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# Mini hydropower for increasing access to energy in Tanzania

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# Abstract

The UN Millennium Development Goal of eradicating extreme poverty will not be achieved unless substantial progress is made on improving energy access. To meet the goal by 2015, an additional 395 million people need to be provided with electricity and 1 billion with access to clean cooking facilities. Access to modern forms of energy is strictly related to income levels because allows lighting, mechanical power, transport and telecommunication services, besides it's essential for the provision of clean water, sanitation, health care and indoor cooking.

Tanzania, located in the East Africa, well represents this 'lack of energy' situation. Due to its tropical climate, rivers and lakes abundance, Tanzania has the largest hydropower potential in East African Community with about 5 GW, of which only about 10% are tapped. Potential small scale hydropower sites are situated in remote isolated areas and their development is expected to serve as an engine towards economical and social development of the remote communities which are currently supplied by isolated diesel powered stations. The government underscores the advantages of investing in hydro electricity generation only for those sites which have been evaluated and proved to be viable.

The tanzanian 'Dar Es Salaam Institute of Technology' is working on undertaking pre-feasability studies on a number of rivers in the Southern Highlands of Tanzania, but they are still improving their building capacity, requesting the cooperation of 'Politecnico di Milano' to achieve it.

To enable potential developers to quick take-off and build the earmarked sites, a model for mini hydropower plant sizing has been developed in the form of the software *Mini hydro plants simulator*, based on *Microsoft excel 2007* ®. The software makes use of some input data, obtainable by a single survey on the desired location, to generate an optimization of the installed electrical power, that best fits the features of both the river and the connected utilities, and an exhaustive economic analysis of the investment. The difficulty in obtaining components costs from worldwide and local suppliers, and the lack of detailed hydrological data for the rivers in analisys, have been the hardest tasks. During the time spent in Tanzania the model has grown taking information from the local contest and finally has been tested upon the Madunda power plant, a mini hydro installation recently built by the italian NGO ACRA. Moreover the software has been built attempting to make it as user friendly as possible.

It is hoped that these tools can lead to increase hydropower production in the country and at the same time improve rural areas access to electricity, involving in the project the DIT, sponsoring societies and tanzanian government.

**Keywords:** Mini hydropower, MHP, Access to energy, Rural electrification, Run-

of-river plant sizing, Tanzania.

**Conventions:** All the numbers included in the thesis are shown with comma "," as decimal separator. Units of measure and acronyms are written in *italic* style.

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## Parte I

### Accesso all'energia

Il Programma per lo Sviluppo delle Nazioni Unite (UNDP) ha posto come primo tra gli obiettivi del millennio lo sradicamento della povertà estrema e della fame nel mondo. Come primo passo per conseguire tale obiettivo è stata identificata la necessità di aumentare l'accesso all'energia elettrica e a sistemi moderni e puliti per provvedere alle necessità alimentari. Infatti è un dato allarmante che nel nostro secolo 1,4 miliardi di persone vivano senza accesso all'elettricità, localizzate principalmente nelle aree rurali. Inoltre 2,7 miliardi basano la loro sussistenza sull'utilizzo non controllato di biomassa, col principale effetto di una elevata incidenza di morti per intossicamento o malattie respiratorie.

In questo contesto la tecnologia mini idroelettrica si pone come una soluzione economicamente sostenibile, con elevata penetrazione negli ambienti rurali. Inoltre molti paesi in via di sviluppo possiedono abbondanti potenzialità, con la possibilità di elettrificare in breve tempo ampie fette di popolazione.

### Obiettivi della tesi

- Creare un modello che partendo da un primo studio di fattibilità, sia capace di fornire un dimensionamento di massima dell'impianto ed effettuare l'analisi economica dell'investimento.

- Rendere tale modello accessibile e fruibile dallo staff del Dar Es Salaam Institute of Technology (DIT), in modo che cooperando con il governo Tanzanese e altri enti locali operanti nell'ambito dell'energia e dello sviluppo, ne faccia uno strumento per promuovere l'elettrificazione delle aree rurali del Paese.

- Condurre una analisi della situazione energetica della Tanzania, per meglio comprenderne le necessità, i problemi e i punti di forza, con attenzione alle aree rurali.

- Rispondere alla richiesta del DIT di condurre una analisi tecnico-economica sui principali siti di interesse da loro individuati, situati principalmente nella Tanzania sud-occidentale. Come principale obiettivo di ogni analisi si pone la verifica dell'auto-sostenibilità economica del progetto stesso, non essendo presente un programma statale di sostegno all'elettrificazione rurale.

- Portare avanti il progetto di cooperazione tra il Politecnico di Milano e il DIT, iniziato nell'Agosto 2007.

## Outlook della Tanzania

Il territorio tanzanese è localizzato nell'emisfero australe, in prossimità della linea equatoriale, si affaccia sull'Oceano Indiano e gode di un clima tropicale, caldo e umido sulla zona costiera, temperato nell'altopiano centrale. Il territorio è racchiuso tra il monte Kilimanjaro e i grandi laghi Vittoria, Tanganyika e Malawi, assicurando un ecosistema ricco e verdeggiante che alterna savana, foresta tropicale e ampie zone coltivate, ricco di fauna e famoso per i parchi nazionali del Serengeti e del cratere di Ngorongoro.

