# DESIGN OF A
# MICRO - HYDRO POWERED BATTERY CHARGING SYSTEM
# FOR
# RURAL VILLAGE ELECTRIFICATION

by

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## Abstract

Many remote villages or farms in developing countries are not yet connected to the grid due to the high costs and the complex technology of village electrification. Rechargeable batteries are commonly used to cover the basic demands for lighting and radio / TV operation. Often, villagers carry their batteries a long way to the next town to recharge them. Solar battery charging would be one comfortable but also very expensive possibility to charge batteries directly in the house of the consumer; but using available hydropower potential to charge batteries seems to be a better solution to supply energy at low costs into remote areas.

This thesis investigates and explores the possibilities of battery charging using small hydropower resources in rural areas with respect to its economical and technical feasibility. In Part 1 of the study different management options are introduced and basic economic calculations are performed. It will be shown that battery- or pre-electrification schemes can be economical, especially when compared to other conventional sources of energy like candles, LPG or non-rechargeable batteries. Part 2 deals with the technical aspects of a battery charging system and shows simple and cost effective solutions for the implementation. All different parts of a MHP scheme are evaluated with respect to their possible application in battery charging systems. Furthermore, options for battery charging and discharging procedures are explained and evaluated.

## Zusammenfassung

Ein~~e~~ hoher Anteil der Bevölkerung in Entwicklungsländern ist auf Grund der hohen Kosten und der komplexen Versorgungstechnik nicht an das nationale Stromnetz angeschlossen. Besonders in ländlichen Gebieten werden deshalb häufig wiederaufladbare Batterien genutzt, um die grundlegende Bedürfnisse nach Beleuchtung, Kommunikation und Unterhaltung zu befriedigen. Oft müssen die Dorfbewohner ihre Batterien auf einem langen und beschwerlichen Weg zur nächstliegenden Stadt bringen, um sie dort wiederaufladen zu lassen. Die Nutzung von Solarenergie wäre eine bequeme, aber leider auch eine sehr kostspielige Möglichkeit, Batterien direkt im Haus des Verbrauchers aufzuladen. Eine einfache und kostengünstige Alternative kann die Nutzung von Kleinstwasserkraftanlagen darstellen.

Diese Arbeit beschäftigt sich deshalb mit den Möglichkeiten der Batterieladung mit Hilfe von Kleinstwasserkraft in den ländlichen Gebieten. Dabei wurde sowohl die ökonomische als auch die technische Machbarkeit untersucht.

In Teil 1 der Arbeit werden unterschiedliche Optionen des Managements aufgezeigt und grundlegende ökonomische Berechnungen durchgeführt. Es wird gezeigt, dass Batterieladesysteme, besonders im Vergleich zu anderen traditionellen Energiequellen wie Kerzen, Flüssiggas oder konventionellen "Einweg" – Batterien, ökonomisch arbeiten können. Teil 2 der Arbeit beschäftigt sich mit den technischen Aspekten des Batterieladesystems und zeigt einfache und kostengünstige Lösungen für die Implementierung. Die unterschiedlichen Bestandteile eines Kleinwasserkraftwerks werden in Bezug auf ihre Anwendbarkeit in Batterieladesystem ausgewertet; zusätzlich werden Optionen für Lade- und Entladestrategien von Akkumulatoren diskutiert.

# Table of Content

## List of Figures

## List of Tables

## List of Symbols

| Symbol | SI - Unit | Quantity, Explanation |
|---|---|---|
| A | $m^2$ | Area |
| $A_k$ | US$/a, €/a, Rp/a | Total annual cost |
| a | % | Inflation rate |
| B | $T = Wb/m^2$ | Magnetic induction or magnetic flux density |
| C | F = As/V | Capacitance |
| $C_B$ | Ah | Battery capacity |
| g | $m/s^2$ | Gravitational acceleration |
| E | Ws (often kWh) | Electric energy |
| f | Hz | Frequency |
| $f_b$ | - | Battery charging factor |
| $f_c$ | - | Capacity factor |
| $f_p$ | - | Plant charging factor |
| H | A/m | Magnetic field strength |
| H | m | Turbine pressure head |
| I | A | Current |
| $I_\mu$ | A | Magnetizing current |
| i | % | Interest rate |
| K | US$/a, €/a, Rp/a | Annual cost |
| L | H = Vs/A | Inductance |
| N | - | Number of turns of a coil, or generally number |
| n | 1/min, rpm | Rotational Speed |
| $n_s$ | 1/min, rpm | Synchronous Speed |
| $n_{bat}$ | - | Number of batteries |
| P | W | (Active) Power |
| p | - | Number of pole pairs |
| R | Ω | Ohmic resistance |
| S | VA | Apparent power |
| s | - | Slip |
| t | s | Time |
| T | °C | Temperature |
| T | Nm | Torque |
| Q | Var | Reactive power |
| Q | $m^3/s$ | Flow, discharge |
| U | V | Voltage |
| v | m/s | Velocity |
| X | Ω | Reactance |
| $X_m$ | Ω | Magnetizing reactance |
| $X_\sigma$ | Ω | Leakage reactance |
| Z | Ω | Impedance |

## List of Symbols, continued

| Symbol | SI - Unit | Quantity, Explanation |
|---|---|---|
| $\alpha$ | ° | Angle |
| $\Phi$ | Wb = Vs | Magnetic flux |
| $\varphi$ | ° | Phase angle |
| $\eta$ | - | Efficiency |
| $\mu$ | Vs/Am | Permeability of a magnetic circuit |
| $\rho$ | $\Omega mm^2/m$ | Resistivity of conductor material |
| $\rho$ | $kg/m^3$ | Density |
| $\Omega$ | rad/s | Angular Speed |
| $\tau$ | s | Time constant |
| $\Delta$ | - | Delta connection |
| Y | - | Star (Wye) connection |

## List of Subscripts

| Subscripts | Meaning |
|---|---|
| 0 | No load |
| 1 | Phase 1 / Primary winding transformer |
| 2 | Phase 2 / Secondary winding transformer |
| 3 | Phase 3 |
| C | Capacitive |
| Cu | Copper |
| eff | Effective values |
| el | Electric |
| Fe | Iron |
| i | Instantaneous value |
| L | Inductive |
| n | Nominal value |
| gen | Generator |
| mech | Mechanical |
| r | Rotor |
| s | Stator |
| t | Turbine |

## List of Abbreviations

| | |
|---|---|
| AC | Alternating Current |
| C-2C | System of connecting capacitors on a three-phase IMAG serving a single phase load |
| DC | Direct Current |
| DOD | Depth of Discharge (of a rechargeable battery) |
| AVR | Automatic Voltage Regulator (of synchronous generators) |
| IMAG | Induction Motor as Generator |
| IGC | Induction Generator Controller |
| ELC | Electronic Load Controller |
| IP | International Protection |
| LV | Low Voltage |
| MV | Medium Voltage |
| HV | High Voltage |
| MHP | Micro Hydropower / Micro Hydropower Plant |
| O&M | Operation and Maintenance |
| PAT | Pump as Turbine |
| PE | Protective Earthing |
| RMS | Root Mean Square values (effective values) |
| RF | Recovery Factor (economics) |
| rpm | Revolutions per Minute |
| SOC | State of Charge (of a rechargeable battery) |

## Introduction

The recent advertisement of a big German car manufacturer is a good example for the big inequalities and disparities in our world. The manufacturer advertises with the fact, that only 48 grams of gasoline are enough to accelerate one of its new, comfortable big and heavy cars from zero to 100 km/h.
On the first glimpse this really seems an amazing engineering achievement, but on a second view, from the perspective of under electrified and under energized developing countries, this could be seen as a rather sarcastic statement.

A closer look reveals that the energy content of 48 gram gasoline approximately equal the energy that can be drawn from of one normal car battery[1]. Today, in many areas of the world, car batteries are the only means to gain access to electricity for big proportions of the population.

The energy of one car battery can provide light at night and possibly the operation of a small television set for a couple of days. Car batteries can power small, specially designed refrigerators for medicine and vaccines and sometime they are the only power source for modern communication.

Of course, batteries have to be recharged frequently and for that purpose they are often transported over large distances into the next town or to the next available charging station. This transport again consumes valuable energy and time and if one sums up all the different steps it becomes clear that the overall "efficiency" of the whole process is incredibly small. In many cases, the energy used during transport exceeds the actual energy content of the battery by far.
Additionally, the cost of electricity from rechargeable batteries is often very high when compared to energy cost in Germany or other developed countries. Often, people have to pay more than 1US$ per battery charging, which equals an energy amount of less than 1kWh (as a comparison: in Germany and other developed countries 1kWh of electricity from the national grid costs around 0.10 to 0.30US$). Furthermore, time and cost for the transport of the battery is not yet included in this price and still has to be added.

Despite all those disadvantages many people in developing countries around the world are forced to use rechargeable batteries since they provide the only possibility to gain access to electric power.

This study will investigate and analyse the possibilities of using small micro hydropower plants for battery charging and other central energy services in rural

[1] Gasoline has an energy content of approximately 45 $^{MJ}/_{kg}$. Therefore, 48 grams of gasoline contain an energy of about 2.16 MJ; which equals 600Wh or 0.6kWh. A battery with a rating of 60 Ah at its operational voltage of 12 V has an energy content of theoretically 720Wh (but only 80% of this value (=580Wh) should be used to secure the lifetime of the battery).

areas close to the consumer. Special emphasis was put on the design of a “simple”, failsafe and economic solution which could be easily applied and adopted in rural areas throughout the world. The idea was to design a system that is easy to operate by local people and which requires a minimum of maintenance or adjustment.
The overall goal is to design an economically viable solution to provide electricity services to remote areas at reasonable cost for its users. The final result should be a modular system which could be adjusted to different sites (e.g. sites with different hydraulic potential or with different numbers of inhabitants).

This study is mainly divided into two parts: part one will be a theoretical approach into the system design and possible management strategies, while part two will deal with the technical realisation of the scheme and its single components including turbine, generator, transmission and electricity end-use.
For testing purposes a demonstration system was designed in Bandung, Java, Indonesia during the course of this master thesis. Unfortunately, due to time constrains a fully functional system could not yet be set up.

# 1. The Energy Situation in the Developing World

In developed countries of today's world electricity is taken for granted by everybody. Wall sockets are seen as a naturally available thing and everybody expects them in every room. Electricity is demanded for 24 hours a day and for 365 days a year and people get irritated if there is a blackout for more than 5 minutes.

For about two billion people[2] on our planet the situation is completely different, because they do not have any access to electricity at all. This study was performed in Indonesia and has special emphasis on the situation in this country but could easily be adopted and employed worldwide. Electrification rates in Indonesia, which has an overall population of more than 250 million people, are as low as 45% on the outer islands and 55% in Java[3].

Throughout the vast archipelago of Indonesia there are still many rural communities without access to electricity who will not be connected to the national power grid within the next decades. Villagers in non-electrified areas rely on candles, kerosene lamps and batteries to satisfy part of their energy needs. Rural households typically spend a significant share of their income on these energy sources – despite the inconvenience and the environmental and health hazards associated with them. Fortunately, Indonesia has vast resources of different forms of renewable energy, and an especially big potential of hydropower. Hydropower can help to improve the energy situation of many rural areas, since it is a reliable and well proven technology which is relatively simple to use.

The benefits of electricity, as compared with other forms of energy, are its versatility and convenience. The availability of modern energy or electricity can be considered as one of the factors that facilitate and enhance social and economical development. Electricity provides the social benefits of improved lighting and communication – radio, TV and telephone – and in other cases greatly improves productivity with electrical appliances and machines. Other typical rural electricity applications include refrigeration, the supply of clinics, schools, work shops and shops. Certainly, not all energy needs can be fulfilled with electricity; still thermal energy for cooking and heating (in the form of firewood, kerosene or liquid petroleum gas (LPG)) is needed. But electricity can be a useful substitute for candles, kerosene lamps, or simple "throw-away" alkaline-batteries.

Electricity can stimulate economic development that is already taking place. It will not necessarily initiate development. Communities which are very poor, with very little economic activity, are unlikely to derive much economic benefit from an

[2] Worldbank Statistics: www.worldbank.org
[3] Report of the ENTEC AG to the UNDP on the Energy Situation in Nias, Sumatra

electricity supply, although they may derive substantial social benefits from better lighting and communication.[4]

Another aspect when talking about rural electrification and off-grid schemes is the importance of end-user involvement in the different planning and installation stages of any energy system. Unfortunately, there are numerous examples where attempts to implement off-grid, decentralized electricity schemes have failed. One important factor in the failure of these schemes has been the lack of participation of end-users in the planning and implementation of projects, due to a 'top-down' approach. Consequently, the partaking of the end-user in the whole planning process is a decisive factor for a successful and enduring off-grid electrification scheme. There is no point in installing services or structures which are not accepted or needed by the local community. Often no highly advanced technical solutions are needed but rather communication and understanding of the needs and wants of the local people.

The aim of this study is to show a reliable, rugged, simple and cost-effective system to provide energy services to rural areas with access to hydropower resources. The designed system will not use conventional mini-grid techniques but will rather be in form of a central "energy station" inside a village community. Mini grid systems need to be of a certain size to be economically and technically feasible, furthermore the costs of lines connecting the hydro power plant to the single houses often represents a significant share of the investment. The proposed system with its centralized energy services is technically much simpler and has the big advantage of low investment costs. Certainly, a centralized scheme has also different disadvantages, like, foremost, the transport of energy to the end-user. All those pros and cons will be discussed in detail later in this study.

# 2. Pre-electrification Schemes using Rechargeable Batteries

Like in Indonesia, many rural areas in developing countries will not be connected to the national grid due to economic reasons. These reasons are the very high cost of extending the grid to remote areas, and the related difficulties of maintenance, management and revenue collection. Often the distances between cities and villages are extremely large and the terrain is often difficult to access. The high costs of extending the grid into these often sparsely populated areas can almost never be justified by the “limited benefits” of electrification.[5]

Therefore, decentralized solutions must be found to supply these regions with modern energy. Up to now, diesel generators are often used to supply villages with electricity but besides the environmental problems associated with this kind of

[4] [ITDG_c] pp.1&2
[5] [GATE_92a] p.1

energy production also the economic problems arise with growing fuel prices and possible future shortages in supply.
Where there is sufficient hydropower potential, often stand-alone Micro-Hydropower (MHP) schemes are proposed. But also these solutions require fairly large investments which can seldom be carried by the villagers themselves.
The problem of large investment costs also applies for energy systems using solar and wind power. Furthermore, solar and wind energy production have the disadvantage of very fluctuating power production, which often make large additional storage system necessary.

So called **pre-electrification schemes** using rechargeable batteries and accumulators can be an interesting alternative. For charging these batteries different renewable energy sources could be employed, but if there is a sufficient hydropower potential available in or near the village, then, again, the use of this resource represents the most reliable and economic solution.

Rechargeable batteries are already widely used to cover the basic demand for lighting and radio/TV operation in developing countries. Often, villagers carry their batteries a long way to the next town to recharge them. Using available hydropower potential in a village to charge batteries at a central charging station, near the homes of the potential users, seems to be a good possibility to supply energy at low costs in remote areas. Such a central "Energy Station" or "Energy Shop" could not only charge batteries, but could also provide other energy services like refrigeration, electrical tools, telephone communication or simply entertainment.

## 2.1. Using DC-power and Batteries for Village Electrification in Developing Countries

But what are the features and advantages of using a battery system for rural electrification? On the first view it seems that using a small isolated grid system seems to be much more convenient and effective to electrify a village; but after carefully balancing the pros and cons and considering different aspects like cost, maintenance and control requirements it will become clear that a battery system actually is a viable solution when very small systems (in the range of several hundreds of watts to a few kilowatts) in rural areas of developing countries are concerned.

Such schemes, using the waterpower potential of a village, have the following features and advantages in comparison to "conventional" mini-grid systems[6]:

[6] Compare to [GATE_92a] pp.:1ff.

Increased load factor

Many villages have only limited water resources available for electricity generation. To meet the peak power requirements of the early evening hours when most appliances like lightning, TV and radio, are switched on; the hydraulic energy that has been stored in the batteries or accumulators during the day or the late night hours can be used.

In a conventional mini-grid scheme the size of the hydropower plant has to serve the peak power demand but often during the day the power demand is much less and the energy produced during that time cannot be used. This leads to very poor overall load factor of the plant. The economic viability of such a scheme is therefore low. In contrast to this, the components of an MHP battery charging station (civil construction, turbine, generator and charger) need not to be designed for peak power demand; consequently, the number of families that can have access to electricity is much higher with the pre-electrification system, than with a conventional AC power distribution network (using the same hydraulic potential). In other words, the available water resources of a village are used in a most effective way. The pre-electrification system can therefore be favourable in terms of cost (villagers do not pay for an under occupied scheme), interference with other uses of the available water and its environmental impact.

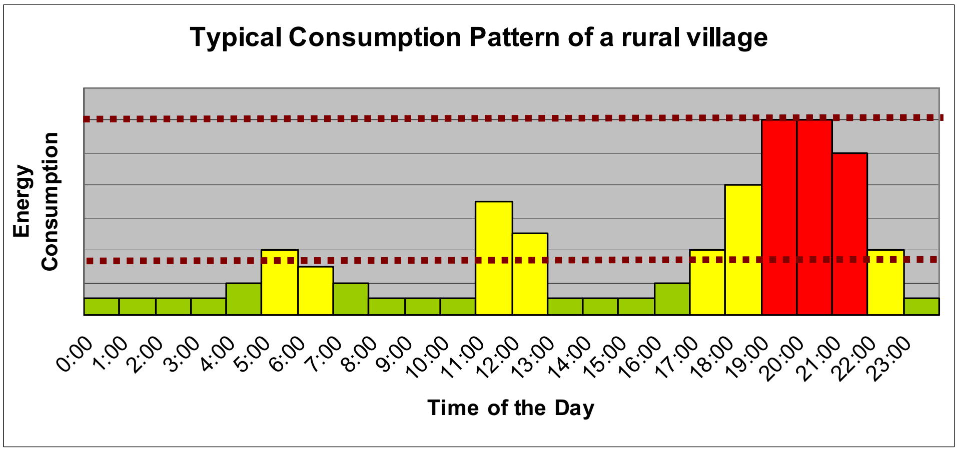



**Figure 2-1: Energy consumption pattern of a rural community.**

**Figure** 2-1 represents the typical consumption pattern of a rural community. Energy consumption during the day is generally very low but rises sharply during the evening hours. A conventional power plant would have to be designed to cover the peak demand but would be largely unused during the rest of the day (upper dotted line). A battery charging system could store the energy that is produced during the day and could consequently be of much smaller size (lower dotted line; a plant size of only less than 30% of the conventional scheme plant size).

No Transmission/Distribution Lines necessary

Electrification of villages with scattered houses and settlements using conventional AC power systems requires long and costly distribution lines and distribution equipment. Additionally, electricity consumption of a family in a newly electrified area is usually so low that the costs for house wiring and meters (or current limiters) are too high as compared to the advantages gained from electricity. Costs for house-wiring and distribution lines can be minimized with the pre-electrification system using rechargeable batteries.

**Figure 2-2: Example of bad and dangerous wiring. Indonesia.**

Safety and Health

The low voltage level of the batteries excludes the danger of electric shock in the houses and therefore is a much less dangerous solution compared with normal AC power systems.

Familiar and Simple Technology

The use and the handling of batteries are relatively simple and a well known technology applied in motorcars and lorries around the world. Rechargeable batteries are widely available in every country. The use of “Deep-Cycle” or “Solar-Batteries” would increase the efficiency of the proposed system considerably and should be used were ever available, nevertheless experience has shown that these batteries are not widely available and also often much more expensive than normal car batteries. Since the initial installation costs are often the decisive factor, these batteries are unfortunately not used very often in rural electrification systems in developing countries, even though the overall efficiency would be greatly improved.

No “Long Term” costs and commitments for the consumers

There are no long term commitments for individual consumers. A villager can discontinue using electricity whenever he likes, not leaving behind costly house-wiring and electricity poles as with conventional AC systems. New users can easily be "integrated" into the system.

Parallel usage of the water

The water of the MHP may be used nearby for washing or irrigation.

Certainly, a battery charging system does not only have advantages and positive effects, but there are also a number of problems connected with it. The disadvantages of village electrification schemes using batteries are discussed below:

Cost of Electricity

Costs of electricity from rechargeable batteries can be very high; if batteries are not properly handled (correctly charged, discharged and maintained), their life time will be significantly reduced with the consequence of major (re-)investment costs for consumers.

Transport of Batteries

The transport of the batteries to and from the charging station represents a big problem (heavy, danger of spilling acidic liquids). Batteries have a low energy density (e.g. the mass per Watt-Hour is very high), this means that a lot of energy has to be put into the transport of a relatively small amount of useful energy.

Danger connected with high current flows

Another potential problem are fires. Fires may occur due to high battery currents and inadequate house wiring (e.g. bad connections or thin cables).

Low Battery capacities and related problems

The use of batteries with their inherently low capacity requires an efficient use of electricity. Energy-efficient appliances such as used for solar systems are a must. The limited energy output of batteries confines their use to lightning, the electricity supply for TV-sets and radios, most of which are not directly productive end-uses. The living conditions of remote villages may be improved by a pre-electrification system but it does not necessarily generate additional income. Though initial investment costs are relatively low, financing a pre-electrification system will in many cases remain a problem.

Use of DC appliances

The availability of DC appliances and spare parts is limited; also the costs of such equipment especially energy-efficient models are often higher than the costs for AC appliances.

Environmental Problems

The problem of a save, environmentally-sound disposal of used batteries (lead and especially nickel-cadmium) has not yet been solved in most developing countries and leads to serious danger to humans and to the environment. However, the recycling or reconditioning of used lead batteries can be economically feasible.

As shown above, there are certainly also disadvantages connected to the use of batteries; solutions to overcome some of the above mentioned problems are discussed in the course of this study. Nevertheless, before installing any system always the situation of the specific site should be carefully checked, to ensure that none of the above problems brings the project to a premature stop, wasting valuable resources that could have been invested into a site were the proposed scheme could work perfectly well.
One should always keep in mind that certainly there is not one solution that fits all the different situations and energy needs. The aim should always be to select the best solution for the relevant situation.

# 3. "The Energy Station"

## 3.1. Introduction: Battery Charging using Micro Hydropower Potential

This part of the study will give a first general introduction into the proposed village pre-electrification scheme. The different parts of the system and their technical realization will subsequently be described in more detail in the second part of this study.

As said before, the aim of this study is to present a rural electrification system using rechargeable batteries to supply basic energy services to a small village. Ideally a central charging station would be at some central point were it could be reached by all end-users in a relatively short time. This would keep the problems of carrying the heavy batteries as small as possible.
The basic outline of such a scheme can be seen in
**Figure** 3-1.

