, provides DC power only and has a useful life of 2 years or less.

Nevertheless, batteries are still used extensively in many parts of Africa. A solar home system, providing a similar amount of power as the pico hydro, suffers the same drawbacks as battery only systems and costs at least 5 times more per house. Clearly pico hydro is limited to areas where suitable hydro potential exists, but given that the flows required are small, an extremely large number of people stand to benefit from this very affordable technology in many parts of Kenya and more broadly in Sub Saharan Africa.



Both demonstration sites are located quite close to each other and convienient for vehicle access. Travelling time is approximately 2.5hrs from Nairobi (Topographical Map: Sheet 121/4 Embu North)

Acknowledgements

The Micro Hydro Centre at Nottingham Trent University would like to thank all the project partners who have worked hard to make this scheme a success. They are Stephen Gitonga and Patrick Balla from the Energy Program at ITDG Kenya; James Muriithi and Theuri Daniel Kahiga from the Renewable Energy Department at the Kenyan Ministry of Energy and the committee and community members of Thima Micro Hydro Group 2000. The Micro Hydro Centre also gratefully acknowledge the funding provided by the European Commission for making this program of demonstration and training possible.