La Repubblica Unita di Tanzania nacque nel 1964 dall'unione di Tanganyika e Zanzibar, dopo che il Tanganyika ottenne l'indipendenza dal governo britannico tramite una transizione diplomatica nel 1961, con Julius Nyerere a capo del neonato governo. La Tanzania fa parte dell'East African Community con Kenya, Uganda, Rwanda e Burundi.

Nel 2010 la popolazione della Tanzania contava 32,6 milioni di persone nelle zone rurali e 11,4 abitanti nelle zone urbane, con tasso di crescita medio del 3%. Il PIL pro-capite si attesta sul valore di 532 $USD/capita$ contro i 35150 $USD/capita$ italiani. L'Indice di Sviluppo Umano (HDI) posiziona la Tanzania al 152esimo posto su 187 paesi, con un valore di 0,466 contro il valore 0,874 dell'Italia, che si trova invece al 24esimo posto nella graduatoria mondiale.

## Situazione energetica della tanzania

L'analisi energetica del Paese è stata condotta secondo lo schema proposto dall'Agenzia Internazionale dell'Energia Atomica (IAEA), che ha definito gli Indicatori Energetici per lo Sviluppo Sostenibile (EISD) divisi nelle dimensioni: Sociale, Economica e Ambientale.

In Tanzania solo il 13,9% della popolazione ha accesso all'elettricità, contro una media mondiale del 74%, mentre l'accesso ai combustibili moderni per uso domestico si attesta al 3% della popolazione. L'Indice di Sviluppo Energetico (EDI), che riassume il ruolo dell'energia nello sviluppo umano, assume il valore di 0,022, posizionando la Tanzania al 60esimo posto su un totale di 64 paesi in via di sviluppo. La Domanda Totale di Energia Primaria (TPES) assume il valore di 19,62 $Mtoe$, delle quali la biomassa primitiva, costituita da legna e carbone da legna, copre circa l'88%. Il rimanente è dominato dai prodotti petroliferi di importazione, mentre l'impatto della fonte idroelettrica si limita all'1,2% dell'energia primaria.

Le risorse energetiche naturali del Paese sono limitate e in gran parte non sfruttate. Si stima un buon potenziale di estrazione del carbone, ma attualmente è in funzione una sola miniera. Sono stati individuati diversi giacimenti di gas naturale, due dei quali sono attualmente sfruttati. Hanno invece dato esiti negativi le campagne di ricerca di giacimenti petroliferi, rendendo il Paese completamente dipendente dall'importazione. Esistono infine giacimenti accertati di uranio, che stanno attraendo le attenzioni di compagnie straniere. La disposizione geografica della Tanzania in prossimità dell'equatore, l'abbondanza di corsi d'acqua, e il clima estremamente favorevole all'agricoltura, offrono ampie potenzialità di sviluppo per tecnologie energetiche rinnovabili. Risulta particolarmente interessante l'applicazione di tecnologie avanzate per: generare energia elettrica a partire dagli scarti dell'industria agricola, sinterizzare biocombustibili da coltivazioni adhoc, sfruttare l'intensa e costante radiazione solare per generazione elettrica distribuita. Inoltre nelle zone interne e remote del Paese sono presenti abbondanti potenzialità per lo sfruttamento dell'energia eolica e idroelettrica, con tecnologie convenzionali.

Il mercato elettrico è dominato dall'organizzazione statale TANESCO che si occupa di generazione, trasmissione e distribuzione dell'energia elettrica. Il parco di generazione della Tanzania conta 1092 $MW$ collegati alla rete nazionale, con una penetrazione dell'idroelettrico del 51%. L'assenza di un mercato libero dell'energia ostacola lo sviluppo e gli investimenti nel settore, con conseguente insufficienza energetica della fornitura e frequenti interruzioni del servizio; limitando di fatto lo sviluppo economico del Paese.

# Parte II

## Schema di impianto mini idroelettrico

Esistono diversi standard che fissano il limite di potenza degli impianti mini idroelettrici, ma in accordo con lo studio effettuato dall'European Small Hydropower Association (ESHA), è stato assunto il valore di 10 $MW$. Le possibili configurazioni di impianto si dividono in:

- Impianto ad acqua fluente, nel quale una traversa devia parte della portata del fiume verso il canale e il gruppo di generazione, mentre la portate rimanente scavalca la traversa stessa, seguendo il corso naturale del fiume. Tale configurazione non prevede l'accumulo dell'acqua, è pertanto l'andamento della portata che regola i ritmi di generazione dell'energia elettrica.

- Impianto su diga esistente, nel quale una macchina viene posta a piede di diga o con configurazione a sifone, sfruttando la presenza di un bacino preesistente.

- Schema integrato all'interno di un canale, dove la turbina viene alloggiata all'interno di un canale appositamente adattato, per ottenere un beneficio energetico.

## Valutazione della portata del fiume

La portata del fiume è il primo parametro di interesse quando si affronta la progettazione di un impianto idroelettrico. Esistono associazioni che raccolgono dati di portate di fiumi e torrenti, per promuovere lo sfruttamento efficiente delle risorse idriche, come la World Meteorological Organisation (WMO) e la Food and Agriculture Organization (FAO).

Quando tali dati non sono disponibili, si rende necessario svolgere una campagna di misura delle portate del corso d'acqua. Tale campagna necessita la costruzione di una stazione di misurazione che registri i dati acquisiti per un periodo complessivo di almeno un anno, per ottenere una accettabile previsione delle portate future. Qualora non fosse possibile svolgere tali campagne di misura, si può fare ricorso a metodi di stima dell'andamento delle portate, che restituiscono valori approssimati.