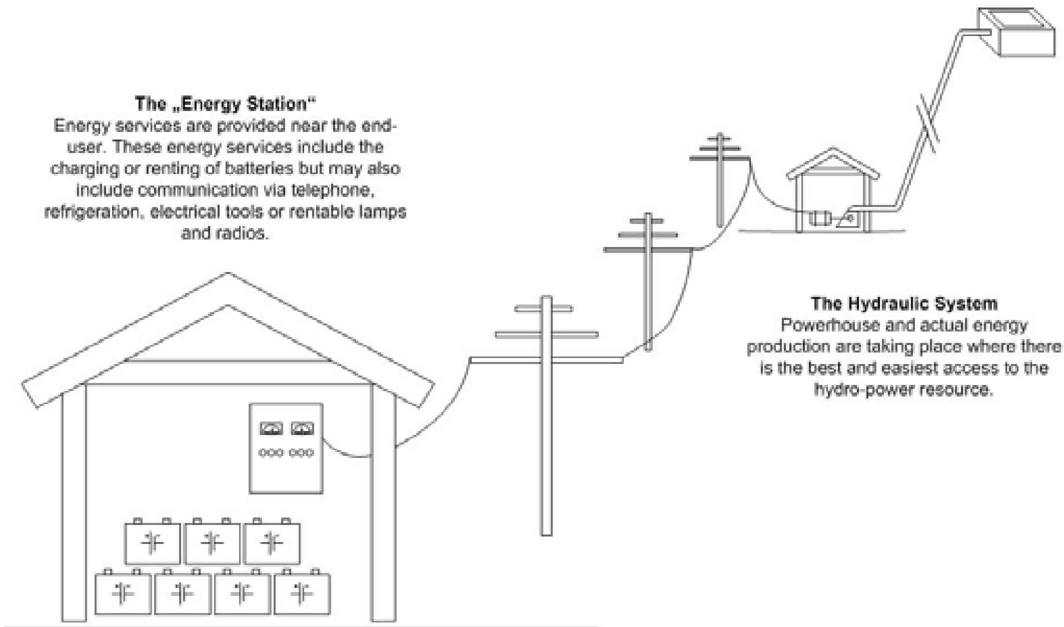



**Figure 3-1: Basic outline of a Hydro powered central battery charging station.**

From the figure above the general structure and the different components of the system become visible: Prerequisite for the application of this scheme is a suitable hydropower site (right side of the picture) in reasonable distance to the village. At the site the hydro turbine is installed and electricity is generated (The picture above might be a little bit misleading in showing turbine and generator inside a powerhouse – in reality the proposed system size of several hundred Watts to a few Kilowatts does not necessarily require a powerhouse but rather only a "box-like" protection against climate, animals and humans). The power is than transmitted via

a power line of up to several hundred meters length into the village where the "Energy Station" is installed, which charges batteries for a number of families and provides different other energy services as described above (left side of the picture). These "energy services" might be various and versatile, depending on the special needs of the respective village. First priority should always have productive end-uses like processing agricultural products or manufacturing goods. Were no productive end-uses are possible; "energy services" could include telecommunication, refrigeration (possible also for medicine or vaccines) or simply entertainment.
Behind the idea of using a "central energy station" to provide electricity to a village (in contrast to conventional mini-grid systems with power lines to every household), are several technical considerations but also considerations concerning the management and the economics of energy distribution.

The mayor reason for using a central energy station is that the "flow" of the energy is easily controllable. The station can be seen as one big consumer with relatively stable and constant energy consumption, this fact makes the design and the technical realisation of the whole plant relatively cheap and simple. A hydropower plant with a constant load connected to it needs only very few regulating components; therefore, the cost and complexity of the system can be kept small.
Also from the point of management the proposed scheme has advantages: The "stealing" of energy will be nearly impossible and all the electrical equipment (besides the home appliances) is in the hands (and under control and supervision) of the operator of the "energy-station". Operation and maintenance can be carried out regularly and properly, increasing the lifetime of the system. The operator of the "Energy Station" should be trained and educated about all the different and relevant aspects of the system. The whole village or community should be aware that the proper treatment of the installation will result in greatly improved lifetime and consequently to lower energy costs.

## 3.2. Plant Size and Energy Demand

The Micro hydropower plant will be designed to provide enough power to cater for the basic energy needs of small villages, or roughly 10 to 50 families.
In a newly electrified area, the electricity demand of a family can be estimated to be about 50 to 200Wh/d (Watt-hours per day) if several fluorescent light tubes and a small radio or tape recorder/CD player are used[7]. A commonly available 12V battery of a useful capacity of 60Ah has a stored energy amount of 720Wh. However, the full energy content of a lead acid battery should never be used up completely, since a repeated complete discharge leads to a rapidly decreasing lifetime of the battery. To ensure a long battery life always at least 20% of battery capacity should remain

[7] [GATE_92a] p.5

in the battery. Therefore only about 580Wh should be drawn from a 60Ah battery before recharging. Depending on the consumption, the recharging cycle for a battery will therefore be 2 to 11 days (580Wh / 50 - 200Wh per day equal a charging interval of 2 - 11 days). Chapter 4.7 about the battery charge and discharge procedures will give more detailed information about this topic.

The overall energy demand and plant size can now roughly be calculated by estimating the number of necessary charging places. The power of one charging place should be sufficient to recharge one standard size battery (in the range of 60 to 80Ah) in one day. A rough approximation for the power output of the charging places can be made using the following formula

$$Power_{Charger} = \frac{Capacity_{Battery}}{Efficiency_{Charging\,Process} \cdot 24h}$$

**Equation 1**

The efficiency of the recharging process can be (pessimistically) assumed to be around 70% and therefore the following power output per charging place is needed:

$$Power_{Charger} = \frac{80Ah \cdot 12V}{0.6 \cdot 24h} = 67W$$

**Equation 2**

The minimum electrical output should therefore be at least 67W per charging place. As the energy demand during the charging process of a battery is not constant but decreasing with increasing SOC of a battery a higher energy output could be considered to increase the charging speed especially at the beginning of the charging process. By introducing a sufficiently high safety margin we can say that a charging power of 100W per charging place can be considered as more than appropriate (this power allows a maximum charging current of 8.3A).

The following table gives an idea about the necessary plant sizes to supply a given number of families with batteries:

| Nr. of families = Nr. of batteries | Average charging interval. (higher consumption = smaller charging interval) | Charging places needed (Nr. of batteries divided by avg. charging interval) | Power needed per charging place (as calculated above) | Energy Output needed | Hydraulic Potential needed (Assuming penstock, turbine and generator losses of 50%) |
|---|---|---|---|---|---|
| 10 | 2 days | ≥ 5 | ~100W | ≥ 500W | ≥ 1000W |
| 10 | 5 days | ≥ 2 | ~100W | ≥ 200W | ≥ 400W |
| 25 | 2 days | ≥ 13 | ~100W | ≥ 1300W | ≥ 2600W |
| 25 | 5 days | ≥ 5 | ~100W | ≥ 500W | ≥ 1000W |
| 50 | 2 days | ≥ 25 | ~100W | ≥ 2500W | ≥ 5000W |
| 50 | 5 days | ≥ 10 | ~100W | ≥ 1000W | ≥ 2000W |
| 50 | 10 days | ≥ 5 | ~100W | ≥ 500W | ≥ 1000W |

**Table 3-1: Necessary plant sizes to supply a given number of families with charged batteries.**

From the table above, it can be seen that the number of families but and also their respective energy consumption (and consequently the resulting number of necessary charging places) have significant influence on the overall plant size.
Nevertheless, the very first determining factor is always the actual hydraulic potential at the specific site: you can only produce the amount of power that head and flow of your site will allow you to. Chapter 4.2 "Hydraulic System" will give more specific information about the requirements of the site and the hydraulic resource needed.
One should also keep in mind, that the table above assumes a plant factor (plant utilisation) of 100%, which means that the batteries are charged constantly and that there are no unutilized (or broken) charging stations. Using a realistic plant utilisation factor (which could be assumed to be around 80%) increases the necessary hydraulic potential and the necessary energy output correspondingly.

The complete process from the theoretical hydraulic potential to the actual end-use energy involves many different energy conversion and "transmission" steps. To find out the overall system efficiency; efficiency values for all the different steps should be considered. The following table shows the different steps of the overall process and gives approximate values for the conversion efficiencies:

| Step | Approximate efficiency |
|---|---|
| Turbine efficiency | 70 – 80 % |
| Generator (IMAG) efficiency | 75 – 85 % |
| Transmission Losses | <5% |
| Battery Charger efficiency | 75 % |
| Plant charging factor | 0.5 – 0.9<br>(depends strongly on operator) |
| Battery efficiency<br>(energy storage losses) | ~ 80 % |
| Effective useful battery capacity<br>(stored energy that should not be used due to rapidly increased wear of the battery) | ~ 80 % |

**Table 3-2: Efficiencies of the different conversion Steps in Hydro powered Battery charging system.**

When considering all the different energy conversions that take place when converting the hydraulic energy of water into battery energy; an overall efficiency of only less than 20% can be assumed **(Table 3-2)**. We receive this low overall efficiency mainly because of the necessity to store the electricity in lead acid accumulators. Charging and discharging lead-acid batteries is connected with relatively big losses in efficiency, nevertheless lead-acid accumulators are still one of the most economic, simple and proven technologies when it comes to electricity storage. Furthermore, one should not forget, that battery charging systems do not need to meet peak demand and therefore can be much smaller than conventional power plants. When considering the economic factors, later in this study, it will become clear that this kind of system can be very competitive.

As said before, the size of the system depends strongly on the number of end-users and their actual consumption but one should also consider that a possible surplus in hydraulic potential can always be used for other energy services that could be provided in the "Energy Station". Besides the charging of batteries which will take up the major part of the electricity produced, other stationary consumers will be connected to the system.

There are many ways to use "surplus" energy but generally it can be said, that the proposed system will only be simple, failsafe and economical up to a plant size of not more then about 5kW of electrical output.
For Systems with a higher energy output the conventional mini-grid systems should be used. With increased plant size all components of a hydropower scheme become more costly and complicated. Furthermore, the handling of big numbers of batteries and charging places will become extremely difficult.

The desired simplicity and the easy operation cannot be guaranteed for such "big" systems of more than about 5kW.

### 3.3. Management Options for a Rural Battery Charging Station

Receiving electricity by charging 12V / 50–100Ah batteries from diesel grids is common for residents in many areas of the developing world. And also a number of examples of renewable energy powered battery-charging stations already exist in such areas. For the management of these schemes a number of different options and practices can be applied:
Transport of the batteries to and from the household can be either the responsibility of the end-user or a service provided by the charging station. The batteries can be individually owned or leased from the station. The batteries can either be charged on a set schedule or as the batteries need a recharge. Such variables are extremely important for a good and economically sound operation of a charging station. Therefore, the training of the operator is one of the key issues when introducing such a pre-electrification system[8].

Different management options with their respective pros and cons will be discussed in the next passage. This will include key question that should always be answered before the actual installation of any battery charging system starts. Such question could include for example:

- How far are the users willing to carry their batteries?
- What end-use appliances will be connected to the battery?
- How much are the consumers willing to pay for charging the battery?
- Who is the owner of the charging station and of the batteries?

Ownership of Batteries

While setting up a battery charging system the ownership of the batteries is one of the most important decisions to take. Batteries could be owned by the station (and leased to the user) or be owned by the user. The lease system is characterized by the following facts:

- **Standardization of the batteries.** The batteries in a lease system can have a standardised size and quality. It is prevented that poor quality batteries with low charging efficiencies are used. By doing so it is assured that the plant works at high efficiency.

[8] [NREL_98] p.2

- **Cost leverage from bulk purchase.** The cost advantage of buying a high number of batteries can be substantial. On the other hand, buying 50 batteries presents a new logistic problem of transport. Furthermore, the amount of money spend to supply a complete village with batteries will certainly make up a very significant part of the whole project costs. Since the initial investment cost are often a determining factor in the decision whether or whether-not an electrification-scheme can be "afforded" at all.

- **Weekly maintenance at a station.** When batteries are owned by the charging station it is easily possible and highly recommended that they are maintained and serviced on a weekly, or at least monthly, basis. Professional service will be possible by the trained operating personnel, which should also understand the importance of a well maintained battery.

- **Recycling or environmentally friendly disposal** may be much easier for large number of collectively owned batteries. Recycling of used batteries is a very important topic when talking about any battery charging system. Battery acids as well as the lead contained in batteries present a high potential danger for humans and also for the environment. Recycling would be a good way of keeping the harmful substances in a closed cycle, especially since recycling and reconditioning of batteries has proven to be economically feasible. Unfortunately however, many developing countries do not have any recycling system installed. Nevertheless, it is much simpler to transfer a larger amount of collectively owned batteries back to a manufacturer (e.g. old and new batteries could be exchanged with one truckload). Small revenues from selling the old batteries might even be possible, since charging stations can deliver bulk quantities of batteries to recycling companies or manufacturers. Since hardly any countrywide collection systems are installed in developing countries, the return of privately owned batteries is difficult and does not make economical sense for the owner of a single battery.

On the other hand, an individual ownership system has also some benefits. The individual customers are responsible for their own battery and, at least in theory, should be more careful and more considerate with their own property. In reality, however, maintenance of privately owned batteries is often bad and battery lifetime is considerably shorted.
One important fact one should keep in mind is, that the initial investment costs of a battery system with privately owned batteries is considerably lower, resulting in a cheaper kWh-cost for the consumer. However, the consumer has obviously additional costs for buying a battery at intervals of months or years. The costs are therefore only transferred to the consumer, who, of course, will try to buy batteries that are cheap but not necessarily suitable.

Transport of Batteries

The transport of batteries from the charging station to the consumer's house (or any other place of use) is another very important topic. Ideally the distance between charging station and place of use should be as short as possible; nevertheless, in reality, distances of several hundred meters (and often some kilometres) are normal and can hardly be avoided. The transport of the heavy batteries is one of the big drawbacks of any battery charging system. Carrying heavy batteries is first of all exhausting and tiring for the user but also could result in severe battery damage and reduced battery performance. Also one should not forget that handling batteries always presents a considerable health hazard, due to the danger of spilling acid.

An alternative is to have a transportation service such as a donkey cart, a truck, a motorcycle or other modes of local transportation. Although this option is more expensive, it may be more economical in the long run because of better battery handling, battery throughput control, and increased business generated by a larger service territory.

Recharging Interval

The recharging interval depends considerably on the energy demand of the single user. The energy density of lead-acid batteries is in the range of only 25-30Wh/kg and therefore energy from one charged battery is very limited. Sensibly, only the use of several low-consumption light bulbs and possibly a radio or a small TV-set is possible. Consumers should be made aware of this fact before the system is installed.

The following table shows selected end-use appliances and gives estimates of their respective power consumption. Since battery voltage is 12V some devices must be adapted to this voltage with losses. To take this into account a correction factor has been introduced.

| Appliances | Power Demand [W] | Correction factor (because of use with 12V battery) | Operation Time per day [h/d] | Daily Energy Demand [Wh/d] |
|---|---|---|---|---|
| fluorescent lamps | 15 | 1.5 | 4 | 90 |
| radio 6V | 2 | 2 | 6 | 24 |
| radio 12V | 2 | 1 | 6 | 12 |
| tape/CD – player 6V | 8 | 2 | 6 | 96 |
| tape/CD – player 12V | 8 | 1 | 6 | 48 |
| small b/w TV 12V | 18 | 1 | 4 | 72 |
| fan | 12 | 1 | 6 | 72 |

**Table 3-3: Energy demand of selected household appliances.**

The following small sample calculation shall give a short introduction on how to calculate consumer demand and battery charging interval:

Example calculation:
A consumer uses kerosene lamps, but wants to use batteries to power one 12V b/w TV (used 4 hours per day) and a 12V radio with tape (used 6 hours per day). He uses a battery with a capacity of 60Ah. How long will the charging interval be?

Daily demand from **Table 3-3**:

| | |
|---|---|
| 1 b/w TV used for 4 hours daily | = 72 Wh/d |
| 1 radio with tape(12V) used for 6 hours | = 48 Wh/d |
| Overall Demand ($E_{daily}$) | = 120 Wh/d |

Useful capacity available (estimated with 80% of the nominal capacity):

$$C = 0.8 \cdot 60Ah = 48Ah$$

Charging interval:

$$t = \frac{U_{bat} \cdot C_{bat}}{E_{daily}} = \frac{12V \cdot 48Ah}{120Wh/d} = 4d$$

Result:
The battery must be recharged at an interval of 4 days. If the consumer keeps to this charging interval the lifetime of the battery is maximised; if he decides to discharge the battery further he can "delay" the recharging by approximately one day but has to be aware that the battery life will be significantly shortened.

Theoretically, an approach with a fixed recharge schedule would be a possibility to control energy output and guarantee a "uniform" distribution of electricity. In reality, however, energy demand might vary considerably between days and weeks and therefore such an approach is hardly realistic.
This is especially the case since one of the main advantages of a battery system is, that users can quit their energy consumption (e.g. in case of a difficult economic situation or if they simply want to move house), without having costly installations and weekly or monthly repayments.

Protection of the Battery

Protection of the battery mainly refers to the protection of the battery against over-charging and over-discharging. While correct charging procedures can be ensured by a properly working charging station and trained operator personnel. Over-discharge of batteries remains a serious problem for all rural electrification schemes using batteries. The frequent, uncontrolled discharge of a lead-acid battery to a SOC of less than 20% leads inevitably to a considerably reduced battery lifetime. While properly handled batteries may have a lifetime of around 3 years (depending on the quality and type of the battery) a constantly deep-discharged battery will hardly survive the first year of operation. Since batteries account for a considerable share of the overall investment costs of a charging system, their proper handling is a prerequisite for an economically sustainable scheme.

A technical solution to protect a battery from deep discharge will be discussed in more detail in Chapter 4.7 “Battery Charging and Discharging”.
Basically, a relatively simple electronic device, which disconnects any loads when the SOC falls below a given level, is permanently attached to the top of the battery. The device may have a simple indicator to show the current SOC with differently coloured LEDs. Where necessary, this "discharge controller" may be sealed, making it impossible to tamper with or shortcut the device without being noticed by the operator of the charging station. Penalties or fines could be imposed to users tampering with batteries or "discharge controllers".

Cost per Battery Charging

A sustainable system that can work for many years should have a sound economic foundation. Donated or sponsored systems without proper financing often have the problem that they break down as soon as there is any major maintenance work to be done and no more funds are available.
For this reason, an appropriate fee has to be collected from every user. One should not forget that the actual fees will vary considerably from site to site. On one site the civil works might be relatively easy and can be done by the local community on another site more difficult and expensive structures are necessary due to the topography of the area.

After a careful calculation of the overall costs of a battery charging system; these costs should be compared with other systems such as:

- existing methods to cover the energy demand (kerosene lamps, non rechargeable batteries etc.)
- solar charging systems (individual solar home systems (SHS) or central charging stations)
- conventional village electrification (e.g. diesel generators or even the extension of the grid)

Only after the comparison of costs with the above mentioned alternative systems of electrification the real benefit of such a micro hydropower pre-electrification scheme can be properly assessed. In some areas micro hydro powered charging stations will be the most economic way to provide basic energy services to rural population.

The next part of the study will deal with economic calculations and the proper determination of an appropriate charging fee for the sustainable operation of a battery charging system using hydropower.

## 3.4. Economic Calculations

In developing countries, where labour and building materials (stone, gravel, bricks etc.) are cheap; the allocation of costs of MHPs may differ considerably from that of industrialized countries. Most of the components of MHPs can nowadays be manufactured locally in the respective country. One big exception is the generator which often has to be imported from overseas and frequently represents the larges single component of the total costs because of import taxes, transport and unfavourable exchange rates. Hydro schemes where the generator accounted for up to 50% of the total investment have been reported.

Using an IMAG (Induction Motor used As Generator) from local motor distributor or manufacturer, instead of an imported synchronous generator can be an important step to make many MHP projects economically feasible and can trigger the support from financing agencies. The low price and the high availability of IMAGs was also the key reason why to use them to power battery charging system proposed in this study. The technical details, advantages and disadvantages of using IMAGs will be explained later in more detail[9].

Another relatively large cost factor is often the governing system of an MHP. The governing system is often rather complicated technical equipment which has to be built and installed by especially trained personnel. The planned charging system is designed in a way which reduces the required control electronics to an absolute minimum. By doing so not only the investment cost are lowered but also the maintenance becomes much easier and less repair work will have to be done.

When comparing the energy costs (or the kWh price) of any MHP system in comparison to other electricity-generation options, all investment costs (including turbine, civil engineering, electricity generation and transmission etc.) and also the operation and maintenance (O&M) should be carefully considered.

[9] See [GATE_92] pp.1ff

Especially in battery charging systems relatively high kWh costs can be expected, values around 1.00 US$/kWh are very usual. One should not make the mistake of comparing these costs with the prices paid when having grid connection (normally energy prices for grid connected users are 5 – 10 times lower), since energy consumption in pre-electrification systems is generally very low and therefore not comparable with power distribution systems. And, as a matter of fact, battery charging stations are certainly only sensible were no grid connection exists and were no grid connection is planned in the foreseeable future.

Comparisons should rather be made with the kWh-costs of kerosene, non rechargeable batteries, solar energy and other energy sources used in rural areas.

### *3.4.1. Identifying Project Costs*

The very first step in an economical calculation is to identify all capital cost items of a project and their respective, expected service life (= technical lifetime). The service live of MHP components in developing countries can be assumed to be in the order of 10 to 25 years, the lower values apply for the generating unit plus generator and the higher ones for civil structures.

As a first approximation it can be stated that in Indonesia the specific cost for an MHP (turbine, including civil engineering, generator and power transmission) are in the order of 2500US$/kW installed power. These values are valid for conventional schemes, in battery charging systems additional costs, namely batteries and battery chargers, have to be considered.
As said before, the costs can vary considerably between different projects depending on the specific requirements of the site. When working on a specific site the following theoretical values should only be seen as a guide.

Generally, the costs involved in an MHP project are approximately allocated in the following way:

| | |
|---|---|
| Civil Works: | 25 – 45 % |
| Electro-Mechanical Equipment: | 30 – 40 % |
| Transmission and Distribution: | 7 – 12 % |
| Project planning, design and supervision: | 8 – 12 % |
| Contingencies: | 4 – 6 % |

**Table 3-4: General allocation of cost in MHP projects.**
**Source: Pt. ENTEC Indonesia.**

**Table 3-5** below, shows all different cost items. Listed are all hardware equipments and services needed when planning and installing an MHP.

| Cost Item | Service Life [years] |
|---|---|
| <u>Civil Works</u><br>- Intake<br>- Head race and tail race channels / conduits<br>- Penstock<br>- Sedimentation chamber / sand trap<br>- Trash racks<br>- Control valves<br>- Powerhouse | 15 to 25 |
| <u>Mechanical Equipment</u><br>(incl. transport, import taxes, and installation costs):<br>- Turbine incl. mounting frame<br>- Transmission gearing (belts and pulleys or gear box)<br>- Flywheel (not always needed, mainly bigger schemes)<br>- Speed governor (not always needed, mainly bigger schemes) | 10 to 20 |
| <u>Electrical Equipment</u><br>(incl. transport, import taxes, and installation costs):<br>- IMAG (or other generator)<br>- Capacitance (for induction machines only) this includes excitation for the IMAG itself and compensation of inductive loads in stand-alone plants.<br>- Load controller incl. ballast load<br>- Switchgear (circuit breaker)<br>- Protection and monitoring equipment (fuses, relays, meters, etc.) | 10 to 20 |
| <u>Distribution Networks</u><br>a) Low-voltage network (LV)<br>b) Medium to high voltage network (MV and HV) incl. transformers | a) 10 to 20<br>b) 20 to 25 |
| <u>Services</u><br>- Project planning<br>- Engineering design<br>- Topographical surveys<br>- Land acquisition<br>- Water rights | 15 to 25 |

**Table 3-5: Capital cost items of an MHP with appropriate values of service lives used in developing countries. Source: [GATE_92] pp. 99ff**

**Table 3-6** gives an overview about the running costs of an MHP system. In some MHP schemes some items shown below might occur very frequently (e.g. repeated repair works of badly designed plant) while other plants might run very smoothly with only basic maintenance. Again the actual values of different power plants might vary considerably because not all of the items occur in all systems and, certainly, schemes with a system size of less than 5 kW (like proposed in this study) have drastically reduced number of cost items when compared to a 100 kW site.

| Cost Items | Description | Yearly Cost in % of capital cost |
|---|---|---|
| Personnel | **Operator:** Supervision of operation, preventive maintenance and inspection<br>**Technicians, Engineers:** General supervision, inspection and repair in case of failures<br>**Administration:** (general manager, secretary?)<br>**Fitters & Labourers:** Inspection and preventive maintenance of distribution networks, replacement of faulty equipment, repainting steel structures, desilting channels, forebay and storage tank | according to local conditions and wage levels |
| Office rents, office supplies and administration costs | | according to local conditions |
| Electro-mechanical equipment (turbine, generator, transmission) | spare parts for the equipment, filters, lubricants, etc. | 0.6 – 2 % of electro-mechanical investment costs |
| Civil works (Intake, sand trap, canal, penstock, gates, trash rack, powerhouse) | Material for refilling of cavities, concrete for relining canals and intake works, paint for all steel structures, etc. | 0.2 – 1 % of capital costs of civil works |
| Distribution Network | Fuses, insulators, cables, etc. | |
| Contingencies for major breakdowns | E.g. flooding of powerhouse or intake | Insurance (yearly costs to be included) |
| Reserve for upgrading equipment | Replacing manual control with automatic governor, etc. | depending on the technological level of the initial design |
| Depreciation allowance (only if investment costs fully or partly covered by subsidies and grants) | | |
| Taxes and water rights, other duties | | according to local rules and regulations |

**Table 3-6: General list of O&M cost items of MHPs and approximate values of respective annual costs. Source: [GATE_92] pp. 99ff**

### *3.4.2. Cost Examples*

The following table indicates some real data and actual cost for the installation and operation of a small MHP for battery charging. The table contains values for all the different components of an MHP scheme and their respective investment costs. The values are valid for the Indonesian market and therefore should be treated with care when applied in other countries.