I valori così ottenuti vengono dapprima organizzati nella forma dell'idrogramma, che raccoglie cronologicamente le misurazioni, e successivamente nella forma della curva delle durate (FDC) che riorganizza le misurazioni in ordine decrescente di portata.

La prevalenza del fiume è indice dell'energia potenziale disponibile, indica la differenza di quota tra il livello dell'acqua nel punto di presa e nel punto di restituzione. Può essere misurata tramite diverse tecniche, attualmente la più semplice e affermata è la misurazione tramite sistema GPS durante i rilievi sul sito.

## Strutture idrauliche

- Diga o traversa: si inserisce nel letto del fiume, creando un bacino (diga) o innalzando la prevalenza ma senza arrestarne il corso (traversa).
- Opera di presa: deriva l'acqua necessaria ad alimentare la turbina, blocca i detriti trasportati dal fiume e permette la regolazione del flusso.
- Canale: convoglia l'acqua a pressione atmosferica dalla presa alla vasca di carico.
- Condotta forzata: convoglia l'acqua sotto pressione, con elevata pendenza, dalla vasca di carico all'ingresso della turbina.
- Edificio della centrale: ospita e protegge il gruppo di generazione e i suoi sistemi ancillari.

## Equipaggiamento elettromeccanico

- Turbine: le turbine ad azione includono: Pelton adatte ad alte prevalenze, Turgo simili alle Pelton ma costruttivamente più semplici e adatte a basse portate, e le Cross-Flow che presentano il vantaggio di essere semplici ed economiche. Le turbine a reazione includono: Francis adatte a prevalenze medie e facilmente reperibili, Kaplan adatte a basse prevalenze e capaci di mantenere un'alta efficienza al variare del carico, e Coclea robuste ed economiche, adatte a salti di pochi metri.

- Generatori: i generatori sincroni presentano il vantaggio di potersi avviare autonomamente in assenza di alimentazione elettrica da parte della rete, sono pertanto adatti ad applicazioni off-grid. I generatori asincroni sono più economici, resistenti e richiedono minore manutenzione, tuttavia offrono minori prestazioni e presentano problemi di avviamento in mancanza di corrente di eccitazione da fonte esterna.

- Sistema di controllo: nei sistemi isolati di potenza superiore ai 100 $kW$, si utilizza un sistema di controllo a regolazione di velocità, che tende a mantenere costante la frequenza della macchina, variando l'apertura della valvola di ammissione dell'acqua ed eventualmente scollegando i carichi.

- Rete di trasmissione: l'allacciamento alla rete nazionale tramite l'estensione di un ramo è la soluzione che presenta i maggiori vantaggi in termini tecnici, tuttavia il trade-off economico tra il costo del collegamento e i benefici di dispacciamento, può portare alla scelta di realizzare una rete locale tra l'edificio della centrale e le utenze vicine.

# Parte III

## Progetto dell'impianto

Ogni sito può presentare una configurazione del terreno adatta a un progetto specifico dell'impianto idroelettrico. Tuttavia, per creare un modello applicabile a diversi siti, si è scelto di utilizzare uno schema standard del tipo ad acqua fluente, composto dalle seguenti parti, divise a loro volta in componenti:

- Gruppo di generazione: composto da uno o più gruppi turbina, ogni gruppo turbina include la turbina, l'alternatore e il sistema di regolazione.

- Equipaggiamento elettrico: include il trasformatore elevatore, la linea di trasmissione e i trasformatori abbassatori in prossimità delle utenze.

- Traversa e opera di presa: include la traversa, i muri di protezione della stessa, la struttura di convogliamento dotata di serranda di regolazione e griglia, la struttura di deposizione dei detriti.

- Canale e condotta forzata: include il canale di convogliamento, la vasca di carico, una o più condotte forzate e l'edificio della centrale.

Per rendere accessibile l'esposizione del modello, i parametri utilizzati nelle funzioni e negli algoritmi sono stati raccolti assieme al proprio acronimo in una tabella. Inoltre ogni capitolo è preceduto da un diagramma di flusso che esplicita graficamente i principali passi logici alla base dei calcoli in esso contenuti.

### Caratteristiche del fiume

L'idrogramma si presenta con una discretizzazione mensile, dovuta all'assenza di dati giornalieri per i siti di interesse. Per andare incontro alla carenza di dati, è stato sviluppato un algoritmo in gradi di stimare l'andamento delle portate avendo come dati di input la portata minima e massima del fiume, ottenute tramite singola misurazione durante due distinti rilievi, e la distribuzione annuale delle precipitazioni della zona.

La perdita di carico attraverso i vari componenti dell'impianto (canale, griglie, struttura di convogliamento e condotta forzata) viene imposta come percentuale della prevalenza lorda.