The following system components costs will be calculated for a hydropower with a generator output of 1 kW. Whenever possible locally produced parts will be used; these parts might not have the highest efficiency but will be significantly cheaper than imported equipment. The quality of the hardware can be a critical factor but often the parts produced in local workshops have a quality that is sufficient for small MHP projects.

| Cost Item<br>(for a MHP with generator output of 1kW) | Actual Cost |
|---|---:|
| Civil Engineering, penstock | US$ 500 – US$ 1000 very much depending on the actual site conditions and availability of skilled local labour |
| Turbine<br>a) Cross flow (medium to high head schemes)<br>b) Propeller turbine (low head schemes) | a) US$ 500<br>b) US$ 200 |
| IMAG purchase price | US$ 100 – US$ 200 |
| Distribution line (500m) | US$ 500 |
| Capacitors (for excitation and regulation) | US$ 50 |
| Load controller / safety equipment / protection | US$ 250 |
| Charger + Charge controller | US$ 20 – US$ 100 per charging place (depending on quality) |
| Batteries | US$ 50 – US$ 100 per battery (depending on quality and battery type) |
| O&M per year | 10% of the initial investment costs per year |
| Overall Initial Investment Costs<br>(Without battery chargers and batteries) | US$ 1600 - 2500 |
| Costs for Battery Charging Equipment<br>(8 charging places (US$50) and 32 batteries (US$75) | US$ 2800 |

**Table 3-7: Approximated costs of a MHP plant with a generator output of 1kW. Source: Pt. ENTEC Indonesia.**

With the above mentioned values and investment costs it now becomes easily possible to calculate the approximate cost of one complete charging station. We have calculated before, that an energy output of 100W per charger is sufficient to charge on battery (of a size of up to 80Ah) during one day.

Therefore in an MHP scheme with a generator output 1 kW up to 10 charging places would be possible. If the energy at the charging station can be used productively (e.g. by a refrigerator, electric tools, telecommunication) than less energy is available for battery charging. Consequently, in that case, the number of charging places would have to be reduced. In the table above 8 charging places and 32 consumers (batteries) were assumed. With such a configuration every consumer has the possibility to recharge his battery every 4 days, which is normally more than sufficient.
From the numbers in **Table 3-7** one can easily see that even for such a small system the batteries represent a very large part of the investment costs.

### *3.4.3. Economic Management of Batteries*

For the just mentioned reasons, the batteries are a very significant factor for the economic success of battery charging systems. As pointed out before, there are basically two main possibilities for managing the ownership of the batteries:

- Option Nr. 1 is that every user owns his own battery. This implicates that the user is also responsible for maintenance and also has to bear the cost for the reoccurring purchase of batteries (in an interval of 1 to 3 years). This approach has the "advantage" that the initial investment cost for the actual charging station seem to be much lower since the single consumers have to cover the investment cost for the batteries themselves. It also follows that the lowest income households might not be able to benefit from the pre-electrification scheme as they might not be able to buy a battery. Also, families that will be able to buy a battery will opt for the lowest-cost solution and rather buy cheap "car batteries" than expensive "solar" or "Heavy Duty" batteries. Another problem associated with private ownership of batteries is that no professional or appropriate maintenance of batteries can be assured. Battery lifetime will most probably be significantly lower if no proper maintenance is performed. Additionally, the overall efficiency of the system will drop if old and worn down batteries are charged instead of well maintained ones.
- Option Nr. 2 would be a system of collectively owned batteries (batteries owned by the charging station). This system increases the initial investment costs for a pre-electrification scheme drastically since batteries for all users have to be bought at the very beginning. If we assume battery prices between 60 US$ (starter battery) and 100US$ (solar battery) investment cost for batteries can easily reach several thousand dollars even for small systems (even if we consider cost advantages because of bulk purchase). Even though the investment costs in alternative two are much higher, still this

option is economically favourable in the medium and long run due to decreased running costs. Right at the beginning appropriate batteries can be bought which have increased efficiency and lifetime. Maintenance can be performed be trained personnel in the charging station at regular intervals which will, finally, yield in much improved battery lifetimes. In this option consumers will not have the burden of buying own batteries, but they will have to face increased charging fees, since the overall system costs are now much higher.

Conclusion:
In the medium and long term a system with collectively used batteries is more economic and efficient due to regular appropriate maintenance possibilities. Nevertheless, it can seldom be employed since the initial investment costs are often too high. Responsibilities for battery purchase and maintenance are often "transferred" to the consumers which often do not have the means and the training to handle the batteries appropriately.

In the following part of this chapter a simple economic calculation to determine the energy costs for the end user is performed. This calculation shall rather give an exemplary calculation than absolute exact values since installation cost and system characteristics may greatly vary from site to site. First, theoretical explanations about basic economical indicator and calculations are given, than concrete examples will be calculated.

### *3.4.4. Economical Factors and Indicators*

Investment Costs of the Installation:

The investment cost hast to include all the different cost items necessary to build an MHP. As already explained above, this includes civil structures, turbine, electromechanical equipment, power transmission and also planning and engineering.

Interest Rate

The real interest rate is calculated from market interest rate and the actual inflation rate. At the moment, the situation in Indonesia is characterized by a high inflation rate of more than 15% (November and December 2005). Since the real interest rate has a significant influence on any economic calculation it is important to use plausible values in any case. Under normal circumstances interest is always higher than inflation.

The following equation is used to calculate the real interest rate:

$$i = \frac{(i° + 1)}{(a + 1)} - 1$$

**Equation 3**

Where: $i$ = corrected / real interest rate
$i°$ = nominal interest rate
$a$ = inflation rate

Generally it can be stated, that due to the relatively high investment costs, low real interest rates are favourable for any renewable energy project.

Capital Recovery factor

By using the capital recovery factor it becomes possible to represent the initial investment costs as a series of annual, equal payments over the lifetime of the project. These payments are also called annual equivalent cash flows or annuities. To calculate the annuities, real interest rate and project lifetime are related in the following way:

$$RF = \frac{i \cdot (i + 1)^n}{(i + 1)^n - 1}$$

**Equation 4**

Where $RF$ = recovery factor
$i$ = real interest rate
$n$ = project lifetime in years

Total annual cost

To calculate the total annual costs during the lifetime of the project it is now possible to multiply the initial investment cost with the recovery factor and add the yearly expenses for O&M and the yearly income or benefit for the operator of the charging station. The following formula applies:

$$AK = K_0 + B_{operator} + I_0 \cdot RF$$

**Equation 5**

Where $AK$ = total annual costs
$K_0$ = annual costs for O&M
$B_{operator}$ = annual income or benefit for the operator
$I_0$ = total initial investment costs
$RF$ = recovery factor

The total annual costs represent the value which hast to be covered by the charging fees of the consumers. By approximating the number of batteries charged per year the average charging fee can now be calculated.

### *3.4.5. Example calculation*

The following calculation will again be based on the assumption that we have an MHP with a generator output of 1kW. 10 charging places will be installed to serve the maximum number of customers with charged batteries. The charging places have power ratings of 80W–100W and will be able to charge 60Ah–80Ah batteries during one day. Any surplus energy will be used in the charging station for refrigeration, telecommunication and entertainment. If we assume that every consumer recharges his battery once every 4 days we can theoretically supply 40 end-users with batteries. In practice, however, a plant factor of 100% can never be reached. More appropriate is to assume a plant utilization factor of 80% due to broken chargers or unused charging capacities. Consequently, it will only be possible to supply 0.8 × 40 = 32 consumers with battery power.

| | |
|---|---|
| Investment costs for the MHP including 500m power line from the MHP to the central energy station:<br>(average values from **Table 3-7**) | 2050 US$ |
| Investment costs for 10 charging places: | 500 US$ |
| Overall Investment costs: | 2550 US$ |
| Investment costs for collectively owned Lead-Acid batteries<br>(bulk purchase, "Heavy Duty" batteries, lifetime: 3 years) | 32 × 80 US$<br>= 2560 US$ |
| Investment costs for privately owned Lead-Acid batteries<br>("car" battery, lifetime: 1.5 years) | 50 US$ |
| Annual O&M costs: | 128 US$<br>assumed to be 5% of the initial investment costs (MHP + charging places) |
| Lifetime of the installation | 10 years |
| Interest Rate: | 10% |
| Inflation Rate: | 5% |
| Annual income of the Charging station.<br>This could also be seen as a yearly safety deposit for expensive repair work, or the savings for buying a new charging station after the end of the lifetime of the old one. | 500 US$ |

**Table 3-8: Approximate costs of a charging station supplying 32 consumer with charged batteries.**

The following two calculations will cover the two main management options: collectively owned batteries versus privately owned batteries. The result will show the corresponding charging fees for both options, but also the total annual expenses per user.

## Case 1:
## Yearly Costs of a Battery Charging Station with collectively owned Batteries:

- Corrected interest rate (from **Equation 3**):

$$i = \frac{(i^{\circ}+1)}{(a+1)} - 1 = \frac{(0.10+1)}{(0.05+1)} - 1 = \underline{\underline{0.048}}$$

- Recovery factor (for 10 years) for the initial investment costs (MHP + charging equipment) from **Equation 4**:

$$RF_1 = \frac{i \cdot (i+1)^n}{(i+1)^n - 1} = \frac{0.048 \cdot (0.048+1)^{10}}{(0.048+1)^{10} - 1} = \underline{\underline{0.128}}$$

- Recovery factor (for 3 years) for the batteries used in the charging station from **Equation 4**:

$$RF_2 = \frac{i \cdot (i+1)^n}{(i+1)^n - 1} = \frac{0.048 \cdot (0.048+1)^{3}}{(0.048+1)^{3} - 1} = \underline{\underline{0.366}}$$

- Now, the total annual costs can be calculated according to **Equation 5**:

$$AK = K_0 + B_{operator} + I_0 \cdot RF_1 + I_{Bat} \cdot RF_2$$
$$AK = 128US\$ + 500US\$ + (0.128 \cdot 2550US\$) + (0.366 \cdot 2560US\$)$$
$$AK = 128US\$ + 500US\$ + (326.40US\$) + (936.96US\$) = \underline{\underline{1891.36US\$}}$$

**The total annual costs for the charging station including O&M and purchase of batteries for the whole village are therefore 1894 US$.**

- Consequently the cost per battery charging can be calculated:
  As said above, we assume a plant utilization factor of 80%. Therefore, the number of charged batteries per year $n_{bat}$ and the number of customers is calculated as follows:

$n_{bat}$ = 0.8 × 10 bat per day × 365 days = **2,920 batteries/a**
$n_{customer1}$ = 0.8 × 10 bat per day × 4 day recharge interval
= **32 customers**

The fixed costs per battery charging are therefore:
**Charging fee = AK/$n_{bat}$ = 1,892 US$ / 2,920 bat = 0.65 US$/bat**

The fixed annual costs for battery charging per customer are consequently:
**Annual costs = AK/$n_{customer}$ = 1,892 US$ / 32 cust. = 59.13 US$/a**

**The cost for the consumer are therefore, as calculated above, 0.65 US$ per battery charging or 59.13 US$ per year.**

## Case 2:
## Yearly Costs of a Battery Charging Station with privately owned Batteries:

- Corrected interest rate (from **Equation 3**):

$$i = \frac{(i^\circ + 1)}{(a+1)} - 1 = \frac{(0.10+1)}{(0.05+1)} - 1 = 0.048$$

- Recovery factor (for 10 years) for the initial investment costs (MHP + charging equipment) from **Equation 4**:

$$RF_1 = \frac{i \cdot (i+1)^n}{(i+1)^n - 1} = \frac{0.048 \cdot (0.048+1)^{10}}{(0.048+1)^{10} - 1} = 0.128$$

- Now, the total annual costs can be calculated according to (**Equation 5**):

$$AK = K_0 + B_{operator} + I_0 \cdot RF_1 + I_{Bat} \cdot RF_2$$
$$AK = 128US\$ + 500US\$ + (0.128 \cdot 2550US\$)$$
$$AK = 128US\$ + 500US\$ + (326.40US\$) = 954.40US\$$$

- Cost per charged battery:

The number of charged batteries and customers can be calculated as above and are therefore: = 2,920 batteries per year
= 32 customers

The fixed costs per battery charging are therefore:
Charging fee = $AK/n_{bat}$ = 955 US$ / 2,920 bat = 0.33 US$/bat

The fixed annual costs for battery charging per customer are consequently:
Annual costs = $AK/n_{customer}$ = 955 US$ / 32 cust. = 29.84 US$/a

In this case "2" the single consumers additionally have to bear the costs for the purchase of their own batteries. Assumed that the consumer buys a normal "car" battery for 50 US$ (which, as an optimistic estimation, will last probably about 1.5 years) the following costs have to be added:

- Recovery factor for batteries with a lifetime of 1.5 years:

$$RF_2 = \frac{i \cdot (i+1)^n}{(i+1)^n - 1} = \frac{0.048 \cdot (0.048+1)^{1.5}}{(0.048+1)^{1.5} - 1} = 0.707$$

The yearly costs for a 50US$ battery are therefore:

$$K_{Bat} = I_{Bat} \cdot RF_{Bat} = 0.707 \cdot 50US\$ = 35.35US\$$$

The overall costs for the consumer are now the sum of the annual costs for battery charging plus the investment costs for the own battery:

Total yearly costs for the consumer: 29.84 US$ + 35.35 US$ = 65.19 US$

The result now shows, that although the price per battery charging is much lower in case "2" (only 0.33 US$), the overall costs per year are higher since every consumer has to buy an own battery.

From the calculations above it becomes clear, that more expensive batteries with a longer lifetime can be economically feasible. The investment costs for "Solar" or "Heavy Duty" batteries might seem very high at the beginning but pay with their increased lifespan.
Another fact, which in is not visible from the calculations above is, that the overall system efficiency is also significantly decreased when bad, unsuitable or worn out batteries are used. The charging interval of used up batteries becomes short and shorter; creating problems since only a limited number of charging places are available.

As a summary, it can be stated, that a micro hydro powered charging station can be an economic alternative for special regions in developing countries. Energy costs of 60.00US$ to 65.00US$ per year have been calculated, these values are competitive when compared with other sources of energy like "one-way"- batteries or kerosene lamps.

From the point of view of the "developed world" 60US$ do not seem much to cover electricity expenses of one complete year. But one should not forget that 60US$ in a poor country often represent more than an average monthly income.

# 4. Technical Realisation of a Micro Hydro Powered Battery Charging Station

## 4.1. Technical Overview: Micro Hydropower Systems

Every hydro power system principally consists of the same set of technical components. We can distinguish four main elements of a micro hydropower plant. All of these four components may exist in different forms but they are always present and are influencing each other[10]:

1. The hydraulic system comprising intake, sand trap, head race channel or conduit, forebay or surge tank, penstock, turbine and tail race: Here the potential energy of the water is converted into mechanical (rotational) energy.
2. The electricity generating system (in short: electrical equipment) covering the generator, the monitoring and protection equipment and the switchgear (+ possibly a transformer): Here the mechanical energy of turbine is converted into electric energy.
3. The consumer system including means of distribution and the appliances or electrical loads (lighting, radios, TVs, stoves or cookers, heaters, cooling devices, motors, etc.)
4. These three systems are interrelated by the governing system which matches the power demand with the supply of the generator. The governing system comprises two functions:
   - Control of the generated frequency by a turbine governor or load controller
   - Control of the voltage of the system by an AVR (automatic voltage regulator) or a load controller

   These two factors properly controlled within the permissible range of variation determine the quality of the generated electricity.

**Figure** 4-1 shows the main components of the projected MHP charging station. The following sections of this study will describe the different technical components (hydraulic system, electricity generation, power transmission and battery charging) in more detail.

[10] "System Components of an MHP with Stand-alone Electricity Generation" See [GATE_92] p.7

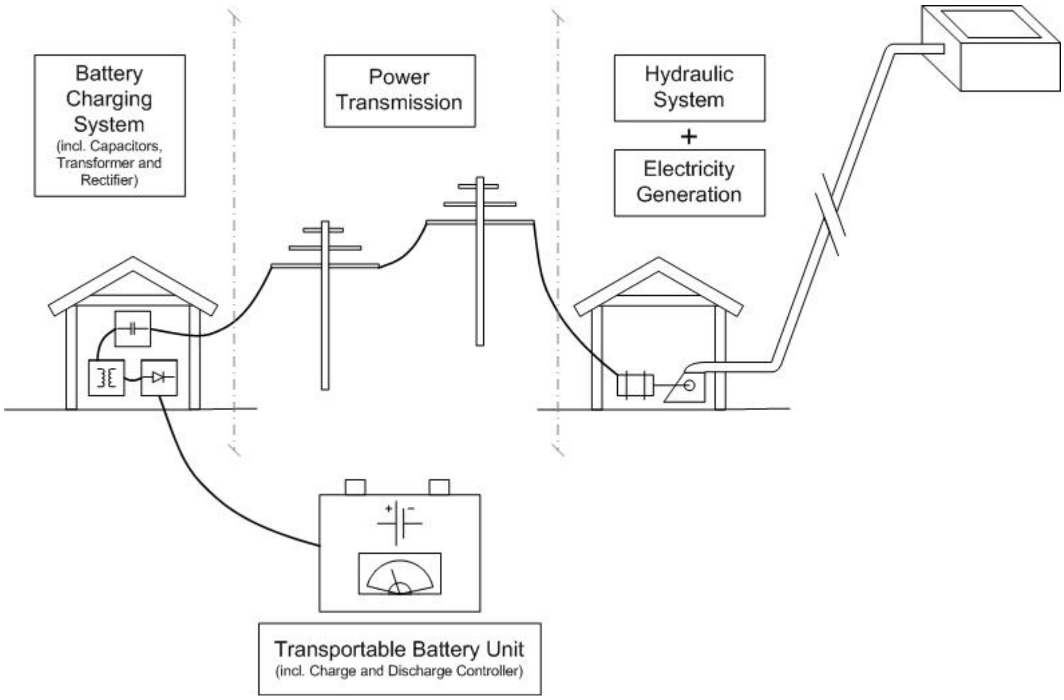



**Figure 4-1: Components of a battery charging system using hydro power**

Generally, the planned charging station shall work in the following way: The available hydraulic potential is converted into mechanical work in the turbine. The turbine is then coupled to a generator. In this case, a simple 3-phase induction motor will be used as a generator (IMAG). The IMAG produces electricity at a voltage of 220/380V which can be transported over a certain distance to the central charging station without major losses (provided the transmission cables have large enough diameters). In the charging station the energy is partly used directly by normal AC. household appliances, but the by far biggest part of the energy is used to charge batteries for the rural population.

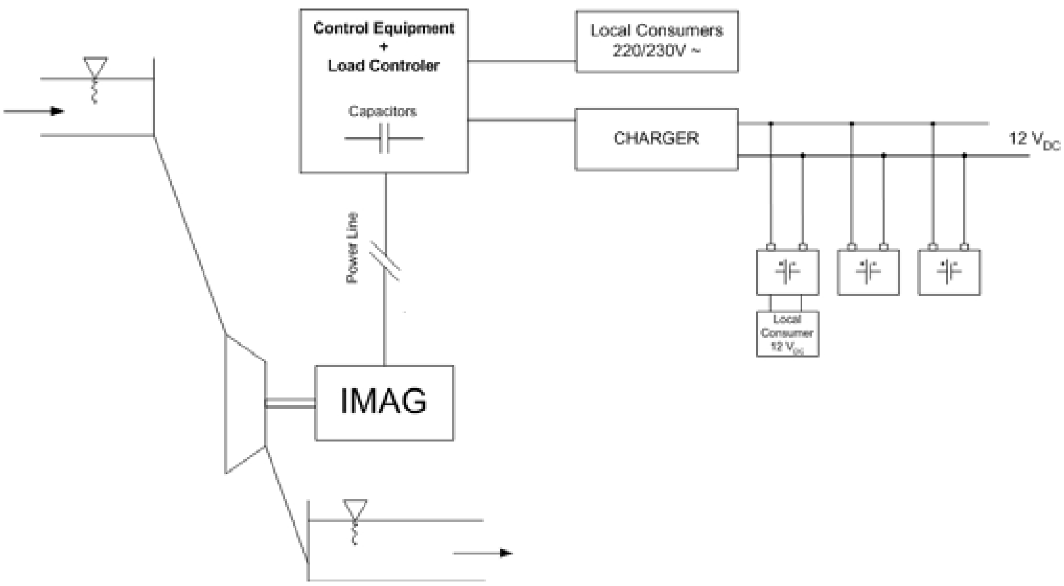



**Figure 4-2: Technical representation of battery charging system using hydro power**

**Figure 4-2** gives a more technical representation of the whole MHP battery charging system. In this picture it also becomes visible, that the capacitors (which provide the reactive power) for the IMAG and all other control equipment are not in the powerhouse but at the charging station. The idea was to keep the energy consumption of the charging station as stable as possible and by doing so minimizing the control demand of the system. An electronic load controller (ELC) that would be installed at the charging station might switch different dump loads to keep the overall load stable (the overall load has to be kept stable to have a stable voltage a frequency). The dump loads which are switched automatically by the ELC or manually by the operator could be productive uses like heating of water or drying of agricultural products.
The capacitors that provide reactive power to the IMAG are also situated in the charging station. This has a big safety advantage, because in an emergency case the capacitors can be quickly disconnected and the whole system is shut down immediately. In the very moment the capacitors are disconnected from the IMAG, turbine and IMAG are going to run-away speed since no load is connected anymore. This does not pose a big problem since these two components will be chosen to withstand a certain over-speeds.

The next sections of the study will give a more detailed insight into the different parts of the complete scheme.

## 4.2. The Hydraulic System

### *4.2.1. Introduction[11]*

The purpose of a hydraulic turbine is to transform the potential energy of the water into mechanical rotational energy. This study will not go very deep into the topic of turbine design and construction since this could cover a whole encyclopaedia on its own.
However, there will be short introduction into the basic physical principles of hydro turbines and, furthermore, a number of selection criteria are provided to guide the choice of the appropriate turbine for a given site.

The hydraulic system does not only include the hydro turbine (although it is by far the most important part) but also the necessary civil structures normally including

[11] See [LAY_98] pp. 155-175

intake, sand trap, head race channel or conduit, forebay or surge tank, penstock and tail race. These civil structures will not be discussed in detail but a short introduction will be given on the following pages.

This study will cover only hydraulic systems up to a size of approximately 5kW of electrical output. As discussed above the planned battery charging system or "Energy Station" can only be economically and technically applicable up to a size of a few kilowatts. For small systems of such size the hydraulic systems become relatively simple and cheap since only limited volume flows and heads need to be considered.

A simple approximating calculation for the hydraulic potential (potential energy of the water) of a site can be derived from the equation for the calculation of the potential energy (of the water):

$$E_{pot} = m \cdot g \cdot h$$

**Equation 6**

Where $E_{pot}$ = Potential Energy [J, Wh, kWh]
$m$ = mass in [kg]
$g$ = gravitational constant: 9.8 [m/s$^2$]
$h$ = head in [m]

It follows that the hydraulic potential (Watt) can be calculated, by substituting the mass with volume flow and density, as follows:

$$P_{Hydraulic} = \dot{V} \cdot \rho \cdot g \cdot h$$

**Equation 7**

Where $P_{Hydraulic}$ = hydraulic potential in [W]
$V$ = volume flow in [m$^3$/s]
$\rho$ = density [kg/m$^3$]
$g$ = gravitational constant: 9.8 [m/s$^2$]
$h$ = head in [m]

From these simple calculations we receive the following table giving necessary heads and flow values for different hydraulic potentials.

| Head [m] | Flow [l/s] | Hydraulic Potential [W] |
|---|---|---|
| 100 | 5 | 5000 |
| 50 | 10 | 5000 |
| 25 | 20 | 5000 |
| 10 | 50 | 5000 |
| 20 | 20 | 4000 |
| 40 | 10 | 4000 |
| 30 | 10 | 3000 |
| 20 | 10 | 2000 |
| 10 | 10 | 1000 |

**Table 4-1: Basic calculation of the hydraulic potential of MHP-site.**

From the above calculations we can see, that for a plant size of up to 5kW (hydraulic potential) we will deal in the vast majority of cases with flow volumes of 50l/s or less and with heads far below 100m.