### Dimensionamento del gruppo di generazione

Il dimensionamento dell'intero impianto è stato ricondotto alla potenza nominale del gruppo di generazione, scelta come parametro libero di ottimizzazione. La scelta del tipo di turbina adatta all'impianto viene effettuata sulla base dell'esperienza, confrontando le caratteristiche del sito di interesse con quelli esistenti, raccolti in un database. Il rendimento idraulico delle diverse macchine e l'andamento di tale rendimento in funzione della portata turbinata sono stati ottenuti dalla teoria (ESHA) per macchine allo stato dell'arte, si prevede infatti di utilizzare turbine importate dall'Europa, non essendo esistenti produttori locali. Vengono dapprima calcolati, tramite formule empiriche, alcuni parametri tecnici relativi alla turbina, come la velocità di rotazione, le dimensioni del rotore e l'altezza di aspirazione necessaria ad evitare fenomeni di cavitazione. Quindi, dalla potenza nominale del gruppo, viene calcolata la portata nominale necessaria ad azionare le macchine.

### Dimensionamento dell'equipaggiamento elettrico

Per l'equipaggiamento elettrico sono stati utilizzati componenti standard quali trasformatori e linea di trasmissione di media tensione (11 $kW$), resi disponibili da produttori locali.

### Dimensionamento della traversa e dell'opera di presa

Il dimensionamento della traversa rispetta i parametri di sicurezza al fine di impedire il collasso della struttura sotto la spinta idrostatica dell'acqua, anche a fronte di situazioni critiche come una inondazione. Il dimensionamento ottenuto per la traversa e gli altri componenti è una approssimazione e trascura numerosi accorgimenti che possono rendersi necessari in un caso reale, tuttavia fornisce una indicazione di massima abbastanza accurata da permetterne una stima del costo.

Strutture ancillari quali griglie, serranda e struttura di deposizione dei detriti, vengono dimensionate al fine di proteggere la macchina dalle inondazioni e dai detriti trasportati dall'acqua durante il normale funzionamento dell'impianto.

### Dimensionamento del canale e della condotta forzata

Il canale viene dimensionato per permettere all'acqua richiesta dal gruppo di generazione di confluire dall'opera di presa alla vasca di carico; il calcolo considera dunque la forma del canale, la rugosità della sua superficie e l'inclinazione media. La vasca di carico è invece dimensionata per permettere la continuità del servizio a fronte di brevi variazioni o interruzioni dell'approvvigionamento dovute alla movimentazione degli organi di controllo. Infine il diametro della condotta forzata è calcolato considerando il vincolo imposto in fase di progetto delle perdite di carico desiderate lungo il percorso dell'acqua dalla traversa all'ingresso della turbina.

### Produttività della centrale idroelettrica

La produttività viene calcolata su base mensile, seguendo la distribuzione dell'idrogramma. la produttività tiene conto della portata d'acqua disponibile in ogni periodo, una volta assicurato un deflusso minimo vitale, della prevalenza disponibile, essendo la prevalenza variabile con la quantità di acqua che scavalca la traversa, e in particolare del rendimento equivalente del gruppo di generazione in funzione della portata totale turbinata. Al fine di calcolare tale rendimento è stato implementato un algoritmo capace di calcolare il rendimento equivalente di un gruppo di generazione formato da più turbine, in modo da poter introdurre nel modello la possibilità di simulare l'utilizzo di più macchine in parallelo, ottenendo una curva di rendimento più regolare e attestata su valori elevati anche a fronte di forti variazioni di portata.

### Costi della centrale idroelettrica

La determinazione dei costi dei componenti dell'impianto segue due metodologie differenti a seconda del tipo di componente.

La metodologia della funzione di costo si applica a componenti complessi, prodotti in officina, trasportati in loco e assemblati. Tali componenti sono: gruppo turbina, trasformatori, linea di trasmissione e condotta forzata. Per la sua flessibilità, adattabilità e intuitività è stata scelta la forma della funzione potenza, che lega il costo o il costo specifico di un componente a parametri propri del sito o dell'impianto. Ad esempio la funzione di costo che restituisce il costo specifico della turbina è funzione del tipo di turbina, della prevalenza netta avvertita dalla macchina e della sua potenza elettrica nominale. La determinazione dei coefficienti di tali funzioni di costo è stata condotta adattando la funzione a database di costi esistenti. Adattando le funzioni di costo a database più ampi o più aggiornati di quelli finora utilizzati sarà possibile incrementare l'affidabilità delle stime ottenute tramite tali funzioni, facendo di questo aspetto uno dei punti aperti al miglioramento futuro del modello.

La metodologia del costo specifico dei materiali di costruzione si applica ai componenti costruiti in loco tramite operazioni edili quali: scavi, deposizione di rivestimenti e costruzione di strutture in calcestruzzo. A tale categoria appertengono:

struttura della traversa, opera di presa, canale e vasca di carico, edificio della centrale. La determinazione del costo di tali componenti passa attraverso la scelta del loro materiale costitutivo, il conseguente dimensionamento, e il calcolo del costo totale del materiale di costruzione, inclusivo della messa in opera della struttura stessa. Per questa categoria i costi specifici utilizzati si rifanno a produttori locali della Tanzania.

## Utenze

Come ultimo tassello prima dell'analisi economica viene introdotto il limite delle utenze. Essendo che l'impianto ad acqua fluente è privo di capacità di accumulo e molti siti presentano una configurazione off-grid, l'energia elettrica generata deve essere istantaneamente utilizzata e valorizzata. Pertanto la stima della capacità di assorbimento delle utenze allacciate e la stima della loro disponibilità a pagare (aspetto critico nelle zone rurali) devono essere considerate per portare a termine una analisi affidabile della redditività dell'impianto idroelettrico. A tale scopo sono state introdotte due alternative di contratto. La prima, ufficiale, prevede l'installazione di contatori per ogni utenza, che misurino l'energia consumata e la valorizzino secondo le tariffe nazionali. La seconda alternativa, attualmente utilizzata solamente da ONG, prevede un contratto che valorizzi l'allacciamento alla rete locale nella forma di un abbonamento annuale, e tariffe determinate sulla base della disponibilità economica degli utenti.

## Analisi economica

L'analisi economica raccoglie i dati di costo dei vari componenti ottenendo un costo di investimento dell'impianto. Successivamente, tramite una stima dei costi annuali di manutenzione e il calcolo dei ricavi generati, calcola i seguenti indici economici: Net Present Value, Pay Back Time, Levelized Cost of Energy, Internal Rate of Return.

## Sviluppo del software

Il modello è stato quindi implementato nel programma *Mini hydro plants simulator* sviluppato in *Microsoft excel 2007 ®*. Il programma è diviso in cinque fogli: Informazioni sul sito, Informazioni sulla turbina, Informazioni sull'impianto, Analisi economica, Simulazione. La struttura logica facilita la comprensione e l'utilizzo, dividendo ogni foglio nelle sezioni: Dati di input, Dati da altri fogli, Dati dalla teoria, Calcoli, Output del foglio.

Il generico utente del programma si limita ad inserire i dati di interesse nella sezione Dati di input di ogni foglio, e avvalendosi delle opportune Macro per svolgere i calcoli, legge i risultati nella sezione Dati di output; le altre sezioni possono infatti rimanere nascoste all'utente inesperto, rendendo il programma di semplice utilizzo.

Per ottimizzare la potenza nominale del gruppo di generazione sulle caratteristiche del sito di interesse, è stata implementata la Macro Simulation che scorre un range di 100 valori di potenza, delimitato dalle necessità delle utenze, calcolando per ogni valore i principali parametri tecnici ed economici dell'impianto. Tali parametri sono: ore equivalenti, ore operative, fattore di carico dell'impianto, produttività annuale, costo di investimento, NPV, PBT, LEC e IRR. Tali valori vengono quindi memorizzati in un database e mostrati graficamente in funzione della potenza nominale del gruppo di generazione, individuando quindi la zona di ottimizzazione dell'impianto.

Una volta effettuata la scelta di ottimizzare l'uno o l'altro parametro di interesse, il software *Mini hydro plants simulator* restituisce in una dettagliata analisi tecnico-economica il costo e le caratteristiche principali di ogni componente dell'impianto. Inoltre presenta i disegni quotati dei componenti appartenenti alle opere idrauliche come la traversa, l'opera di presa, il canale, l'edificio della centrale, ecc.

# Parte IV

## Validazione del modello sulla centrale di Madunda

La validazione del modello è stata effettuata tramite una simulazione sulla centrale esistente di Madunda, localizzata nella regione di Iringa e finanziata dalla ONG italiana ACRA. Si sono confrontati i risultati dell'analisi economica svolta dal software con i reali dati di costo sostenuti e resi disponibili da ACRA. Inoltre sono state confrontate le dimensioni dell'edificio della centrale e della condotta forzata ottenute come output dal software con quelle delle componenti reali. I risultati ottenuti sono soddisfacenti, con una variazione del 16% tra il costo totale della centrale reale e quella simulata. Anche la distribuzione del costo tra i vari componenti risulta in prima approssimazione rispettata. La più grande differenza è stata riscontrata nel costo dei trasformatori che, mentre nella simulazione contribuiscono al 12% del costo totale, pesano per solo il 7% nel report ACRA. Il gap tra i due valori è spiegabile considerando che la centrale di Madunda utilizza per la maggior parte trasformatori usati recuperati in Italia dalla ONG, decisamente più economici di quelli prodotti localmente, che richiedono l'importazione di diverse materie prime.

## Makete nel distretto di Ijangala

Si è scelto di simulare quattro dei nove siti potenziali selezionati. Makete è considerato il sito più importante poichè la progettazione, da parte del DIT e della REA è già iniziata. Per ogni sito sono state simulate diverse configurazioni, selezionando infine la più redditizia. Ogni configurazione si distingue nel numero di utenze connesse e quindi nella lunghezza della linea di trasmissione, nel tipo e numero di turbine installate o nel tipo di contratto imposto alle utenze. Conoscendo la portata massima e minima, registrate dallo staff del DIT durante i rilievi, e le precipitazioni della zona, è stato possibile calcolare l'andamento della portata del fiume durante l'anno (idrogramma) e la relativa curva delle durate. Durante i rilievi il DIT ha anche raccolto le coordinate GPS delle possibili posizioni di traversa, vasca di carico, edificio della centrale e punti di allacciamento delle utenze, da cui è stato possibile, tramite l'utilizzo del software *Map Info Pro* ®, calcolare le lunghezze di canale, condotta forzata e linea di trasmissione. La potenza richiesta dalle varie utenze è stata stimata dallo staff del DIT.

Nella prima configurazione si è previsto di collegare solo le utenze principali. Il potenziale del fiume viene sfruttato solo in piccola parte, e i ricavi ottenuti dal limitato numero di utenze non sono sufficienti per sostenere l'investimento, che risulta economicamente infattibile.