### *4.2.2. Components of a scheme*

Figure 4-3 shows the major components of a typical micro hydropower scheme. The water in the river is diverted by the weir through an opening in the river side (the 'intake') into an open channel. A settling basin is used to remove sand particles from the water. The channel follows the contour of the hillside to preserve the elevation of the diverted water; sometimes aqueducts or tunnels are necessary for this purpose. The water then enters a tank known as the 'forebay' and passes into a closed pipe known as the 'penstock'. At the lower side it is connected to the turbine. The turning shaft of the turbine can be used to operate an electricity generator. The machinery or appliances which are energised by the hydro scheme are called the 'load'.

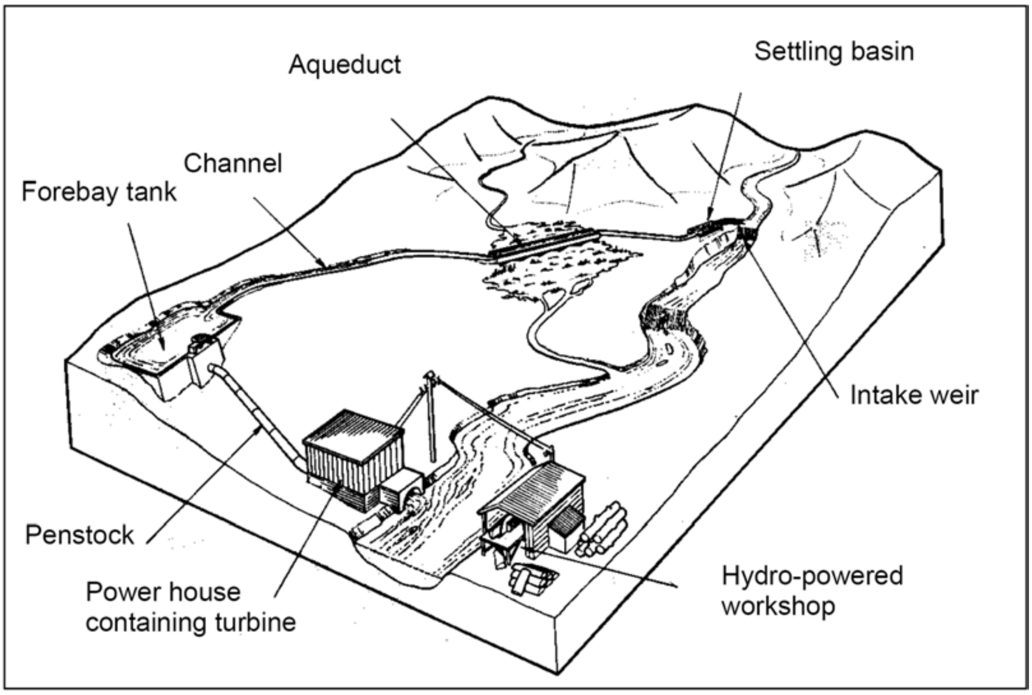



**Figure 4-3: Main components of a Micro Hydro Scheme.**
**Source: [ITDG_a]**

### *4.2.3. Civil structures*[12]

Various possibilities exist for the general lay-out of a hydro scheme, depending on the local situation. Possibilities are:

1. low head with a river barrage
2. low head with a channel
3. high head with no channel
4. high head with channel

Different essential factors must be kept in mind when designing a micro hydropower system. These factors include:

1) Use of available head

The design of the system has effects on the net head delivered to the turbine. Components such as the channel and penstock cannot be perfectly efficient. Inefficiencies appear as losses of useful head of pressure.

[12] See also: www.hydropower.org

### 2) Flow variations

The river flow varies during the year but the hydro installation is designed to take a constant flow. If the channel overflows there will be serious damage to the surroundings. The weir and intake must therefore divert the correct flow whether the river is in low or in high flow. The main function of the weir is to ensure that the channel flow is maintained when the river is low. The intake structure is designed to regulate the flow to within reasonable limits when the river is in high flow. Further regulation of the channel flow is provided by spillways.

### 3) Sediment

Flowing water in the river may carry small particles of hard abrasive matter (sediment); these can cause wear to the turbine if they are not removed before the water enters the penstock. Sediment may also block the intake or cause the channel to clog up if adequate precautions are not taken.

### 4) Floods

Flood water will carry larger suspended particles and will even cause large stones to roll along the stream bed. Unless careful design principles are applied, the diversion weir, the intake structure and the embankment walls of the river may be damaged.

### 5) Turbulence

In all parts of the water supply line, including the weir, the intake and the channel, sudden alterations to the flow direction will create turbulence which erodes structures and causes energy losses.

## Weir and Intake

A hydro system must extract water from the river in a reliable and controllable way. The water flowing in the channel must be regulated during high river flow and low flow conditions. A weir can be used to raise the water level and ensure a constant supply to the intake. Sometimes it is possible to avoid building a weir by using natural features of the river. A permanent pool in the river may provide the same function as a weir.

The intake of a hydro scheme is designed to divert a certain part of the river flow. This part can go up to 100 % as the total flow of the river is diverted via the hydro installation. For small systems only a tiny fraction of a river might be diverted, this also has the advantage that MHP output can be kept constant even when the flow of the river is strongly fluctuating.

The following points are required for an intake:

- the desired flow must be diverted,
- the peak flow of the river must be able to pass the intake and weir without causing damage to them,
- as less as possible maintenance and repairs,
- it must prevent large quantities of loose material from entering the channel,
- it must have the possibility to remove piled up sediment.

Different types of intakes are characterised by the method used to divert the water into the intake. For micro hydro schemes only the small intakes will be necessary the main type of intake for such purposes will be the side intake since it is cheap and simple to construct.

## Channels

The channel conducts the water from the intake to the forebay tank.

The length of the channel depends on local conditions. In one case a long channel combined with a short penstock can be cheaper or necessary, while in other cases a combination of short channel with long penstock suits better.

Most channels are excavated, while sometimes structures like aqueducts are necessary. To reduce friction and prevent leakages channels are often sealed with cement, clay or polythene sheet.

Size and shape of a channel are often a compromise between costs and reduced head. As water flows in the channel, it loses energy in the process of sliding past the walls and bed material. The rougher the material, the greater the friction loss and the higher the head drop needed between channel entry and exit.

Incorporated in the channel are the following elements: settling basin (removes sediments from water), spillways (used for controlled overflow) and forebay tank.

The forebay tank forms the connection between the channel and the penstock. The main purpose is to allow the last particles to settle down before the water enters the penstock. Depending on its size it can also serve as a reservoir to store water.

## Penstock

The penstock is the pipe which conveys water under pressure from the forebay tank to the turbine. The penstock often constitutes a major expense in the total micro hydro budget, as much as 40 % is not uncommon in high head installations, and it is therefore worthwhile optimising the design. The trade-off is between head loss and capital cost. Head loss, due to friction in the pipe, decreases dramatically with increasing pipe diameter. Conversely, pipe costs increase steeply with diameter. Therefore a compromise between cost and performance is required.

## 4.3. Turbine

### *4.3.1. Classification of Turbines*

The potential energy in the water is converted into mechanical energy in the turbine, by one of two fundamental and basically different mechanisms:

1. - The water pressure can apply a force on the face of the runner blades, which decreases as it proceeds through the turbine. Turbines that operate in this way are called ***reaction turbines***. The turbine casing, with the runner fully immersed in water, must be strong enough to withstand the operating pressure.

2. - The water pressure is converted into kinetic energy before entering the runner. The kinetic energy is in the form of a high-speed jet that strikes the buckets, mounted on the periphery of the runner. Turbines that operate in this way are called ***impulse turbines***. As the water after striking the buckets falls into the tail water with little remaining energy, the casing can be light and serves the purpose of preventing splashing.

For the operation in our proposed scheme both, impulse and reaction, turbines are applicable, depending on the specific site conditions. Generally, impulse turbines work at higher head and lower flow rates, while the reaction turbines normally need lower head but higher flow rates for the same energy output. The civil structures of reaction turbines have to be able to stand higher flow values and therefore are more complex and expensive to build.

### *4.3.2. Impulse turbines*

There are three basic types of impulse turbines which can be distinguished and which have different physical principles and characteristics. These are the Pelton-turbine, the Turgo-turbine and the Crossflow-turbine (also known as Banki-Mitchell or Ossberger – turbine)

<u>Pelton turbines</u>

Pelton turbines are impulse turbines where one or more jets impinge on a wheel carrying on its periphery a large number of buckets. Each jet issues through a nozzle with a needle (or spear) valve to control the flow. They are only used for relatively high heads. The axes of the nozzles are in the plane of the runner. To stop the turbine (for example when the turbine approaches runaway speed due to load rejection) the jet may be deflected by a plate so that it does not impinge on the buckets anymore. In this way the needle valve can be closed very slowly, so that overpressure surge in the pipeline is kept to an acceptable minimum. Any kinetic energy leaving the runner is lost and so the buckets are designed to keep exit velocities of the water to a minimum. The turbine casing only needs to protect the surroundings against water splashing and therefore can be very light.

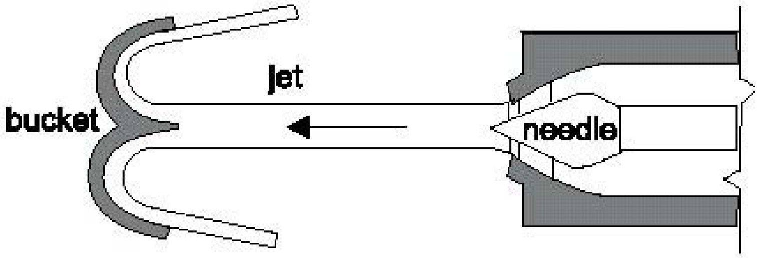



**Figure 4-4: Graphical Representation of the basic functioning of a Pelton turbine. Source: [LAY_99] p. 157**

**Figure 4-5: Pelton wheel with a diameter of about 60 cm Source: Home Power 103 / October & November 2004 / "Intro to Hydropower" p.18**

**Figure 4-6: Small, self-made Pelton turbine with 4 jets, driving a small permanent magnet alternator. Source: Home Power 103 / October & November 2004 / Intro to Hydropower [p.18]**

In large scale hydro installation Pelton turbines are normally only considered for heads above 150 m, but for micro-hydro applications Pelton turbines can be used effectively at heads down to about 20 m. Pelton turbines are not used at lower heads because their rotational speeds becomes very slow and the runner required is very large and unwieldy. If runner size and low speed do not pose a problem for a particular installation, then a Pelton turbine can be used efficiently with fairly low heads. If a higher running speed and smaller runner are required then there are two further options:

I. Increasing the Number of Jets

Having two or more jets enables a smaller runner to be used for a given flow and increases the rotational speed. The required power can still be attained and the part-flow efficiency is especially good because the wheel can be run on a reduced number of jets with each jet in use still receiving the optimum flow.

II. Using Twin Runners

Two runners can be placed on the same shaft either side by side or on opposite sides of the generator. This configuration is unusual and would only be used if the number of jets per runner had already been maximised. It allows the use of smaller diameter and hence faster rotating runners.

Turgo turbines

The Turgo turbine can operate under a head in the range of 30-300 m. Its buckets are shaped differently from the Pelton turbine and the jet of water strikes the plane of its runner at an angle of about 20º. Water enters the runner through one side of the runner disk and emerges from the other. Whereas the volume of water a Pelton turbine can admit is limited because the water leaving each bucket interferes with the adjacent ones, the Turgo runner does not present this problem. The resulting higher runner speed of the Turgo makes direct coupling of turbine and generator more likely, improving overall efficiency and decreasing maintenance cost.
Despite the advantages, Turgo turbines are seldom build today and are only applied in very small MHPs.

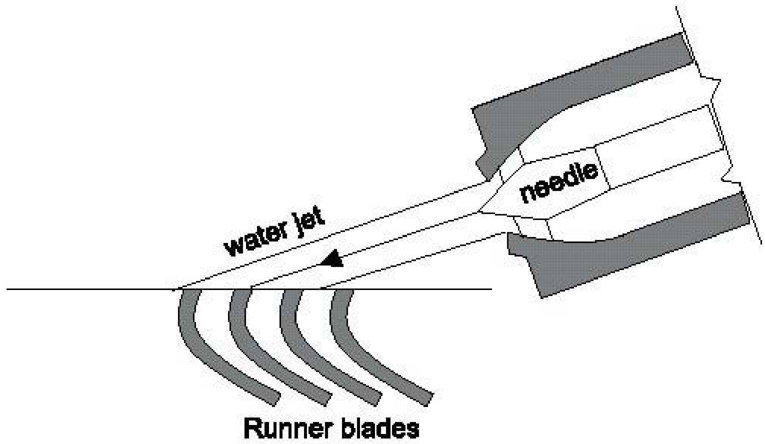



**Figure 4-7: Basic principle of a Turgo turbine. Source [LAY_99] p. 158**

**Figure 4-8: Small Turgo wheel like used in the Australian manufactured "Platypus" turbine. Source: Home Power 103 / October & November 2004 / "Intro to Hydropower" p.18**

**Figure 4-9: A Canadian-made Energy Systems and Design turbine uses a permanent magnet alternator and a Turgo runner. Source: Home Power 103 / October & November 2004 / Intro to Hydropower p.19**

**Figure 4-10: Bottom View of a Turgo Pico Turbine. Runner is made of bronze; the housing is made of cast aluminium. Source: www.hydropower.ca**

Cross-flow turbines

This impulse turbine is used for a wide range of heads overlapping those of other turbine types. It can operate with discharge flows between 10 l/s and 10 $m^3$/s and heads between 1 and 200 m. Its versatility is the major advantage of this type of turbine. It is widely used (and partly also manufactured) in developing countries due to its relatively simple design.
One proper and reliable design of a cross-flow turbine can relatively simply be altered, only by changing the diameter and the width of the runner, to adjust it to different site characteristics (namely different head and flow characteristics).

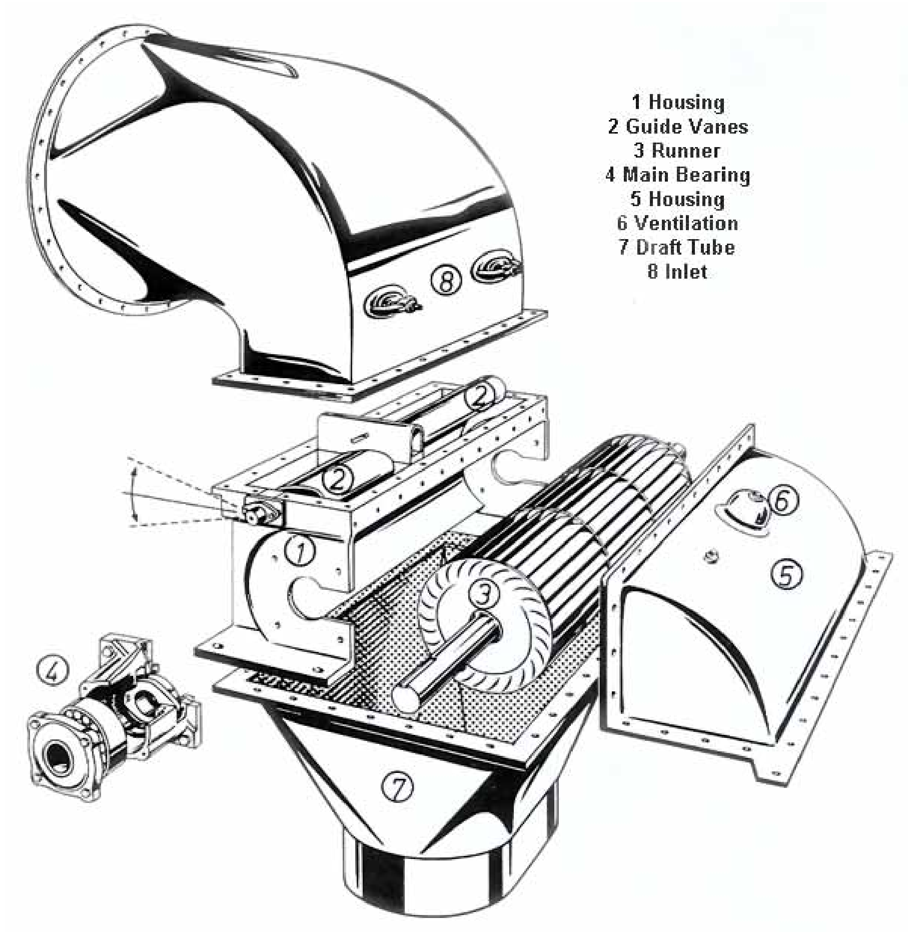



**Figure 4-11: Parts of a crossflow turbine. Source: Ossberger www.ossberger.de**

The cross-flow turbine functions the following way: Water enters the turbine, directed by one or more guide-vanes located upstream of the runner. Then the water "flows" through the first stage of the runner; at that point the runner receives only a small part of the actual impulse, since direction and speed of runner and water are similar. Now, flow is leaving the first stage and crosses the open centre of the turbine. As the flow enters the second stage, a compromise direction is achieved which causes significant impulse onto the runner.

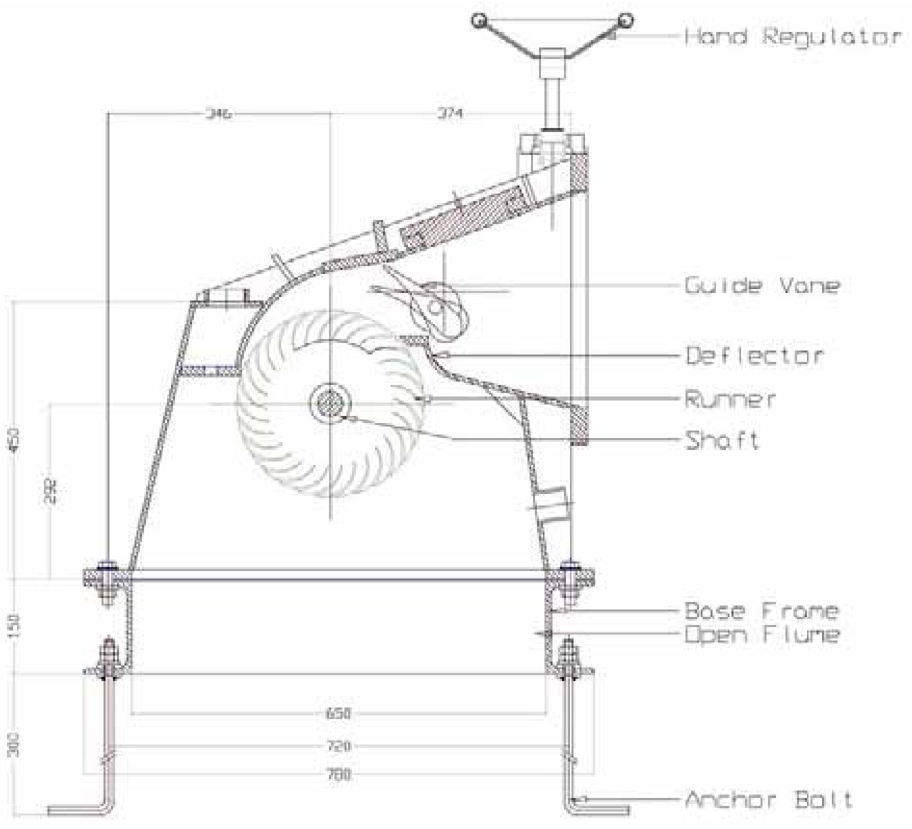



**Figure 4-12: Cross sectional view of the T14-T15 cross flow turbine of the ENTEC AG. Source: ENTEC AG. Brochure "T15XFLOW: The ENTEC Cross Flow Turbine T15"**

**Figure 4-13: Small, fully operational cross-flow turbine (ca. 1kW), coupled to a small IMAG. Turbine manufactured locally in Indonesia.**

The efficiency of a cross-flow turbine is generally lower than of other conventional impulse turbine types, but remains at practically on the same level for a wide range of flows and heads. **Figure 4-14** gives the application limits for the small cross-flow turbine T14 (Pico) from the ENTEC AG. From this graph it becomes possible to choose the correct runner with for a given site characteristic. As an example we can assume a flow of 40l/s and a net head of 20m, from the graph we receive the information, that we need a runner-width between 50mm and 100mm and that we will receive an electrical output of about 5kW.

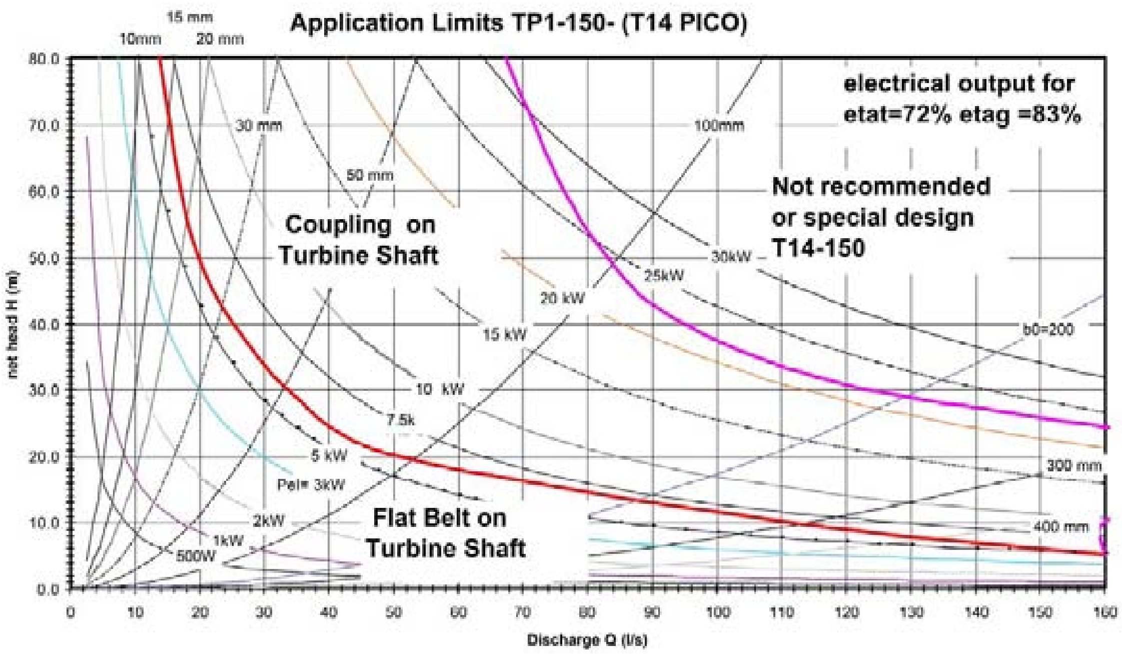



**Figure 4-14: Application Limits of the T14 (Pico) cross flow turbine. Source: ENTEC AG. Brochure "T15XFLOW: The ENTEC Cross Flow Turbine T15"**

### *4.3.3. Impulse turbines*

Impulse turbines are generally not well suited for pico or micro hydropower plants due to their more complex structural requirements and their complexity. However, in situations where only a limited head of less than 10 meters is available there are possibilities to use simple propeller turbines to produce electric power of up to several kW.

Basically we can distinguish between Francis, Kaplan and unregulated propeller turbines. The basic principle is to convert the kinetic energy of the water onto a rotor or runner which is completely immersed into the flow.

## Francis Turbines

Francis turbines are radial flow reaction turbines, with fixed runner blades and adjustable guide vanes, used for medium heads. In the high speed Francis turbines the admission of the water flow is always radial but the outlet is axial. The guide vanes have the task is to control the flow volume into the runner; in case of emergency they can also completely close, to stop the turbine.

Francis turbines can be set in an open flume or attached to a penstock. For small heads and powers open flumes are commonly employed. Steel spiral casings are used for higher heads.

**Figure 4-15: A "Power Pal" (manufactured in the USA) turbine with a Francis runner direct-coupled to the alternator above. Source: Home Power 103 / October & November 2004 / Intro to Hydropower p.19**

**Figure 4-16: Indonesian manufactured small, unregulated Francis turbine, coupled to an IMAG (ca. 0.6kW)**

**Figure 4-17: Indonesian manufactured unregulated Francis turbine working. Flow: ca. 25l/s; Net head: 3.5m; Power output ca. 450W.**

<u>Kaplan and Propeller Turbines</u>

Kaplan and propeller turbines are axial-flow reaction turbines, generally used for low heads. The Kaplan turbine has adjustable runner blades and may or may not have adjustable guide vanes If both blades and guide-vanes are adjustable it is described as double-regulated. If the guide vanes are fixed it is single-regulated.
Unregulated propeller turbines are used when both flow and head remain practically constant.
Bulb units are another constructional form derived from Kaplan turbines, with the generator contained in a waterproofed bulb submerged in the flow.

### *4.3.4. Pumps working as turbines*

It should be added that also standard centrifugal pumps may be operated as turbines by directing flow through them from pump outlet to inlet. Since they have no flow regulation they can operate only under relatively constant head and discharge. In some situations this relatively simple solution can prove as sufficient, even though the reached efficiencies are not as high as in the other turbine types.

### *4.3.5. Turbine selection criteria*

The type, geometry and dimensions of the turbine will be fundamentally conditioned by the characteristic of each given site. These important these criteria are described in the following part:

<u>Net head</u>

The gross head is the vertical distance, between the water surface level at the intake and at the tailrace for reaction turbines and the nozzle level for impulse turbines. Once the gross head is known, the net head can be computed by simply subtracting the losses along its path.
The first criterion to take into account in the selection of the turbine is the net head.
**Table 4-2** specifies for each turbine type its range of operating heads. The table shows some overlapping, so that for a certain head several types of turbines can be used.

| Turbine Type | Head Range in m |
|---|---|
| Kaplan and Propeller | 2 < H < 40 |
| Francis | 10 < H < 350 |
| Pelton | 50 < H <1300 |
| Banki-Mitchell | 3 < H < 250 |
| Turgo | 50 < H < 250 |

**Table 4-2: Turbine types and their respective range of heads. Source: [LAY_98] p.170**

The selection is particularly critical in low-head schemes, where large discharges must be handled. In the specific application which is dealt with here the only economic and sensible low-head turbine would be an open flume propeller turbine. This kind of turbine is technically simple and can be produced locally for very low costs (see **Figure 4-16**).

Range of flow volume and discharges through the turbine

A single value of the flow has only very little significance. It is necessary to know the flow regime of a site.

The rated flow and net head determine the set of turbine types applicable to the site and the flow environment. To determine the correct turbine type one solution is to use graphical tools which show the suitability of different turbine designs in relation to head, flow volume and power output. **Figure 4-18** shows an example for such a graphical representation.

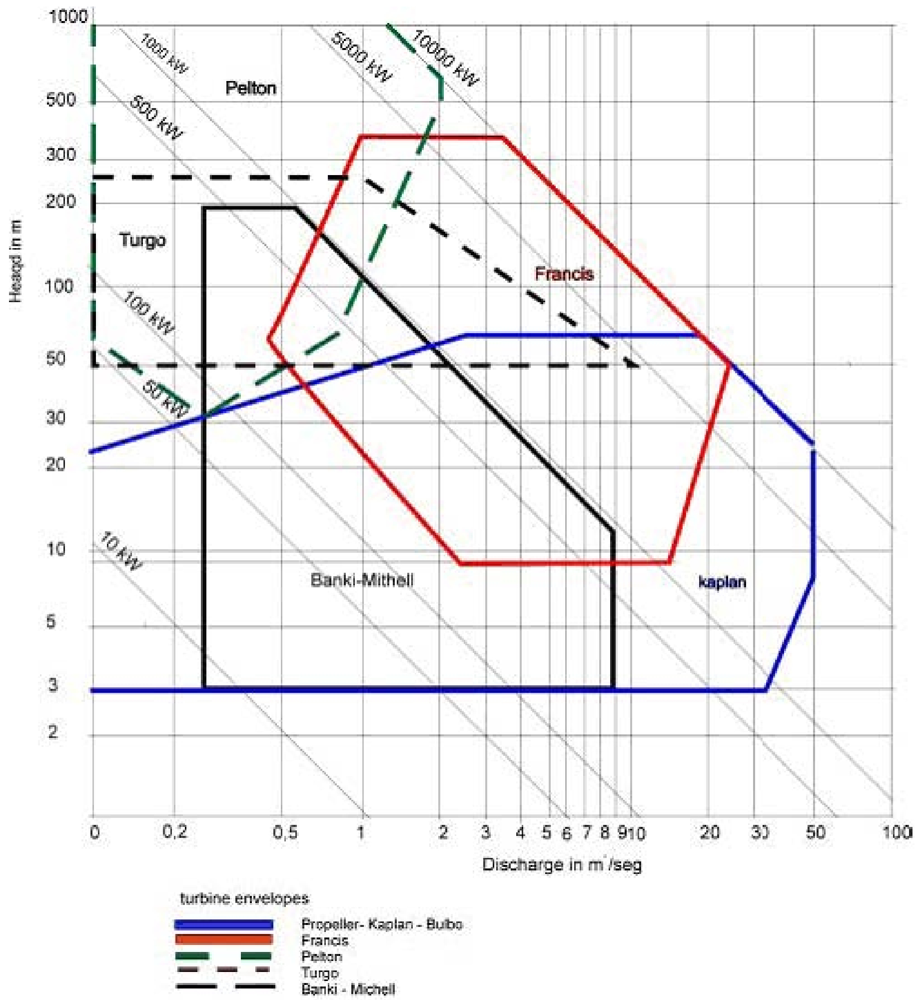



**Figure 4-18: Graphical representation of application ranges of different turbine types. [LAY_98] p. 175**

All of the turbines types which are "overlapping" the desired operational point in the graph are appropriate for the specific job, and now it will be necessary to compute installed power and electricity output against costs before taking a final decision about which type to use. It should be remembered that the "envelopes" vary from manufacturer to manufacturer and they should be considered only as a guide. Also, it is often a problem to find appropriate graphs for small turbine outputs. E.g. from **Figure 4-18** it seem that hardly no turbine is suitable for outputs smaller than 10kW – this statement is definitely wrong.

Specific speed[13]

The specific speed, $n_s$, of a turbine characterizes the turbine's shape in a way that is not related to its size or power output. The specific speed is a dimensionless number that only depends on the geometrical form of a turbine. This allows a new turbine design to be scaled from an existing design of known performance. The

[13] See also [LAY_98] p.166

specific speed of a turbine can also be defined as the speed of an ideal, geometrically similar turbine, which yields one unit of discharge for one unit of head. The specific speed is also a very reliable criterion for the selection of an appropriate turbine.

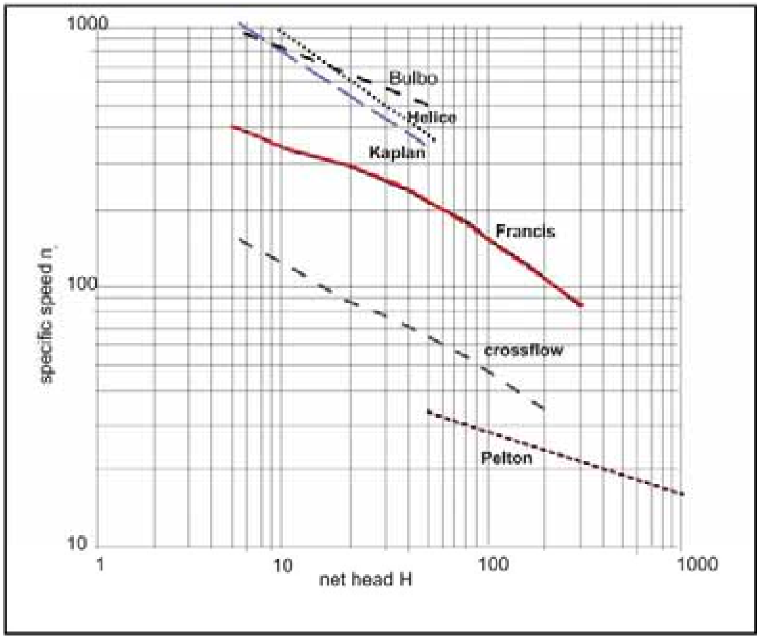



**Figure 4-19: Specific Speeds of different turbine types.**
**Source: [LAY_98] p.167**

Given a flow and head for a specific hydro site, and the rpm requirement of the generator it becomes easy to calculate the specific speed. If we wish to produce electricity in a scheme with 50-m net head, using a 10 l volume flow with the turbine directly coupled to a standard 1500-rpm generator we can compute the specific speed according to the following equation:

$$n_s = n \cdot \frac{\sqrt{Q_n}}{H_n^{0.75}}$$

**Equation 8**

Where $n_s$ = specific speed [-]
$n$ = rotational speed of turbine [RPM]
$Q_n$ = volume flow [$m^3/s$]
$H_n$ = net head [m]

We receive a result of for the specific speed of 8 this value tells us that for such high head and low flow schemes a Pelton turbine would be the ideal turbine type (a cross flow turbine could also be applied accepting slightly increased turbine speed). **Figure 4-20** gives a graphical representation of the specific speed calculation and also shows the application ranges of the different turbine types. One should note that the specific speeds for the different turbines vary considerably between different manufacturers.

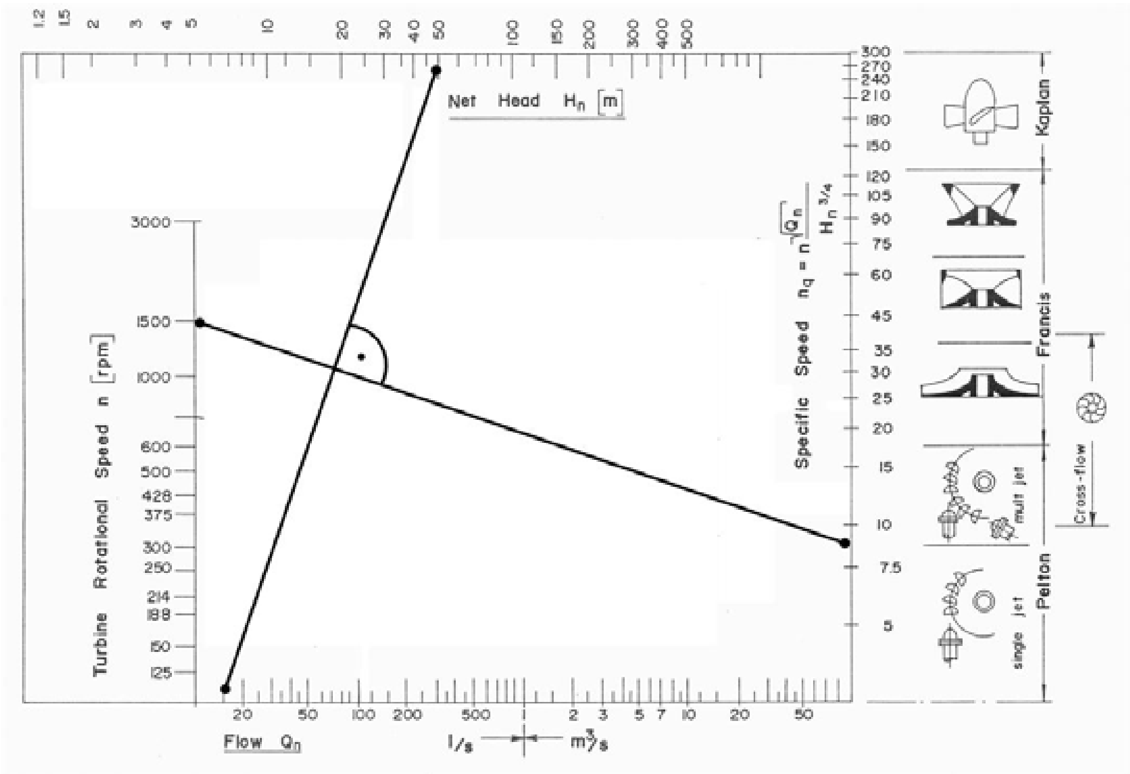



**Figure 4-20: Graphical aid to determine the correct turbine type for a given site characteristic. Source: [GATE_92] p. 196**

It was described before, that our proposed battery charging system will only need a power output of very few kW. As an example we could assume, that we need a hydraulic potential of 5kW. This amount of power can theoretically come from a head of 50 m and a flow volume of 10 l/s; but also from a head of 5 m (but then it would need a flow volume of 100 l/s). For the first case we calculated a specific speed of 8 and would have to choose a Pelton turbine correspondingly. For the second case the calculation (**Equation 8**) would yield a specific speed of 142. We can see from **Figure 4-21** that this value lays on the "opposite side" of the graph and the appropriate turbine would be a Kaplan turbine with a fast runner.

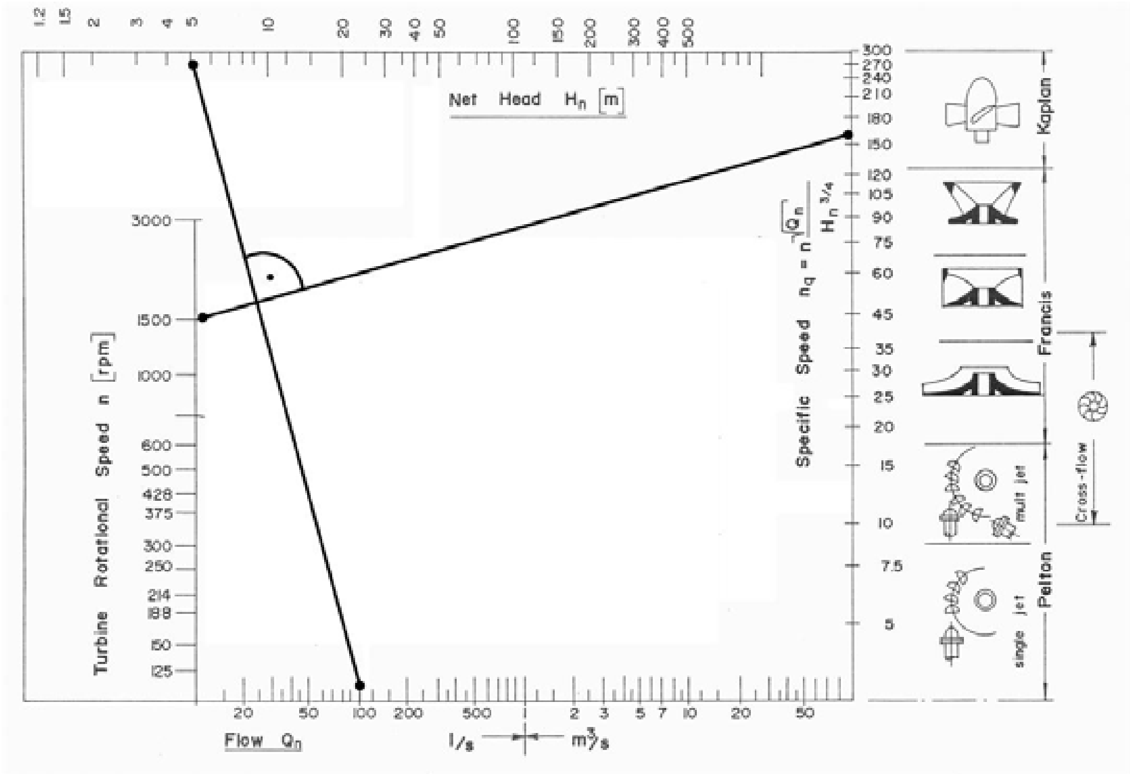


**Figure 4-21: Graphical aid to determine the correct turbine type for a given site characteristic. Source: [GATE_92] p. 196**

An alternative option is to accept the possibility of using a speed increaser or speed transmission from the turbine to the generator. A sensible ratio would be up to 1.3. Normally, the spectrum of appropriate turbines can be considerably enlarged by the accepting a speed transmission of suitable size.

Runaway speed

Another factor which should be kept in mind when selecting a turbine is the runaway speed. Each runner profile is characterised by a maximum runaway speed. This is the speed, which the unit can theoretically attain when the hydraulic power is at its maximum and the (electrical) load has become disconnected. Depending on the type of turbine, it can attain 2 or 3 times the nominal speed. The lowest possible runaway speed is desirable since the connected transmission and generator must be designed to withstand this speed. It must be remembered that the cost of both generator and gearbox may be increased when the runaway speed is higher.

For our proposed battery charging system normal 3-phase induction motors are used as generators. The advantage of these motors is their simple and rugged design and their ability to withstand rather high speeds. Normally, runaway speeds of 2 times the rated rotational speed are no problem for IMAGs.

Turbine efficiency

Turbine efficiency is defined as the ratio of power supplied by the turbine (mechanical power transmitted by the turbine shaft) to the absorbed power (hydraulic power equivalent to the measured discharge under the net head).

Generally, it can be said that efficiency is increasing with plant size. Turbines in small Micro and Pico systems seldom reach efficiencies of more than 70%; obviously the effort of optimising small turbines to the absolute limit does not pay of since only relatively small amounts of energy can be won.

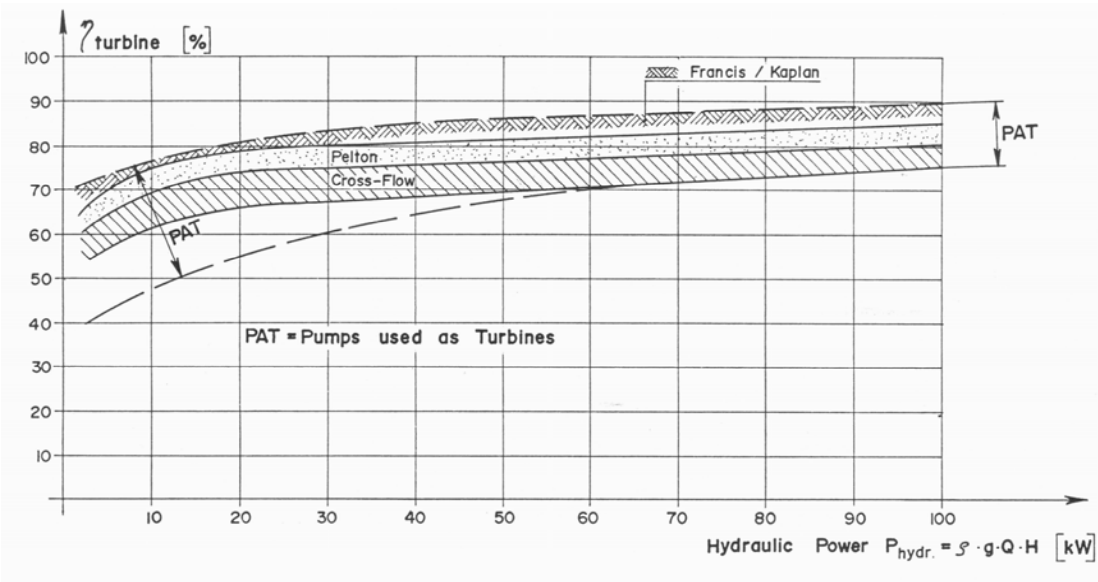



**Figure 4-22: Efficiencies of different turbine types with respect to hydraulic potential of a site or plant size. Source: [GATE_92] p. 195**

A turbine is designed to operate at or near its best efficiency point, usually at 80% of the maximum flow rate, and as flow deviates from that particular discharge so does the turbine's hydraulic efficiency. Approximate ranges for satisfactory efficiency vary considerably for different turbine types. Generally Pelton turbines have the highest efficiencies over the broadest range of discharge. In contrast, "Pumps used as Turbines" (PATs) have only a small gap where optimum efficiency is reached.

The next **Figure 4-23** will show different types of turbines and their respective efficiencies at different discharge.

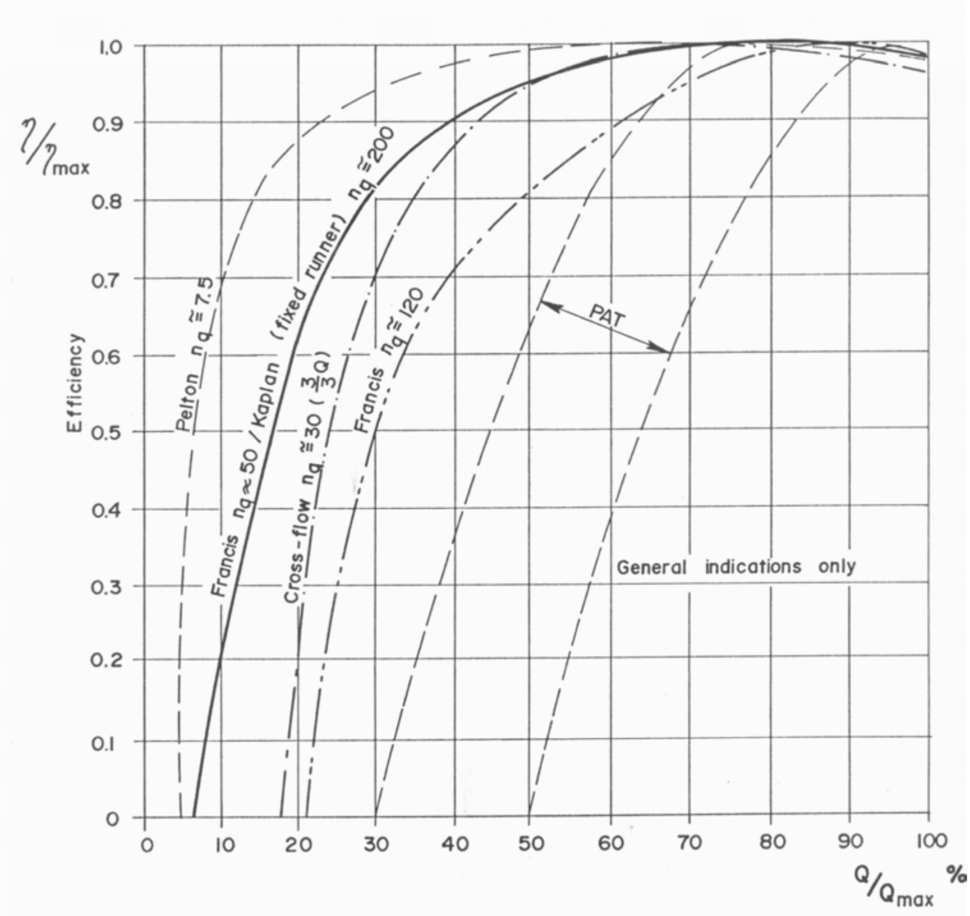



Figure 4-23: Turbine efficiencies at part flow. Source: [GATE_92] p. 196

### *4.3.6. Demands on a Turbine applied in small Battery charging systems*

For our specific proposed application: "Battery charging systems using IMAGs" a set of design criteria for appropriate turbines can be given.
A turbine that can be applied successfully for our purpose should have the following characteristics:

- Power Output not much bigger than 5kW. Bigger turbines increase the complexity of the whole system considerably (civil structures, control mechanisms, generator costs).
- The turbine should be economic in purchase and maintenance. Ideally the turbine should be manufactured locally to keep cost low and create local business.
- The turbine should be technically simple and repairable by local people. No or only simple maintenance work should be necessary.

- The turbine should have a speed of approximately 1500 to 1600 RPM at the respective site. As we will use normal 3-phase induction motors as our mode of electricity generation we will need to exceed synchronous speed of these motors (normally around 1500 RPM) in order to generate electricity.
- The runaway speed of the turbine should not exceed about 3000 RPM since a higher speed could damage the generator (IMAG)
- The efficiency of the system may play only a secondary role, since only relatively small amounts of additional energy can be gained. More important is a simple and rugged system that is very reliable.

## 4.4. Electricity generation

### *4.4.1. Overview*

The potential energy in the water is converted into mechanical or rotational energy in the turbine. Now, this mechanical energy has to be converted in to electric energy by a device called generator.

Generally, machinery could also be driven directly by a turbine as for instance in traditional corn mills or some modern timber sawing mills; but converting the power into electricity does have several advantages. It enables the use of all types of electrical appliances from lighting to small electric motors and the flexible positioning of these appliances to wherever a "power point" can be set up near or far from the turbine.