Si è deciso quindi di analizzare una seconda configurazione con un maggior il numero di utenze, allacciando anche due villaggi vicini, in modo da sfruttare maggiormente le potenzialità del fiume e aumentare la quantita di energia elettrica prodotta. La simulazione in questo caso restituisce un valore della potenza nominale del gruppo di 340 $kW$, che massimizza l'IRR dell'investimento. Il costo specifico della centrale diminuisce da 6103 $USD/kW$ (prima configurazione) a 3990 $USD/kW$ mentre l'IRR aumenta da 3,08% a 12,78% rendendo la seconda configurazione vincente.

Nella terza e ultima configurazione è stato simulato l'allacciamento alla linea di trasmissione nazionale, in modo da poter sfruttare a pieno le potenzialità del fiume immettendo gli eccessi di energia prodotta in rete ed evitare problemi di interruzione del servizio dovuti a scarsità d'acqua. Il valore di 500 $kW$ trovato dal software massimizza tutti i parametri economici dell'investimento. Il costo specifico risulta maggiore della seconda configurazione con un valore di 4550 $USD/kW$ mentre l'IRR diminuisce a 8,21%. La terza configurazione, pur risultando meno redditizia rispetto alla seconda, è preferibile poichè, garantendo l'accesso all'elettricità a un elevato numero di persone, risponde al piano nazionale di elettrificazione rurale voluto dal governo della Tanzania.

## Applicazione su altri siti

- Madaba: le prime configurazioni di questo sito si caratterizzano per tre possibili posizioni della powerhouse che comportano diverse lunghezze della condotta forzata. Le prime due offrono una prevalenza di 160 $m$ e 120 $m$ rispettivamente, quindi vincolano l'utilizzo di turbine Pelton, mentra la terza configurazione, con un salto di 80 $m$, permette di utilizzare anche una turbina Francis. Dalle tre simulazioni si evince che la prima risulta migliore con una potenza del gruppo di 568 $kW$ a cui corrispondono un IRR del 26% e un NPV di circa 2,5 milioni di dollari. Dato l'elevato valore dell'IRR è stato possibile effettuare una quarta simulazione identica alla prima, ma con tariffe più basse. In particolare è stato utilizzato un contratto ad allacciamento in $USD/kW$, decisamente più economico della tariffa a consumo utilizzata nella prima configurazione. Come risultato l'IRR si attesta all'8%, tuttavia tariffe più basse rendono il servizio economicamente accessibile anche alle famiglie povere.

- Macheke: le due simulazioni effettuate per questo sito differiscono per le posizioni di vasca di carico ed edificio della centrale. La prima configurazione risulta economicamente migliore ma durante i rilievi sono stati evidenziati possibili problemi di cedimento del terreno e allagamenti nei periodi di piena del fiume. Se tali problemi verranno confermate in futuri rilievi, la scelta della seconda configurazione diverrà quindi obbligata.

- Mpando: in questo caso è stata eseguita una sola simulazione poichè un'unica possibile configurazione è stata identificata durante i rilievi. Si è verificato che le utenze connesse sfruttano al massimo il potenziale del fiume, rendendo superflua una eventuale connessione dell'impianto alla linea di trasmissione nazionale, presente nelle vicinanze.

## Conclusioni

- Il modello implementato nel software *Mini hydro plants simulator* risponde alle richieste avanzate dal personale del DIT che ne ha inizialmente proposto lo sviluppo.

- Per rendere il software fruibile e aperto a futuri aggiornamenti è stata realizzata una Guida per l'Utente, inoltre il materiale informatico e la documentazione completa saranno resi disponibili al Dar Es Salaam Institute of Technology, attualmente in cooperazione con la Rural Energy Agency (REA) operante in Tanzania.

- Lo studio della situazione energetica della Tanzania e in particolare l'esperienza di due mesi trascorsa nel Paese hanno permesso una maggiore comprensione delle problematiche affrontate in paesi in via di sviluppo, permettendo di superarle seppure con qualche limitazione.

- L'analisi tecnico-economica effettuata su quattro dei siti analizzati, per i quali la taglia dell'impianto è stata ottimizzata sulle specifiche del sito, ha mostrato che tali investimenti risulterebbero economicamente auto-sostenibili.

# Part I.

# Introduction

# 1. Access to energy

It's an alarming fact that, in $21^{st}$ century, there are still billions of people without access to electricity or clean cooking facilities. The ambitious goal that have been set to eradicate extreme poverty can never be fully realized without acknowledging and confronting this fact [UNDP2].

The 2010 edition of the "World Energy Outlook" (WEO) by IEA assesses two indicators of energy poverty at the household level: the lack of access to electricity and the reliance on the traditional use of biomass for cooking. In Sub-Saharan Africa the electrification rate is 31% and the number of people relying on the traditional use of biomass 80%: this is where the greatest challenge lies.

Today, there are 1,4 billion people around the world that lack access to electricity, some 85% of them in rural areas. Without additional dedicated policies, by 2030 the number of people drops, but only to 1,2 billion. The number of people relying on the traditional use of biomass is projected to rise from 2,7 billion today to 2,8 billion in 2030. This biomass is burnt in non-conventional cooking devices, resulting in increased indoor air pollution, and growth of premature deaths [IEA1].

Addressing these inequities depends upon international recognition that the projected situation is intolerable, a commitment to effect the necessary change, and setting targets and indicators to monitor progress.