### *4.4.2. Possibilities of Generating DC Power for Battery Charging*

As described in the first part of the study our proposed MHP will mainly serve the purpose of charging batteries. Therefore, on the first glimpse it might seem useful to directly produce DC voltage with the help of a DC generator or a car alternator. On the second view this option shows several drawbacks which make this alternative unsuitable for our purposes. DC voltage can either be produced by a proper DC-generator or by an adopted car alternator. Both of these options have disadvantages: while DC generators are generally very expensive, car alternators are cheap and readily available but not engineered for continuous operation. A further problem arises if we want to transmit the electricity to a point in some distance of turbine and generator. Low voltage DC power transmission is very limited and extremely big cable diameters would be necessary.

Therefore, our systems will use an AC generator whose output is transmitted to the charging station and then converted into DC for charging batteries. Basically, there are two options of producing AC voltage: Firstly, using a synchronous generator with automatic voltage controller (AVR) or secondly, using an induction generator or an induction motor used as generator (IMAG). In the following section the advantages and disadvantages of using an IMAG for power production in an MHP will be described.

### *4.4.3. Introduction to IMAGs[14]*

The electro-mechanical equipment is one of the decisive factors when installing an MHP. Many small-scale hydroelectric power projects have failed already in the planning and design stage because of insufficient means to purchase the electrical equipment (expensive generator and controls). Unlike the mechanical (turbine) and the civil engineering components of an MHP, generators are still rarely manufactured in developing countries and importing such equipment is often beyond the capacity of a local project.

In MHPs of low output range (less than 1 or 2kW), DC generators from cars and lorries have been used because of their ready availability and their relatively low costs. As said before, results have not been completely satisfying due to the inconvenience of the low voltage generated (making the transmission of the electricity extremely difficult). Another problem is the limited life-span of car/lorry alternators, which are not designed and engineered for continuous operation and normally have a life time of less than one year.

A good and economic alternative to generate electricity in an MHP is the use of standard Induction Motors used As Generators (IMAG).
The main advantage of the IMAG is its ready availability. Induction motors are widely used in industry and agriculture in practically any country and therefore are less expensive than conventional generators, especially if they are manufactured or assembled locally. This is especially true for low power ratings. For example, a 10 kW induction generator is typically only half the cost of a synchronous generator.
Furthermore, induction machines are very robust and have a simple construction. They have no winding, diodes or slip rings on their rotor. Solid, normally cast bars replace the rotor winding and enable the rotor to withstand considerable overspeed.

As explained in the last chapter, the overspeed capability of a generator is an important criterion for hydropower plants. For induction machines of 4 poles and more, manufacturers can usually guarantee a maximum speed of twice the nominal speed.
Synchronous generators are usually only designed to stand runaway speeds of diesel engines, i.e. only 1.2 to 1.3 times the nominal speed.

An additional plus of IMAGs provides the fact that these machines are normally totally closed, ensuring good protection against dirt and water. They are designed for continuous operation with belt drives under difficult industrial conditions and therefore well suitable for even the roughest MHP sites.

[14] For detailed information see [GATE_92]

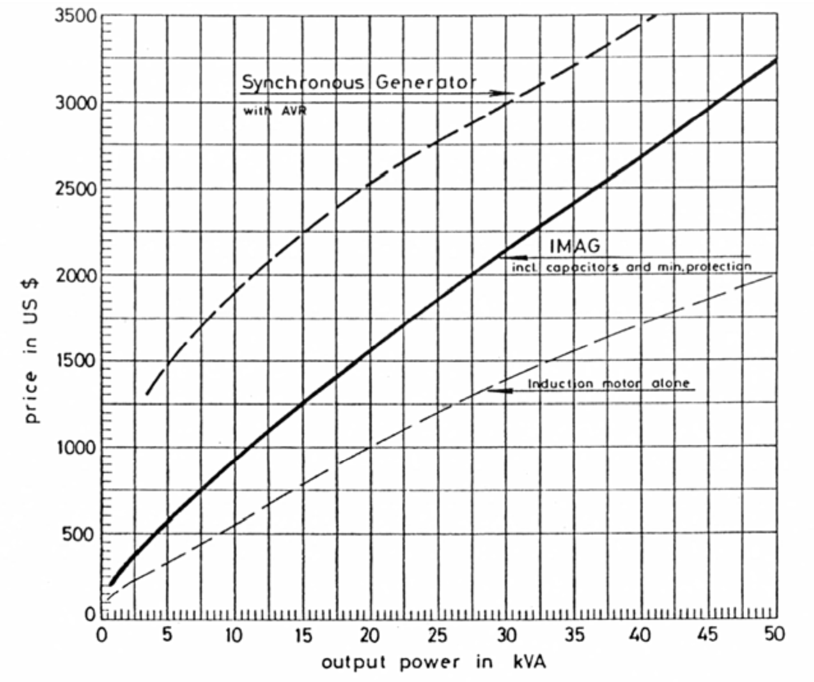



**Figure 4-24: Cost comparison between IMAGs and synchronous generators (4 pole machines, $n_s$ = 1500 rpm, prices of the European market, 1990). Source: [GATE_92] p. 13**

The use of IMAGs for power generation in MHP has certainly not only advantages; there are also a number of problems connected to them:

Standard induction machines are not always available with suitable voltage ratings for use as generators. Modifications to the winding connections, or in extreme cases rewinding, may be required.

Furthermore, the application of IMAGs is not as straightforward as the use of standard generators. Whilst synchronous motors can be purchased ready for use, the induction machine will not work without capacitors of suitable value being fitted. The IMAG cannot generate magnetizing or reactive power by itself; to establish its magnetic field and to actually produce power; the IMAG requires reactive power to be supplied to it. This reactive power can be generated by capacitors, which are connected to the induction generator. Always calculations and/or tests are necessary to determine the correct capacitance for a system. One also has to keep in mind that the capacitors create additional costs and are an additional source of failure and might have to be exchanged in intervals.

Another problem when using IMAGs is connected to the starting of motors: Motors are more easily started with synchronous generators than induction generators. Induction motors; with a capacity that is large compared to the generator rating; can cause severe voltage dips or even loss of excitation when started from induction generators.

### *4.4.4. Induction Machine Construction and Operation*

Construction

The mechanical features of an induction machine can be seen from **Figure** 4-25 and **Figure** 4-26. From an electrical point of view, the induction machine consists of two parts: a fixed wound stator core on the outside and a rotor that rotates in the centre. The stator winding consists of coils of insulated copper wire fixed into slots in the core to form a distributed winding of a similar type to that used in synchronous generators.

The induction machine rotor is very different from that of a synchronous generator. The standard squirrel cage rotor core is cylindrical and builds up from thin sheets of steel into which slots have been punched to for the conductors. The conductors generally consist of aluminium bars that are short-circuited at each end by aluminium rings.

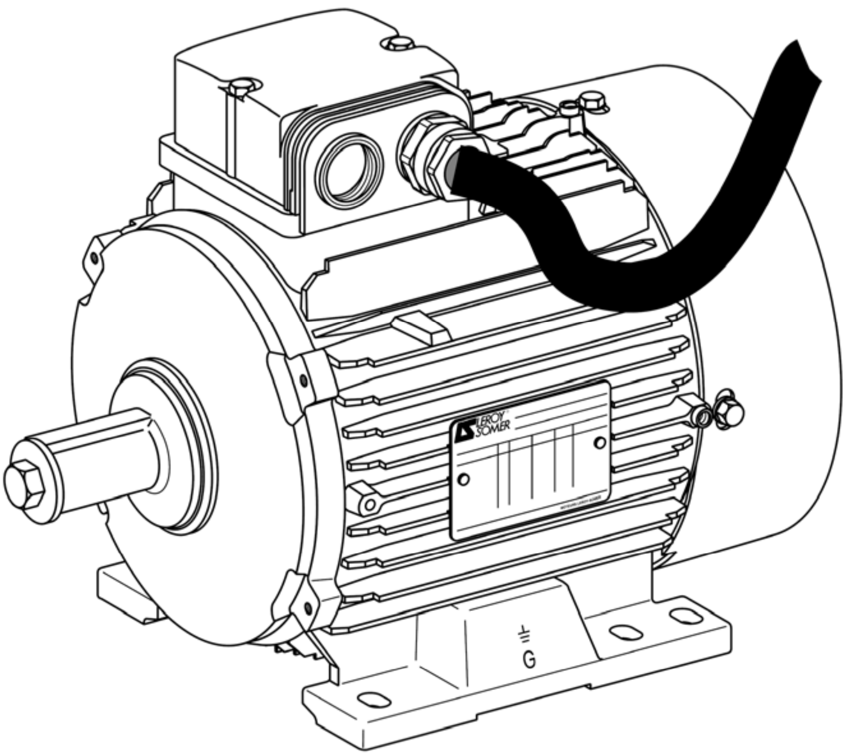
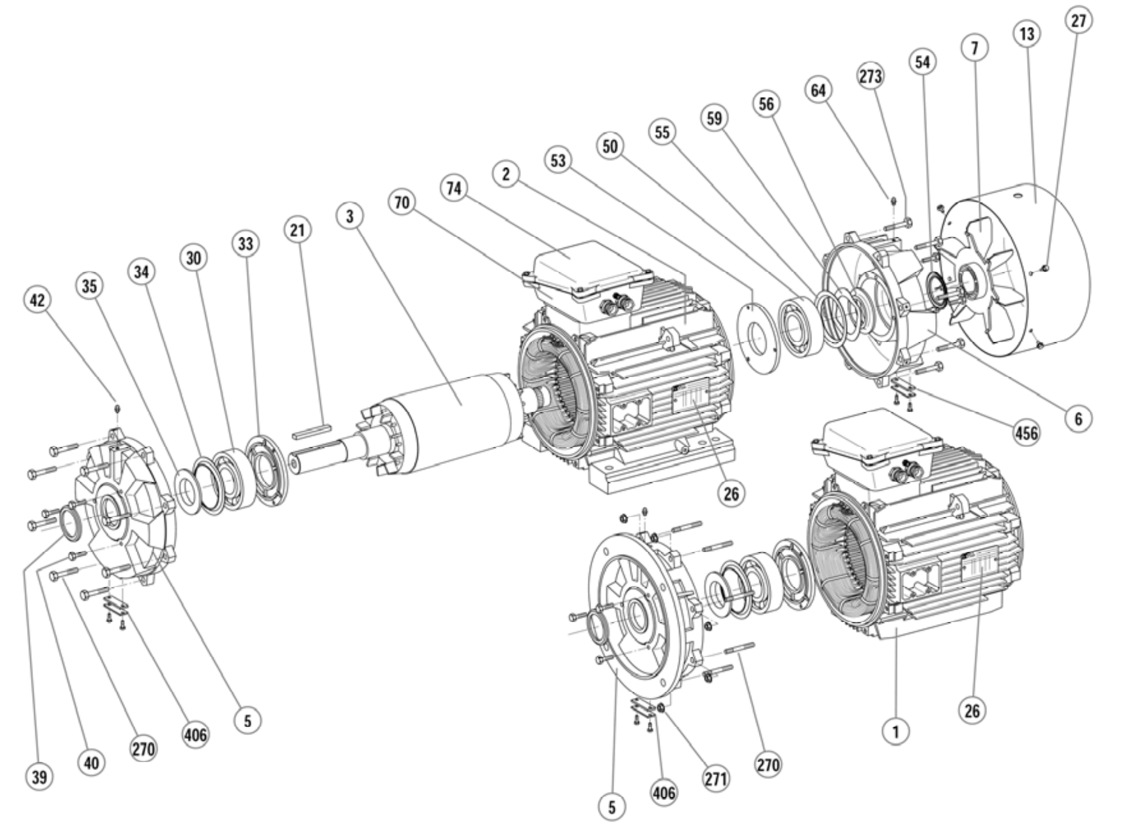



**Figure 4-25: 3-phase Induction Motor.**
**Source: Leroy Somer, www.leroy-somer.com**




| No. | Description | No. | Description | No. | Description |
|---|---|---|---|---|---|
| 1 | Wound stator | 33 | Inner drive end cover | 59 | Non drive end preloading washer |
| 2 | Casing | 34 | Fixed part of the DE grease valve | 64 | Non drive end grease nipple |
| 3 | Rotor | 35 | Moving part of the DE grease valve | 70 | Stator terminal box |
| 5 | Drive end shield | 39 | Drive end seal | 74 | Stator terminal box cover |
| 6 | Non drive end shield | 40 | Cover fixing screw | 270 | Drive end shield fixing screw |
| 7 | Fan | 42 | Drive end grease nipple | 271 | Drive end shield fixing nut |
| 13 | Fan cover | 50 | Non drive end bearing | 273 | Non drive end shield fixing screw |
| 21 | Shaft extension key | 53 | Inner non drive end cover | 406 | DE grease valve cover plate |
| 26 | Nameplate | 54 | Non drive end seal | 456 | NDE grease valve cover plate |
| 27 | Fan cover screw | 55 | Fixed part of the NDE grease valve | | |
| 30 | Drive end bearing | 56 | Moving part of the NDE grease valve | | |

**Figure 4-26: Exploded 3-phase Induction Motor.**
**Source: Leroy Somer, www.leroy-somer.com**

## Operation of an IMAG

In order to understand the operation of a stand-alone, i.e. non grid connected, induction generator it is very helpful to take normal motor operation as a starting point:

When an induction machine is connected to an A.C. supply, magnetizing current flows from the supply and creates a rotating magnetic field in the machine. The rotating field cuts the short-circuited rotor bars, inducing currents in them. Now, these currents interact with the rotating stator field and a torque is produced. This torque drags the rotor round with the field, but at a slightly lower speed. The small difference in speed arises because without it no currents would be induced in the rotor and, therefore, no torque would be produced to turn it. When a load is applied to the motor the speed difference will increase as a greater torque must be produced.

The difference between the speed of the rotor and the speed of the rotating field is called the 'slip' and is defined as:

$$Slip, s = \frac{(n_s - n_r)}{n_s}$$

**Equation 9**

Where $n_s$ = the synchronous speed (the speed of the rotating field)
$n_r$ = is the rotor speed

Without load connected, the slip of the induction motor will be very small, less than 0.01 (or 1%). For a machine of 1 kW the full load slip will be about 0.05 (or 5%). Larger machines have smaller slips.

Calculation of Slip and Shaft Speed in Generator Mode for a 50 Hz, 4.0 kW induction motor with rated full load speed of 1420 rpm

The full load motor shaft speed is given as 1420 rpm.
The synchronous speed is calculated from:

$$n_s = \frac{120 \cdot f}{p}$$

Where *f* = the supply frequency
*P* = is the umber of poles

In this case $n_s$ equals 1500 rpm. Hence, using the equation for calculating the slip we receive:

$$Slip, s = \frac{(n_s - n_r)}{n_s} = \frac{1500 - 1420}{1500} = 0.053$$

Since full load generating slip is approximately equal in magnitude to full load motoring slip, but negative, $s_{gen}$= -0.053.

By rearranging the previous equation we receive the theoretical shaft speed for full load generator operation:

$$n_r = n_s \cdot (1 - s) = 1500 \cdot (1 - [-0.053]) = \underline{\underline{1580}}$$

Supply Connected Induction Generator Operation

If the same supply-connected induction machine is now driven at above synchronous speed, so that the slip becomes negative ($n_r > n_s$), a torque is supplied to the rotor rather than by the rotor and the machine acts as a generator, supplying power to the network. However, it still takes its magnetizing current from the supply in order to create the rotating field, just as though it were still a motor. The full load power output is achieved at a slip of similar value (but negative) to the full load motoring slip.

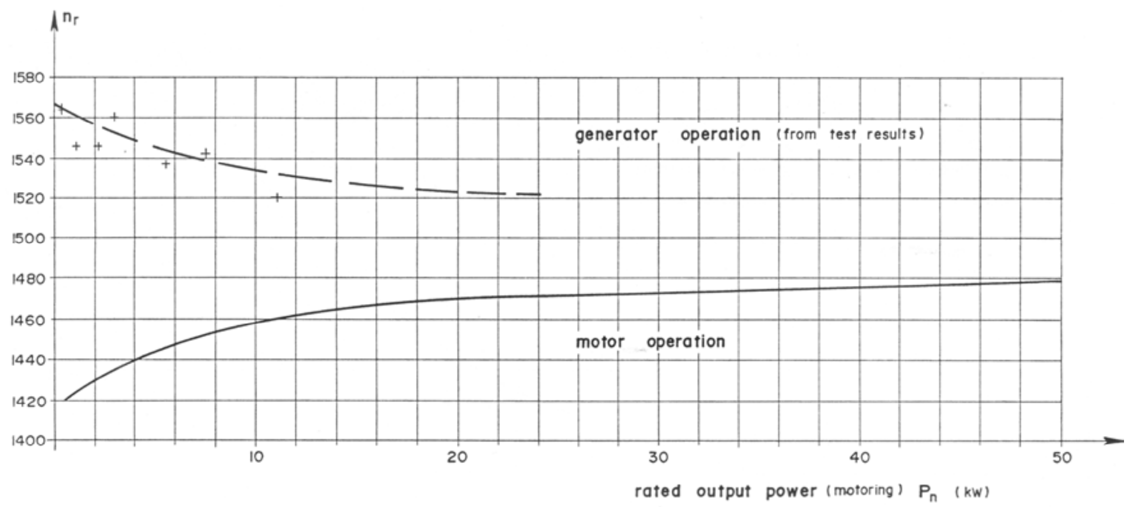



**Figure 4-27: Slip of (different size) induction machines in motor and in generator mode. Source: [GATE_92] p. 191**

Stand-alone Induction Generator Operation

The magnetizing current of an induction machine can also be supplied, in total or in part, by capacitors. Often, also in normal motor operation capacitors are connected to induction machines to reduce the reactive current drawn from the supply, this is especially important when the electricity company imposes charges for poor power factor.

In the case of the stand-alone induction generator, the capacitors are the only external source of magnetizing current. Therefore, in order to obtain the required operating voltage at the desired frequency, the amount of capacitance must be carefully chosen.

A simplistic but useful way to understand the basic operation of a stand-alone induction generator is to represent the machine simply by its magnetizing reactance. The highly simplified equivalent circuit is shown in

**Figure 4-28.** This is a fairly accurate representation for the purpose of determining capacitor requirements.

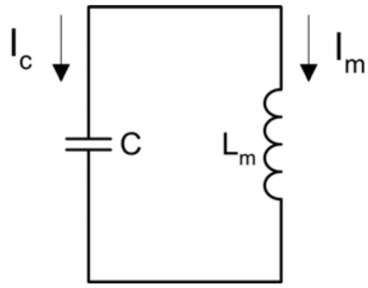



**Figure 4-28: Simplified equivalence circuit for IMAG stand-alone generator operation. Source: [Smith_XX]**

With the shaft rotating, current will begin to flow due to the remanent magnetism present in the rotor. The capacitor current, $I_c$, will equal the magnetizing current, $I_m$, and the machine and capacitors will act as a resonant circuit at an angular frequency, ω, fixed by the shaft speed of the machine. Provided that sufficient capacitance is present, the current will rapidly increase until stable operation is reached when the impedance of the capacitors equals the magnetizing impedance as given by the following equation:

$$\frac{1}{\omega \cdot C} = \omega \cdot L_m$$

**Equation 10**

Where $C$ = the capacitance
$L_m$ = the inductance of the machine
$\omega$ = the angular frequency

Stable operation occurs because the magnetizing inductance is a non-linear function of current, due to magnetic saturation of the rotor and stator steel. Provided that sufficient capacitance is connected, the voltage against current characteristic for the capacitor(s) meets the voltage against current characteristic for the magnetizing inductance (generator). This is the operating point of the generator. Increasing the capacitance will increase the operating voltage but, since more current flows into the machine, additional power will be lost as heat in the stator windings.

### *4.4.5. Excitation Capacitor Requirements*

For a three-phase generating system, the capacitors can either star (Y) or delta (Δ) connected, as shown in the following figure.

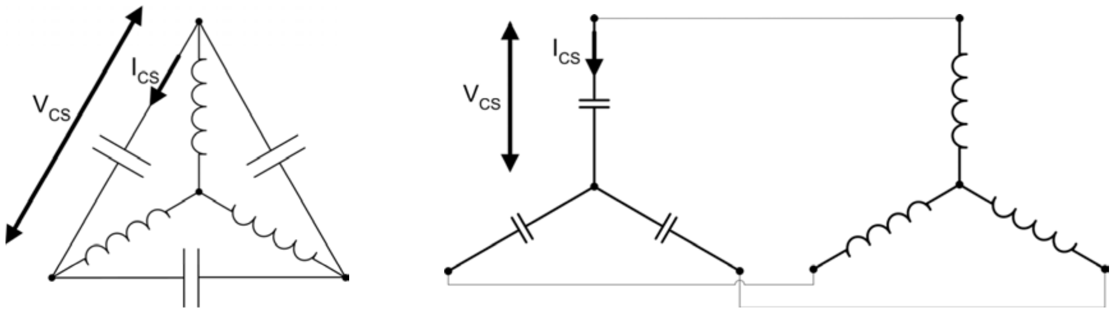



**Figure 4-29: Delta and Star Connection of excitation capacitance. Source: [Smith_XX]**

If the capacitors are connected in star, then three times as much capacitance is required than for delta connection; though lower voltage and therefore cheaper capacitors may be used.

## Calculation of excitation capacitance[15]

A precise calculation of the capacitance required to generate a given voltage under a specific load is only possible with knowledge of the electrical parameters of the induction machine in question. These parameters can be obtained by means of a number of standard tests, but expensive equipment is required. In practice it is sufficient to calculate an approximate value of excitation capacitance and adjust the turbine speed until the required system voltage is obtained. This will mean that the operating frequency may differ from the rated frequency of the induction machine, which is acceptable provided that the frequency is kept within reasonable limits.

A simple method for an approximate calculation of the excitation capacitance required is shown below. The method uses manufacturer's data from the motor plate to calculate the reactive power required from capacitors by means of full load current and power factor.
The capacitive reactance for full power factor correction can be obtained from this information and the rated voltage of the induction motor. The Appendix of this study gives more information about approximate values for all common motor sizes.

[15] For extensive information see [Smith_XX]

How to calculate the correct capacitance?

A 4 kW, 4 pole, 50 Hz, 415/240V induction motor is delta connected for the operation as a generator. Using only the information on the motor plate, the amount of excitation capacitance that should be connected in delta is calculated in the following way:

From the motor plate we can get the information, that the full load current is 8.4/14.5 A and the power factor is 0.80.

1) The total apparent power at full load is therefore:

$$\sum S = \sqrt{3} \cdot V_{line} \cdot I_{line} = \sqrt{3} \cdot 240V \cdot 14.5A = 6028VA$$

2) Hence the real power is:

$$\sum P = \sum S \cdot \cos\varphi = 6028VA \cdot 0.80 = 4822W$$

3) The reactive power can be obtained using the power triangle and Pythagoras theorem:

$$\sum Q = \sqrt{\Sigma S^2 - \Sigma P^2} = \sqrt{6028VA^2 - 4822W^2} = 3617VAR$$

4) Hence, the reactive power per phase is:

$$Q_{phase} = \frac{\Sigma Q}{3} = \frac{3617VAR}{3} = 1206VAR$$

5) For delta connected capacitors it holds:

$$V_{phase} = V_{line}$$

$$I_{phase} = \frac{Q_{phase}}{V_{phase}} = \frac{1206VAR}{415} = 2.91A$$

6) From the following equation we can now calculate the necessary capacitance:

$$C = \frac{I}{2\pi \cdot f \cdot V} = \frac{2.91A}{2\pi \cdot 50Hz \cdot 415V} = 22.3\mu F$$

**The necessary capacitance is therefore 22.3 µF.**

### *4.4.6. Single Phase Output from a Three-Phase Machine*

Single phase induction motors could be used as generators, but problems can be experienced in achieving excitation and in determining the size and arrangement of the capacitors required. In addition, single phase induction motors are more expensive than three phase induction motors and are only available for small power outputs. Fortunately, it is possible to use a three-phase induction motor as a single phase generator and this is the preferred approach to provide a single phase supply. The method for obtaining a single-phase output from a three-phase machine is as follows:

1) Use a three-phase machine suitable for 240/415V (220/380V) operation and connect the machine in delta.
2) Calculate the per phase capacitance, 'C', required for normal three-phase 240V delta operation.
3) Instead of connecting 'C' to each phase connect twice 'C' to one phase, 'C' to a second phase and no capacitance to the third phase. This is known as the 'C-2C' connection. The load should be connected across the 'C' phase as shown in the following figure.

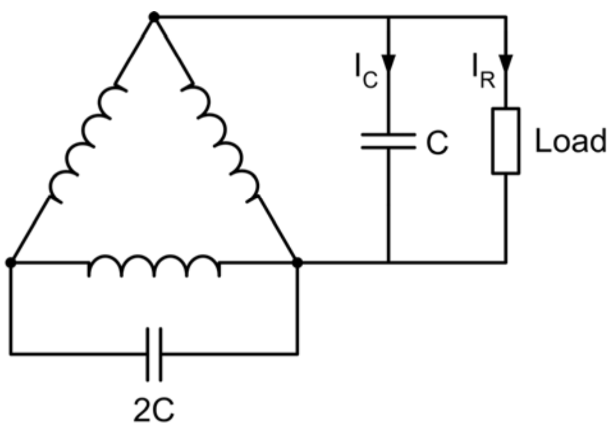



**Figure 4-30: C-2C connection of capacitors to an induction machine.**

### 4.4.7. Suitable IMAGs

Unfortunately not all of the various designs and types of induction machines available on the market show good performance when generating although they may perform well as motors. The problem of how to distinguish the suitable from the unsuitable IMAGs cannot be solved easily. The engineer in the field may not have the possibility to carry out test previous to installing the IMAG in an MHP and manufacturers of motors see rarely an interest in measuring and publishing test results of their standard motors in generator mode.
Generally, the best machine to be used as a generator is the squirrel-cage motor with a simple rotor bar design. The wound-rotor type may be used but is slightly less sturdy than the squirrel-cage design, is more expensive and not always readily available. The machine should have high efficiency and a low full-load slip and low starting but high pull-out torque.

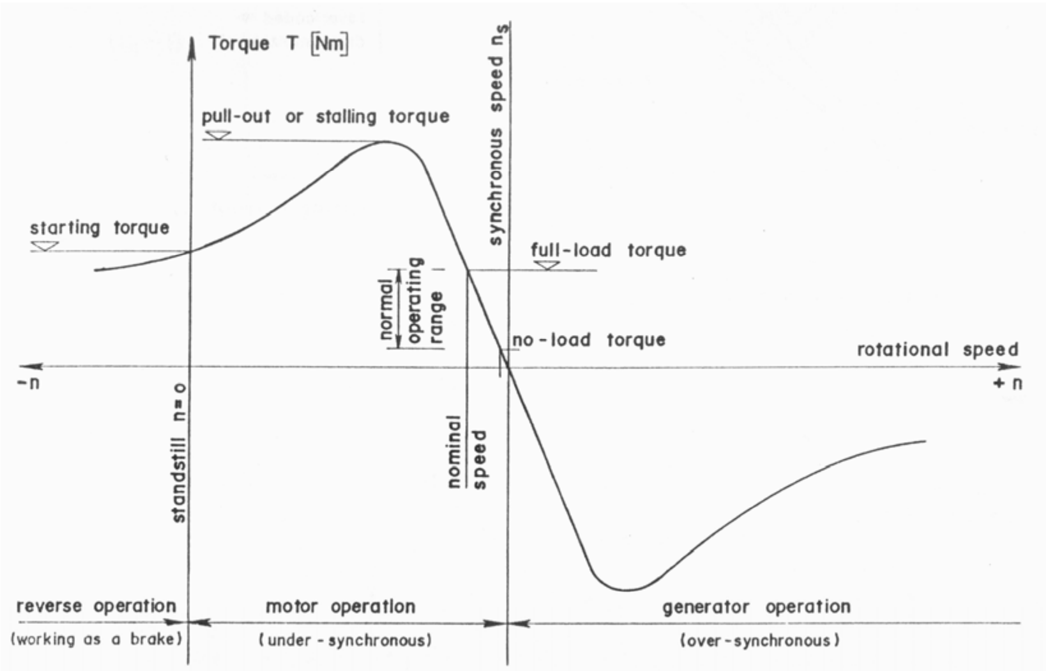



**Figure 4-31: Torque characteristic of an induction machine in motor and in generator operation. Source: [GATE_92] p. 32**

## Efficiency

Induction machines have a slightly lower efficiency when operated as generators than as motors. Generally, energy efficient machines have better efficiencies as when operated as generator at part load as well as full load.

## Power Rating

The greater the power drawn from the generator, the higher it's operating temperature and hence the shorter the life of its windings. To ensure long winding life when used as a generator, the machine should be kept below its full load operating temperature as a motor.

Induction machines should therefore be derated when used as generators. A derating factor of 0.8 is recommended and is also applicable to single phase generation from a three-phase machine. A derating factor of 0.8 provides a good safety margin, since heat transfer between the stator windings helps to correct for temperature differences due to unequal currents in the windings. Using generators larger than required should be avoided, as induction machines, especially smaller capacities, have poor part load efficiencies.[16]

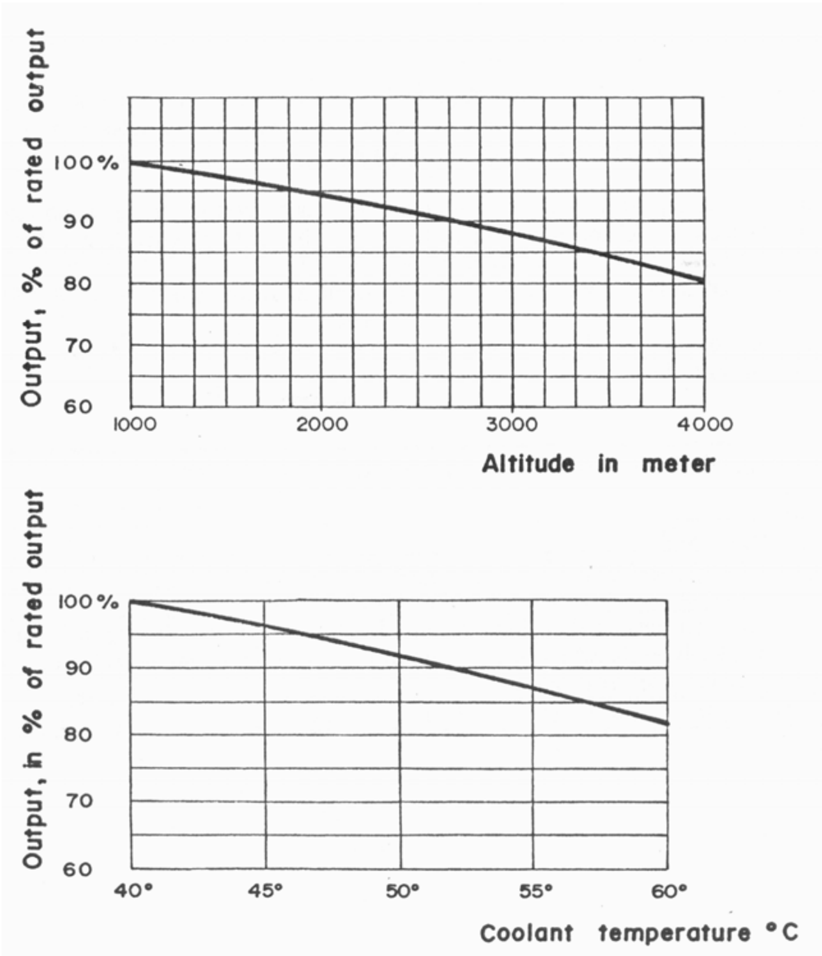



**Figure 4-32: Output of an IMAG as a function of altitude and coolant temperature. Source: [GATE_92] p. 41**

[16] [Smith_XX] p. 17

#### Speed Rating

Ideally the generator should be directly driven by the turbine. This has advantages in terms of increased efficiency, reduced drive system costs, lower maintenance and simpler installation. Unfortunately, turbine speeds are often much slower than standard generator speeds and therefore this approach is not always possible. Nevertheless, it may be suitable for high head or low flow installations or were high specific speed turbines are appropriate.

### 4.5. Power Transmission

Unfortunately, sites with good renewable energy production are frequently far away from the point of use. This is particularly true of hydro systems, where the location of the energy source cannot be easily altered.

The location of turbine and powerhouse are determined by the characteristics of the area and of course chosen to give a maximum power output. Obviously the best location for a turbine is at the lowest point in a valley to make use of the greatest possible head. Unfortunately villages are often not located exactly at this very same point but rather further up. Therefore it is necessary to transport the energy over a certain distance to some place where it can be used productively.

Especially for a battery charging system the location of the charging station is important. Everybody knows from own experience how heavy lead-acid batteries are and everybody can imagine how difficult and exhausting it would be to carry them over long distances.

Ideally a central charging station should be situated in or near the centre of the village, so that all customers or consumers have to carry their batteries only a relatively short way into their homes and houses. As explained before, the concept of the our charging station (or "Energy Service Station") includes the idea of locating the energy services at some central place which is accessible to as many people as possible.

Using an IMAG to produce high voltage electricity gives us the possibility to transport the energy over a certain distance to some location where the electricity can be used far more productively than for example near the powerhouse.

This chapter will give some basic ideas about the possibilities and constrains of power transmission. Simple calculation will be given to approximate possible power line distances and cable sizes.

### *4.5.1. Theoretic Calculations*

When transmitting power over any distance, losses inversely proportional to the square of the of transmission voltage are incurred. Minimizing the losses therefore requires maximizing the, within economic limits, the voltage at which the power is transmitted.
For short supply lines, the conductor size is based on keeping heating of the conductors within acceptable limits. For longer lines, it is the maximum acceptable voltage drop which determines the conductor size. Some loads or consumers are sensitive to large voltage fluctuations (e.g. motors) while others are less (e.g. incandescent lamps).
To determine the necessary conductor size either the permissible voltage or the corresponding power loss can be used. When deciding about the appropriate conductor size one should balance the additional costs of bigger conductors against the amount of energy lost in transmission.
Note that the following formulae are only correct if the inductance of the cables and conductors is negligibly small compared to their ohmic resistance. The calculations below are, nevertheless, sufficiently accurate to give good ideas about permissible line lengths and conductor sizes.

Calculating voltage drop and power loss requires knowing the size of the load supplied by the line and its power factor, along with the conductor's resistance and reactance. The conductor's resistance is determined by its type (usually either copper or aluminium) and size (cross-sectional area).

For DC Systems the voltage drop can be calculated by using the following formula:

$$\Delta U = \frac{2 \cdot l \cdot I}{\kappa \cdot A}$$

**Equation 11**

| | | |
|---|---|---|
| *Where* | *ΔU* | = the resulting voltage drop |
| | *L* | = the length of the line |
| | *I* | = the line current |
| | *κ* | = the conductivity of the used material |
| | *A* | = the size or cross-section of the line |

Correspondingly the voltage drop for three-phase systems can be calculated by using the following derived formula:

$$\Delta U = \frac{\sqrt{3} \cdot l \cdot I \cdot \cos\varphi}{\kappa \cdot A}$$

**Equation 12**

| | | |
|---|---|---|
| Where | *ΔU* | = the resulting voltage drop |
| | *L* | = the length of the line |
| | *I* | = the line current |
| | *K* | = the conductivity of the used material |
| | *A* | = the size or cross-section of the line |
| | *Φ* | = the power factor |

Since our system is will be technical restricted to a delta connection we can exchange the line current in the equation above with the produced active power the following way:

Since $P = U \cdot I \cdot \cos\varphi$ and consequently $I \cdot \cos\varphi = \frac{P}{U}$ we can derive the voltage drop also the following way:

$$\Delta U = \frac{\sqrt{3} \cdot l \cdot P}{U \cdot \kappa \cdot A}$$

**Equation 13**

By using standard induction motors in delta connection our line voltage will be restricted to 240V. Assuming this we can now calculate approximate voltage drops for different system sizes, power line lengths and conductor sizes. Results for this calculation are shown in

**Table** 4-3. For the calculations it was assumed that copper wires are used. Conductivity values for copper and other wire materials are shown in the appendix of this study.

| System Size / Power Output [kW] | Power Line Length [m] | Conductor Size [mm²] | Voltage Drop [V] | Voltage drop [%] |
|---|---|---|---|---|
| 1 | 100 | 10 | 0.7 | 0.3 |
| 1 | 100 | 50 | 0.1 | 0.1 |
| 1 | 1000 | 10 | 7.4 | 3.1 |
| 1 | 1000 | 50 | 1.5 | 0.6 |
| 5 | 100 | 10 | 3.7 | 1.6 |
| 5 | 100 | 50 | 0.7 | 0.3 |
| 5 | 1000 | 10 | 37.2 | 15.5 |
| 5 | 1000 | 50 | 7.4 | 3.1 |

**Table 4-3: Voltage drops of different cable configurations.**

To find an appropriate cable size for any installation the above equation can be rearranged as follows:

$$A = \frac{\sqrt{3} \cdot l \cdot P}{U \cdot \Delta U \cdot \kappa}$$

**Equation 14**

As said before, when choosing the size of the conductor firstly the permissible voltage drop from the technical side has to be assessed; but secondly also economic factors play an important role. The main question will be if it is economically sensible to use a bigger conductor (with higher purchase costs) to increase the power output at the consumer site, or vice versa.

## 4.6. The Consumer System and its Control

The quality of the generated electricity should always depend on the requirements of the end-use appliances. The different electrical loads of a scheme are designed to operate under constant frequency and voltage. Deviating from these nominal values might affect the lifetime of some appliances while others might work not properly.

Generating units using synchronous generators (with AVR and speed governor or load controller) usually provide a high quality of electricity with only small voltage and frequency variations. Induction motors used as generators are, in today’s most common applications, not able to maintain frequency and voltage variations within the same range. By the use of control systems it can be managed to maintain a certain degree of energy quality.

Fortunately, the approach used in this study does not need "high quality" electrical energy. Fluctuations in frequency and voltage are tolerable up to a certain degree. The advantage of a central charging station is, that all consumer are easily controllable at one point only which makes it easy to keep the loads constant all the time, either automatically or manually by the operating personnel.

In the following section some of the most frequently used governing and control systems are introduced.

### *4.6.1. Governors and Controllers Requirements of Synchronous Generators and Induction Generators*

Electricity generation in isolated plants requires constant speed of the turbine/generator unit in order to maintain the constant frequency and voltage. When switching on electrical loads, the speed of the generating unit will drop until a new equilibrium between generated and consumed power is reached. Such changes of speed and the subsequent voltage and frequency variations of the generated electricity are undesired from the point of view of the end-use appliances (see above).

#### FLOW CONTROL

The speed of the generating unit can be kept constant if, upon an increase of electrical load, a corresponding increase of turbine output, i.e. water flow through the turbine, is brought about. Or, in other words: generated power matches at any instant the consumed power due to progressive flow control.
Flow-control governors exist in various forms. However, flow-control governors are usually of a fairly complex design and require good maintenance; additionally, they are seldom manufactured locally and therefore tend to be very costly for small hydropower projects in developing countries. Furthermore, flow-control governors are more accurate in their performance than is usually required in rural areas. For these reasons, speed governing by means of flow control is seldom used in conjunction with IMAGs since the cost advantage of the generator would be ruled out by the high costs of a mechanical speed governor.

#### LOAD CONTROL

An alternative to speed governing on the hydraulic system is the control of the generator output, called load control. In its simplest form it incorporates a consumer system of constant loads requiring no governor at all: the generating unit continuously operates at rated power which is at any instant absorbed by the consumers. When disconnecting an electrical load another one of similar magnitude must be switched on immediately in order to keep generated and consumed power in equilibrium.
These adjustments of loads could also be done automatically by an electronic device called “Electronic Load Controller” (ELC, for synchronous generators or) “Induction Generator Controller” (IGC). These devices switch any power not consumed by the regular circuit into a ballast load (resistors, heating elements); hence, generator output power and consumed power always match.

### *4.6.2. Control strategies of the "Energy Station"*

One main goal of this study was to show ways for the design of a simple and failsafe rural electrification scheme. The control and governing system plays of course a vital role in achieving this goal.
Ideally, the proposed MHP - charging station would need only limited manual control and could run continuously with only minimal supervision.

In this study a rural electrification system with centralized energy services was proposed. The main reason why this centralized approach was chosen, is the easily controllable "energy flow". The operator has all loads in his hands and should be able to react on load fluctuation by switch additional loads on or off. Generally the "energy station" should be designed in a way which assures that a nearly constant load is connected to the turbine at all times.

Of course, the manual load control can only be one part of the control strategy. An electronic load controller could provide additional safety by automatically adding the correct size of "dump loads".

**Figure 4-33: ELC for small MHP schemes (several hundred Watt), locally manufactured in Indonesia.**
**Source: PT. Heksa Indonesia.**

The main purpose of the energy station will be the charging of lead-acid accumulators. For this task, also the major part of the energy is used. Fortunately, charging batteries is not connected with high fluctuation of power demand. A

problem arises only from the fact, that at the beginning of the charging process more power is consumed than at the end of the process.
A charge regulator will charge with the highest charging current at the beginning; with time this charging current will slowly drop until it is almost zero when the battery is filled. During that time charging voltage rises only slightly. For more information about charging procedures please see the next chapter "Battery Charging".
On the first view this changing power demand poses a problem, but since we have a number of charging stations which are normally charging batteries at different levels. The sum of the power demand of the charging stations can assumed to be more or less constant. Small fluctuations are easily controllable by the ELC.

Another problem arises if the battery chargers or charge controllers are equipped with overload protection. These devices automatically disconnect the batteries from the charger once they are completely filled in order to avoid overcharging.
A sudden disconnection of the batteries would lead to a steep decrease in power demand (or load) and would cause the turbine to speed up considerably. A faster rotating turbine in return would increase voltage of the system and might lead to broken equipment.
Simple ELC might not be able to react quickly enough to "catch" a sudden, big load change and therefore other measures have to be found.
A way to avoid the above described situation is the introduction of a simple relay in the charge controller: If the final battery voltage is reached and the battery is full, the battery is disconnected but at the same time a dump load with the same resistance as the battery is connected to the charger. By this mechanism no unexpected load fluctuations due to fully charged batteries can occur.

It is important to keep in mind that all technical measures might fail and that for a continuous and proper operation of any technical machinery well trained personnel is a prerequisite. The operator of the charging station should be aware of all the technical details to undertake the right moves at the right times.

## 4.7. Battery Charging and Discharging

### *4.7.1. Batteries Types*[17]

General

Electricity can be stored in batteries using electro-chemical principles. With rechargeable batteries, the electrochemical process becomes reversible. The best-known application of this principle is the lead-acid battery used as a starter battery in cars and lorries throughout the world. It consists basically of lead electrodes (or plates) submerged in a solution of sulphuric acid and water as an electrolyte.

In charged condition, voltage between two plates (= one cell) is about 2V (nominal voltage). The voltage of standard car batteries (6V, 12V and 24V) is obtained by connecting 3, 6 and 12 cells in series.

When discharging a battery, voltage drops. To avoid damage on the electrodes of a battery, voltage must not fall below 1.75V per cell (except for very low temperatures or fast and quick discharging). Discharging a battery also leads to a lower concentration of the sulphuric acid in the electrolyte. Measuring the density of the electrolyte can therefore be used to determine the actual state of charge of a battery.

As with any machine, conversion of energy – in this case, electrical into chemical and vice versa – is always accompanied with losses. Lead-acid batteries have an efficiency (energy output / energy input) of 60% to 70%.

The Ideal Storage System

Even though lead-acid batteries are now a technology that is more than 100 years old now, it still represents the most economical and technically most simple form of electricity storage. Certainly lead-acid batteries are far from being perfect; ideally a storage system should have the characteristic features shown in the following table. Unfortunately, until now no storage system comes close to these requirements.

| | |
|---|---|
| Absorption of energy… | … should be possible at any state of charge, with high efficiency, at any charging current. |
| Delivery of stored energy… | … should be possible at any state of charge, at high efficiency, at any current. There should be no influence of SOC on potential of energy delivery. |
| Capacity losses… | … should not occur at all. No reversible capacity losses (e.g. self discharge, auxiliary power consumption) and no irreversible capacity losses (e.g. corrosion of active material). |

[17] See also [GATE_92a] p. 5

| | |
|---|---|
| Self consumption | There should be no self discharge and no auxiliary power needed. |
| Ambiental influences | There should be immunity against ambient temperature, atmospheric influences and mechanical stresses (vibration, etc. ...). |
| Ambiental impact | Ambiental impact should be as low as possible when manufacturing, during use and after the end of lifetime. |

**Table 4-4: Features of an ideal storage system. Source: PPRE lecture on batteries, H.Holtorf**

There are a number of different rechargeable battery types on the market, which could theoretically be used in a battery charging system. The following section will, in a very brief way, point out their advantages and disadvantages.

*a) Lead-acid*

Advantages*:* Has been proven for more than 140 years, and batteries of all shapes and sizes are mass produced today. In their price range, lead-acid batteries provide the greatest specific energy density and have the longest life cycle. At least in developed countries they have the environmental advantage of being recycled at a high rate (97% recycled and reused in industrialised countries).
Disadvantages: Lead is heavier than other metals and very toxic. The handling of acid is dangerous and is a potential health hazard. The recycling potential in many developing countries is very poor.

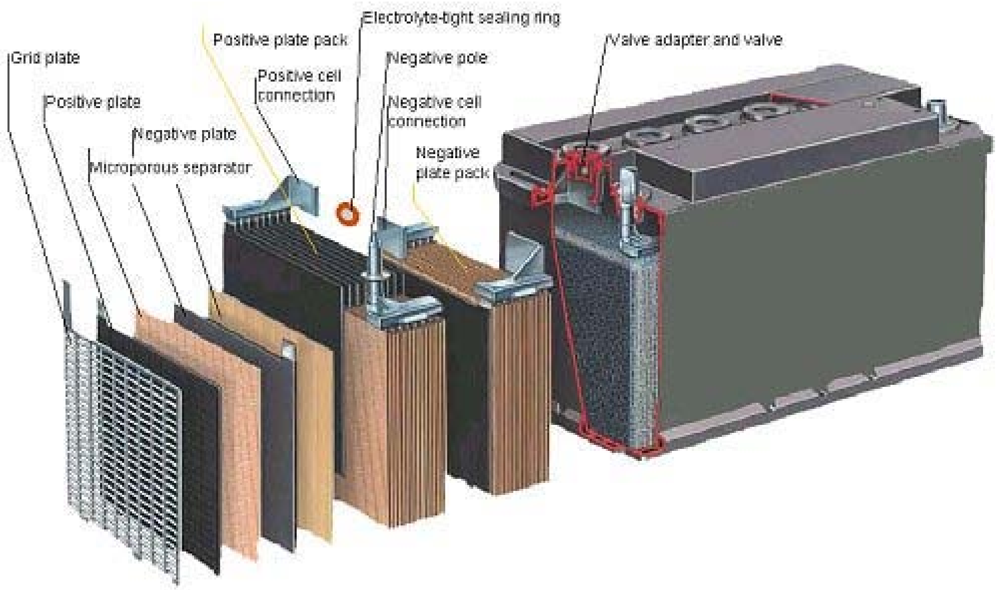



**Figure 4-34: General parts of a lead acid battery. Source: www.mpoweruk.com**

| | Pos. Material<br>Electrolyte<br>Neg. Material | Electrolyte Density (charged, 20°C) | Nominal Voltage<br>Gassing Voltage | Efficiency<br>η | Energy Density | |
|---|---|---|---|---|---|---|
| | | | | | theoretical | practical |
| Lead-acid Battery | $PbO_2$<br>$H_2SO_4$<br>Pb | 1.2 – 1.28 kg/l | 2.0 V<br>2.4 V | <80 % | 161 Wh/kg | 25 - 30 Wh/kg |

**Table 4-5: Physical properties of Leas-Acid batteries.**

*b) Lithium-ion*

**Advantages:** It has a high specific energy density making it useful for mobile applications.

**Disadvantages:** More expensive than lead-acid. As of now, there is no established system for recycling of large lithium-ion batteries. It has a high self-discharge rate and also the so-called "Memory effect".

*c) Nickel-cadmium*

**Advantages:** This chemistry is reliable, can operate in a range of temperatures, tolerates abuse well and performs well after long periods of storage.