The UN Millennium Development Goal of eradicating extreme poverty by 2015 will not be achieved unless substantial progress is made on improving energy access. To meet the goal by 2015, an additional 395 million people need to be provided with electricity and an additional 1 billion provided with access to clean cooking facilities. This will require annual investment in 2010-2015 of 41 billion $USD$, or only 0,06% of global GDP.

To meet the more ambitious target of achieving universal access to modern energy services by 2030, additional investment of 756 billion $USD$, or 36 billion $USD$ per year, is required. This is less than 3% of the global energy investment projected in the New Policies Scenario to 2030. The resulting increase in primary energy demand and CO2 emissions would be modest. In 2030, global electricity generation would be 2,9% higher, oil demand would have risen less than 1% and CO2 emissions would be 0,8% higher, compared to the New Policies Scenario.

Access to modern forms of energy is essential for the provision of clean water, sanitation and healthcare and provides great benefits to development through the provision of reliable and efficient lighting, heating, cooking, mechanical power, transport and telecommunication services. The international community has long been aware of the close correlation between income levels and access to modern energy: not surprisingly, countries with a large proportion of the population living on an income of less than 2 $USD$ per day tend to have low electrification rates and a high proportion of the population relying on traditional biomass. As incomes increase, access to electricity rises at a faster rate than access to modern cooking fuels, largely because governments give higher priority to electrification, though access to both electricity and clean cooking facilities is essential to success in eradicating the worst effects of poverty and putting poor communities on the path to development.

The adverse consequences of the use of traditional forms of energy on health, economic development and the environment are well illustrated by the example of the use of biomass in non-conventional cooking devices. Currently, devices for cooking with biomass are mostly three-stone fires, traditional mud stoves or metal, cement and pottery or brick stoves, with no operating chimneys or hoods. As a consequence of the pollutants emitted by these devices, pollution levels inside households cooking with biomass are often many times higher than typical outdoor levels, even those in highly polluted cities. The World Health Organization estimates that more than 1,45 million people die prematurely each year from household air pollution due to inefficient biomass combustion. The most of these are women and young children, who spend many hours each day breathing smoke pollution from the cookstove. Today, the number of premature deaths from household air pollution is greater than the number of premature deaths from malaria or tuberculosis. Using World Health Organization projections for premature deaths to 2030,8 the annual number of premature deaths over the projection period from the indoor use of biomass is expected to increase in the New Policies Scenario (Fig. 1.1), unless there is targeted action to deal with the problem. By 2030 over 1,5 million people would die every year due to the effects of breathing smoke from poorly-combusted biomass fuels. This is more than 4000 people per day. By contrast, the World Health Organization expects the number of premature deaths from malaria, tuberculosis or HIV to decline over the same period.

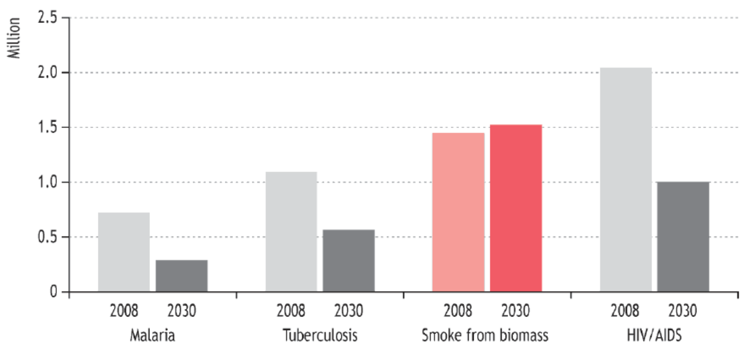


Figure 1.1.: Premature annual deaths, data 2004-2008, [IEA1]

Moreover, in developing regions in which households are heavily reliant on biomass, women and children are generally responsible for fuel collection, a time-consuming and exhausting task. Women can suffer serious long-term physical damage from strenuous work without sufficient recuperation. This risk, as well as the hazards of falls, insect bites or human assault, rises steeply the further from home women have to walk. Inefficient and unsustainable cooking practices also have serious implications for the environment, such as land degradation and local and regional air pollution. Effective environmental management cannot be excluded from energy and development concerns. Preventing irreversible damage to the global climate will require decarbonisation of the world's energy system. For developing countries, however, difficult choices have to be made in allocating scarce resources among pressing development needs and climate change is often viewed as a longer-term concern that must be traded off against short-term priorities. While the poorest developing countries are not major contributors to climate change, their populations suffer acutely from its effects. For net oil-importing developing countries in particular, rising and volatile prices have amplified the challenge of expanding energy access and put an extra burden on fiscal budgets. In a high-energy price and climate-conscious world, it makes sense for governments tackling the energy poverty challenge to choose a course consistent with longterm sustainable development goals, rather than choose the energy technologies and mix used by OECD countries in the 1950s and 1960s.

## 1.1. Energy access and mini hydropower

Hydropower is a renewable and clean energy option, used extensively in the past for shaft power, and in modern times for electricity generation.

Hydropower became an important resource for electricity generation at the beginning of the electricity era. The first hydroelectric scheme was installed in Wisconsin in September 1882 only three years after Thomas Edison invented the light bulb. Soon after, it became a popular option for electricity generation around the world. At present nearly 20% of the total electricity consumed worldwide comes from hydroelectric plants. In some countries hydroelectricity accounts for more than 80% of the total electricity consumed.