**Disadvantages:** It is three to five times more expensive than lead-acid, its materials are more toxic (and potentially dangerous to health) and recycling infrastructure for larger nickel-cadmium batteries is very limited.

*d) Nickel-metal hydride*

**Advantages:** It is reliable and lightweight. These batteries are projected to have very long cycle life. The specific energy density for NiMH material is theoretically, approximately 60Wh/kg.

**Disadvantages:** The metal content in the battery is 25 times more expensive than lead. Nickel has been identified as a carcinogen. No significant recycling capability exists.


**Figure 4-35: Commonly used Ni-MH accumulators. Source: www.wikipedia.org**

*e) Nickel-zinc*

**Advantages:** This battery type has a good energy density, good operating temperature range and performs reasonably well after long periods of storage.

**Disadvantages:** It is expensive and its life cycle, while improved during the past few years, is not adequate.

As on can see, there is no one ideal battery type: every type has its own advantages and disadvantages. After all lead-acid batteries are still the most economic and technically sound technology. For village pre-electrification they have the invaluable advantage of the, by far, lowest costs. Furthermore people throughout the world are familiar to this technology because of the use of lead-acid batteries in cars.

Nevertheless, the perspectives of other battery types like (Nickel-metal hydride and Lithium-Ion) are very promising when it comes to store smaller amounts of energy. Common penlight-size (AA or AAA) batteries have nominal capacities ranging from 500mAh to about 2500mAh at 1.2V and can easily be applied for small lamps and radios in rural electrification.

Nickel-Cadmium batteries should not be used at all because of the potentially very dangerous cadmium content, which can seriously harm human health and environment.

### *4.7.2. Recommended Types of Lead-acid Batteries*

Lead-acid batteries exist in different types; here the main differences of these types are discussed:

- Starter Battery:

Designed for high currents during short periods of time; not especially designed for cyclic charging and discharging as required in pre-electrification schemes. They are however the most common type of lead-acid batteries (since they are normally used in cars) and readily and cheap available. New, recycled and old starter batteries are used in many projects due to their initial cost advantage. However, the log term costs of are much higher due to their relatively short lifetime and reduced capacity.

- Heavy Duty Battery:

Designed for vehicles which are exposed to heavy vibration and shock, this type of starter battery has a slightly improved performance for cyclic charging and discharging operation due to their thicker and more stronger plates/electrodes.

- Traction, Stationary and Solar Batteries:

Designed for the same objectives as required in pre-electrification schemes (cyclic operation, higher tolerance against deep discharge). Unfortunately, traction, stationary and solar batteries are difficult to obtain in developing countries and are very expensive when compared to other lead-acid battery types. Therefore, in theory they are the best solution but in reality solar batteries or traction battery are seldom to be found in developing countries.

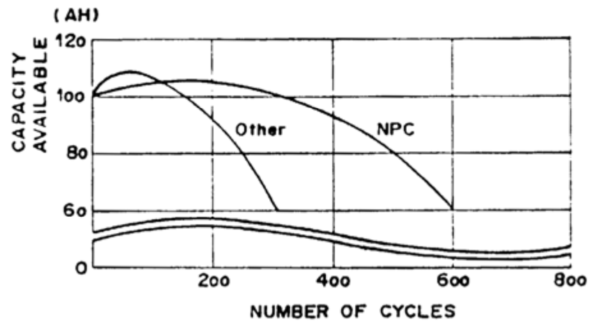



**Figure 4-36: Comparison between a conventional and a special battery for cyclic application (YUASA, NPC: maintenance free, valve regulated) shows that almost a double lifetime is possible. Source: [GATE_92a]**

As a final result it can be stated that a good compromise between life time under cyclic operation and battery price seems to be the heavy duty battery or any other starter-type battery with reinforced plates and separators. Nevertheless, solar batteries are always the best solution when it comes to medium and long term costs and should always considered first despite their high costs.

A general rule that can be applied says that the heavier the battery for a given Ampere-hour (Ah) value the more suitable it is for cyclic operation. The reason is that heavier batteries obviously have stronger plates which can withstand deeper discharge and more charging/discharging cycles.

<u>Size of Batteries</u>

Lead-acid batteries have an energy density of 25 - 30 Wh/kg. Since the battery has to be transported to the central charging station and back to the point of use, the maximum size of a battery is determined by its weight rather than its energy content. Batteries considered for the application here should certainly not weight more than about 40 kg which gives a theoretical energy output of around 1000Wh to 1200Wh (or 83Ah to 100Ah). At this point it should be remembered that only around 80% of this value can actually be used because lead-acid batteries must not be discharged completely to avoid irreversible damage of plates.

### *4.7.3. Charging Procedures*

<u>Introduction</u>

The charging and discharging procedure is of great importance for the lifetime of a battery. Even the most expensive solar battery can easily be destroyed within a short time by inappropriate charging and discharging. The following points have to be kept in mind when charging a battery:

- <u>Deep Discharge:</u> repeated 100% discharge of a lead-acid battery reduces its life time considerably; a deep-discharge protection which disconnects any load at a specified minimum voltage (around 1.75 V per cell) should be mounted on every battery.
- <u>Charging Current:</u> lead-acid batteries should be charged at a current of 10 to 20 A per 100 Ah capacity (e.g. with 5 A to maximum 10 A for a 50Ah battery). However, gas production (electrolysis of water, due to the chemical reactions taking place inside the battery) increases rapidly from the critical voltage of 2.4 V/cell, even at relatively low charging currents. To avoid large gas production, the charger should reduce the charging current to avoid damage to electrodes and excessive loss of water through the electrolysis.
- <u>Overcharging:</u> once the final voltage of 2.6 to 2.65V/cell is reached the charging process must be stopped. Otherwise, the energy supplied to the battery will be used only for the electrolysis of water and heating the battery. Again, water loss and destruction of the plates are the consequences.
- <u>Number of Charging Cycles:</u> standard starter batteries in tropical climates have a technical lifetime of around 200 charging cycles (when not discharge more than 80%) before plates start to disintegrate. In pre-electrification

schemes this corresponds to a lifetime of about 4 years when the average charging interval is 1 week. However, this is a rather theoretical value and can only be achieved if a good charger is used and if the battery is never exposed to deep-discharge, overcharge or lack of water. In reality lifetimes of 50 to 100 cycles are much more realistic.

- Self-Discharge: Lead-acid batteries gradually lose energy even if not connected to consumers. Additionally, electrodes are destroyed if left unused in discharged conditions. That means that a battery must be recharged regularly to maintain its capacity.

Connection of Batteries at the Charging Station (and at consumers): when charging or discharging it is possible to connect a number of batteries simultaneously at the same charging station. In general connection in series and in parallel is possible. It should be stated that ideally on every charger only one battery should be connected.

a) Connection in Series is often used but is not recommended. The advantages are the low currents and the high voltages at the charger terminals (less costly transformers and cables). The big disadvantage is that all batteries receive the same current. One battery which is almost fully charged still collects most energy (due to its highest internal resistance and therefore voltage) and will soon be overcharged while the other batteries might rarely reach final voltage within the charging period. Only identical battery might be charged in series.

b) Parallel connection is therefore to be preferred. Batteries of different SOC and age can be charged simultaneously. Disadvantage: voltage of the charger can be identical to battery voltage but high currents and large transformers are necessary.

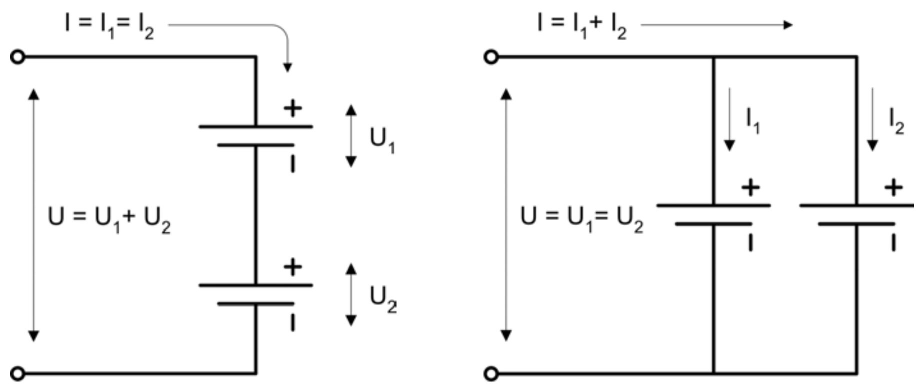



**Figure 4-37: Series and Parallel connection of batteries**

## Charging Procedure

The general behaviour of a lead-acid battery during a charging process with constant current is shown in
Figure 4-38. The cell voltage (2.1V) at the beginning of the charging process is slightly higher than the nominal cell voltage (2.0V). Voltage increases slowly (in the same speed as also the internal resistance increases) until electrolysis starts at 2.4V. The gas produced partly covers the electrodes and voltage rises faster due to the further increased resistance. The battery heats up because the efficiency of charging decreases. If the voltage has reached 2.61V, the charging is completed as all active material is converted and the concentration of sulphuric acid does not change anymore. Continued high charging current will produce gas (loss of water) and destroy the electrodes.

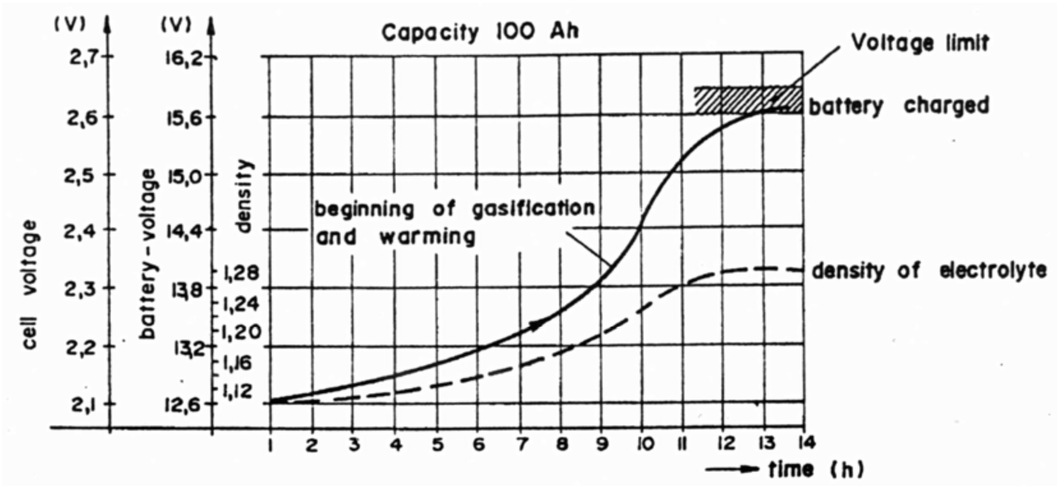



**Figure 4-38: Development of voltage and density of the electrolyte of a lead-acid battery (100Ah; 12V) charged at a constant current of 10A. Source: [GATE_92a] p. 7**

## Battery Chargers

Many different designs of commercial chargers are available on the market. Price and quality of these available chargers varies considerably but technology improved considerably with the emergence and development of the photovoltaic market. Also the prices generally went down considerably during the last years since especially electronically controlled chargers have become a standard product.

In the proposed MHP – charging system the electric energy will be produced by an IMAG and the connected capacitors. The output of this arrangement, as explained above will be electricity at 240V alternating current.

From this point onwards there are basically three more steps necessary to charge our battery appropriately.

Firstly, the high voltage has to be transformed down to a suitable voltage level for charging the respective batteries. For that purpose normal, conventional transformers could be used; another promising alternative could be the use of electronic AC adapters like used for laptops or other low voltage appliances. These appliances often have a high input tolerance and can be feed with 110V – 240V AC to produce a constant DC voltage. Unfortunately, the use of these devices has not been tested yet and therefore no statements about their suitability can be made.
Secondly, the voltage of the "step down transformer" has to be rectified to DC. The above mentioned AC-adapters do this already automatically; other possibilities of rectifying AC voltage including "bridges" like shown in
**Figure 4-39.**

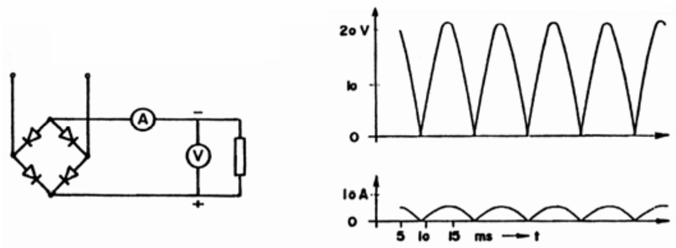



**Figure 4-39: Principle of a rectifying bridge. Source: [GATE_92a]**

The third step in the charging process is the control of the charging process. Some mechanism has to be installed to prevent the charger from overcharging the batteries.

## Ideal Charge Control Methods

The aim of every charging process is to charge the battery carefully to full capacity within a short time. The following procedure represents an ideal charging method used in electronically regulated chargers:

**Phase 1:** High current I, limited by the temperature of the battery (less than 50°C) and the capacity of the power supply. During the process of charging, the active material on the surface of the electrodes is exposed to the electrolyte and converted. The resistance increases with time, because the already converted material on the surface of the electrodes hinders the electrochemical process. An increasing voltage has to be applied to maintain the high current. In many charging systems this phase of the charging process is called "Boost Charging".

**Phase 2:** When the critical gasification voltage (+/- 2.4V) is reached, the gas production due to electrolysis of water becomes evident. The electrodes are covered with small gas bubbles. This increases the resistance significantly. Continued charging at high current and increasing voltage would increase water losses dramatically, waste energy and would finally destroy the electrodes. Therefore, now, voltage should not be allowed to exceed 2.4 V/cell, which means that current is now continuously decreases.

**Phase 3:** If the current falls below a predefined minimum, it should be keep constant until the voltage reaches the final value (+/- 2.65V) and all active material is converted.

**Phase 4:** To maintain the battery in fully charged conditions over a long period it should constantly be charged with a small current (at a voltage of 2.2 - 2.25 V/cell). This phase is often called charging at "Floating Voltage".

The process of charging has a large effect on the efficiency and the lifetime of batteries. Different methods are used in different battery chargers. The most common types of charging procedure are shown in the appendix.

### *4.7.4. Discharging Procedures*

At least as important as the correct charging procedure is also an appropriate discharging. Frequent deep-discharging of any lead-acid battery type results in a significantly reduced lifetime.
**Figure** 4-40 shows a typical discharge curve of a lead-acid battery, while
**Figure** 4-41 gives a good impression about the influence of the DOD on battery life.

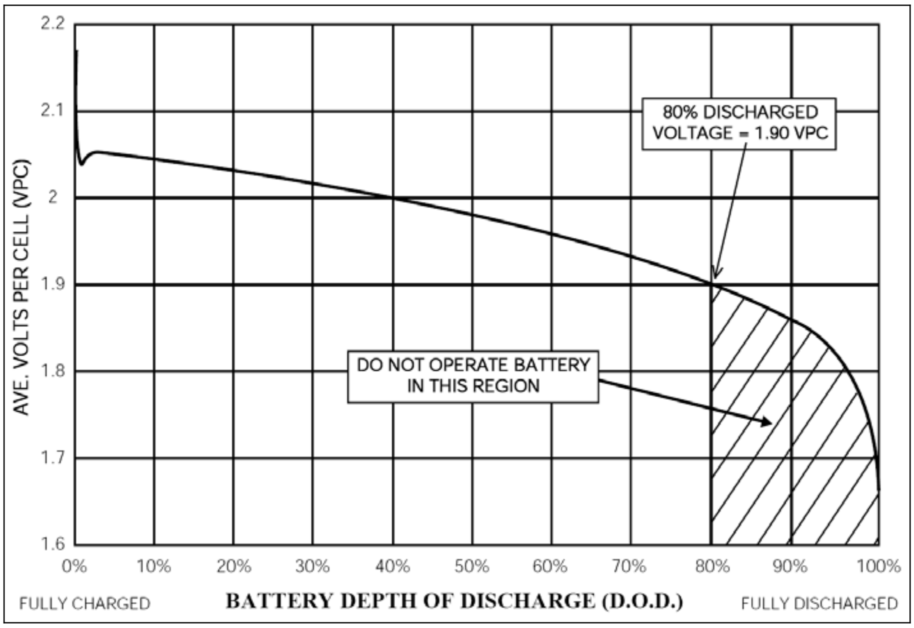



**Figure 4-40: Typical discharge curve of a lead-acid battery.**
**Source: G.N.B. Technologies, www.gnb.com**

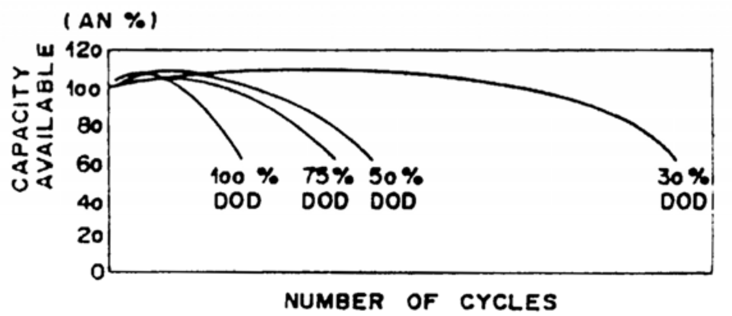



**Figure 4-41: Cycle service life in relation to the average**
**Depth of Discharge (DOD). Source: [GATE_92a]**

It becomes visible, that using only 50% of the theoretically available battery capacity increases lifetime by a factor of two. Keeping the battery at a level of at least 70% SOC (using only maximum of 30% of battery capacity) results in a lifetime that is 3 to 4 times longer. These values are promising, but one should not forget, that people want to make "best use" of their battery and of course want to get as much energy out of their batter as possible. Surely they wound not be too happy if somebody told them that they should only get 30% of the energy out of their battery because it would increase their battery lifetime.

Nevertheless, prolonging the lifetime of the battery has a significant impact on the system costs. As explained before, the purchase of batteries in a rural pre-electrification scheme represents a considerable amount of the total investment and respectively running costs. Therefore the proper handling of batteries and an appropriate deep-discharge protection are essential for the economic sustainability of this kind of project.

A technical solution for the problem of "discharge control" is shown in the next part of the study, but one should not forget that even the best technical solution has no success if the awareness of the consumer and/or user is not raised towards the importance of the issue.

As an example: The user of a battery will always try to draw as much energy from it than possible. He will find ways to bypass an incorporated deep-discharge protection and he will connect consumers that are convenient and comfortable for him regardless whether they are energy efficiency or suitable for battery operation. Education and awareness creation can help to make users understand that this behaviour creates considerable costs in the medium and long run. It is important to create awareness amongst all user and consumer and to convince them that they will profit from considerate and careful treatment of their batteries in future.

## Technical Discharge Protection

From the technical point of view the design and the manufacturing of a device for the automatic disconnection of the load when the battery reaches a low capacity level is no problem.

The capacity level of a battery can easily be approximated by measuring the battery voltage at the terminals. If the voltage falls below a predefined level all consumers are automatically disconnected by a relay. Today, sophisticated electronic controllers exist which also take the actual discharge current into account and vary the disconnection or threshold voltage correspondingly. For the objective of this study, sophisticated devices are not necessary. Cost and effects should always be seen in parallel and one should keep in mind that the most sophisticated solution might not be the most suitable especially when it comes to rural energy supply.

The next picture shows the general functioning of a simple and low-cost "deep discharge protection".

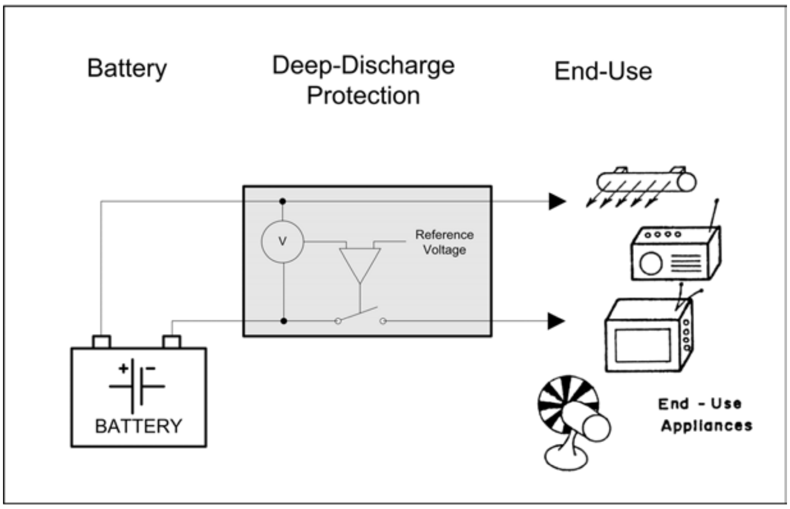



**Figure 4-42: Schematic representation of a deep discharge protection.**

The deep discharge protection device basically consists of something like a "volt meter" which is constantly measuring the voltage of the battery. If the battery voltage is falls below a predefined reference voltage a switch or relay is activated which disconnects all loads from the battery.

Technically it will be possible to incorporate the deep-discharge protection device into a very small and lightweight box. Optionally this box could contain also a number of indicator lamps which show the current state of capacity of the battery.
This would be very useful for the user, as he can see how much energy is left in the battery and therefore has some "warning" before the battery is finally automatically disconnected by the deep-discharge protection.

Of course, people will always want to make "best" and "longest" use of their battery. They will try to squeeze the last bit of energy out of their batteries and it would be very likely that they would try to bypass a deep-discharge protection to make use of the full 100% battery capacity.

Besides education programmes and awareness building also technical solutions can be applied to solve this problem. One approach would be to integrate the deep-discharge protection into the battery casing or permanently connect it to the battery in a way that makes access to the battery poles impossible.
Deep discharge Protection devices could be put on top of each battery of the "charging community" and even could be sealed to make tampering impossible without being recognized from the operators of the charging station.

Possible consumers could be connected to this "box" by an incorporated plug or connector system. A proper connector system would also help to avoid the frequently occurring problems of bad wiring. By introducing a diode and/or a fuse into the "deep discharge protection box" the risk of shortcuts can be absolutely minimized.

Another feature of such a deep discharge device could also be a current limiter, which allows only a predefined current to be discharged. This might seem like a drastic measure, but it would maximise the lifetime of the battery and at the same time would lead the consumers to the use of energy efficient devices. Furthermore, the charging cycles might be prolonged which would in return give the possibility to serve more customers.

## Conclusion

The aim of this thesis project was to develop a simple, save and cost effective possibility to bring basic energy services to rural areas in developing countries by using available hydropower resources. Using hydropower in a central "energy station" to charge batteries and to provide other central energy services like telecommunication, refrigeration and entertainment can be an economically sustainable way to do so. These central "energy stations" can not only be a solution for Indonesia, where this study was performed, but could be an option for many regions worldwide.

Different management options have been discussed in the curse of this study and it became more and more clear that handling and maintenance of the batteries is "the" most critical factor when introducing any pre-electrification scheme. On the one hand, collectively owned batteries have several advantages when it comes to topics like battery quality, maintenance, bulk purchase or reselling capabilities. On the other hand, purchasing batteries for a whole village can be a big challenge and often doubles the total investment costs of the system.

Economically and technically, the installation and the management of a charging station can be easily handled by a well organised village community and a well trained operator. Charging fees will have to be collected from every user to ensure sustainability. The fees should cover the investment costs of the system and also should provide enough funds for possible repair measures. In a well managed system there is a good chance that the operator even might earn some money. Some rather conservative economic calculations resulted in yearly energy costs of around 60 US$ to 70 US$ for an average user. This value is very competitive, especially when compared to other traditional sources of energy like kerosene, candles or conventional "one-way" batteries.

A battery charging station using hydropower can also be technically feasible. The use of basic, locally produced equipment would be absolutely sufficient since there are no big demands on the quality of the produced energy. A problem that remains is the uncontrolled deep-discharge of batteries which often occurs and significantly reduces the lifetime of any lead-acid battery. Here a so called "deep-discharge protection", permanently attached to every battery, could help.

As an overall conclusion one can say that "Central Energy Stations" could be a promising alternative for regions were no grid will be installed in the foreseeable future. Certainly, only the basic energy needs will be served by this kind of "electrification", but battery power can bring light and communication to remote areas and could play an important role in improving the life of many people around the globe.

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