Mini hydro is a clean option based on indigenous resources, and can be reliable and affordable when appropriate technologies and approaches are used for its implementation, operation and management. It can be economically and socially viable, using local materials and capabilities for installation. Hydro is an option which can generate energy 24 hours a day continuously at its full capacity (if needed), the marginal costs are negligible, and it can thus promote job creation and the productive uses of energy for income generation and social development of communities, therefore it is an important and sound energy option to alleviate energy poverty and tackle the MDGs in rural areas.

Moreover mini hydropower is an energy resource which can be usefully harnessed for rural energy demands from small rivers, where there is a gradient of a few meters and the flow rate is more than a few litres per second. Although the amount of available energy is site specific, most developing countries have abundant unexploited potential, which can provide energy for a large proportion of isolated rural communities.

Mini hydro is a sustainable energy option: environmentally friendly because it is generally built using simple structures with minimum alteration of the watershed conditions, it doesn't need the construction of temporary settlements or access roads as large infrastructure systems require when built. It is generally designed to use part of the river flow, which goes back to its original course only few hundreds meters down river, therefore causing minimal or no damage to living species, besides it generates neither heat nor greenhouse emissions; socially sustainable because it uses local resources and technologies which can easily be understood by most people and so it can be built with considerable participation by communities, who can select individuals from among themselves to operate and manage the systems (when proper technology transfer and capacity building is arranged, local people run the systems easily, can do Mini repairs and change spare parts, and maintain all the associated civil works).

For some years, interest in mini hydropower went down drastically due to a number of factors: fast growth in electricity demand globally; progress of other technologies; success of large generation schemes and large grids in bringing down costs; mass production of mini diesel sets that are both portable and easily installed; and easy access to affordable diesel fuel. Therefore it has been turned down by most government electrification programmes, on the basis that they are "an expensive electricity generation option". In contrast there are several institutions that have been working in developing countries and report that the costs are quite affordable. The investment cost is slightly higher than that for its most important competitor for decentralised option: the diesel generator, which generally need less initial investment costs, but hydro operating costs are low because are free of the cost of fuel, while diesel sets require a permanent purchase of diesel, furthermore diesel sets generally have a much shorter life span hence more demanding in reposition costs.

Among the reasons for the low cost of mini hydro schemes are:

- It is by far the most mature technology manufactured in developing countries for renewable electricity generation.
- The technology research and adaptation has reduced the cost of mini hydro, and transfer of technology and know-how to industries, at both national and local level, has created the capacity to manufacture much of the equipment.
- Alternative materials have been developed, and skills transferred to local consultants to design and implement hydro systems.
- Local technicians can operate and maintain these systems, and appropriate management and administrative models have been developed to suit local needs.

As a result, at present, there are several countries with sufficient national capacity to manufacture and install equipment, assess resources and design schemes, at very competitive costs.

Moreover in the more recent past, the energy crisis, climate change, energy poverty in developing countries, and commitments for achieving the MDGs, has led to a rethink. Planners and policy makers are being urged to review all available energy options, especially those decentralised sources that could play a role supplying poor and isolated communities with energy for development. These sources include mini hydropower schemes as well as solar photovoltaic systems, biomass energy generators and wind generators.

Important research activities have been carried out by Academic Institutions, NGOs and others (World Bank, UNIDO and others), to understand and improve the sustainability of decentralised electricity services for mini hydro schemes. But during the last decades, little has been done on advocacy to promote mini hydro in contracts, contrariwise other renewable energy options as solar photovoltaic systems (PV) have been more advocated and have got support from the most encouraged by important organisations like the World Bank and UNDP, supported by ongoing campaigns and advocacy from large manufacturers.

For all the reasons mentioned above, mini hydro technology, if feasible for the particular context, is probably one of the best decentralised options to supply energy and alleviate poverty; therefore development agencies, through international cooperation, should give much more attention to this technology, while governments should put in place the policy arrangements to enhance the dissemination and use of hydro energy resources in the world.

# 2. Thesis objectives

The main objectives of the thesis are:

- Create a model applicable to every run-of-river site that, starting from a simple pre-feasability study, is able to optimize (according to some technical and economical parameters) the mini hydropower plant size and compute the profitability of the possible investment.
- Make the model accessible and usable to the 'Dar Es Salaam Institute of Technology' staff, thus it can become an instrument for supporting assessments and decisions regarding the construction of small hydroelectric plants in Tanzania.

In order to better understand the energy situation of the context where the model will be applied, an energy analisys for Tanzania was conducted in chapter 4.

## 2.1. Local needs

Dar Es Salaam Institute of Technology (DIT) is working very closely with the Rural Energy Agency (REA, see section 4.3.4 for details), on undertaking pre-feasability studies on a number of rivers in the Southern Highlands of Tanzania (regions of Morogoro, Iringa, Ruvuma and Mbeya). They have surveyed about 30 sites to investigate the potential of hydropower for rural eletrification as off-grid but also on-grid hook-up.

They needed to implement a model of low cost small hydropower run-of-river plants (up to 2 $MW$) to enable potential developers to quick take-off and build the earmarked sites.

The difficulties in developing such a project are:

- Absence of local producers regarding some important plant elements (for example turbine and penstock). In these cases import, with its related costs, has to be taken into account.
- Difficulty in obtaining components cost from worldwide suppliers. For example manufacturers of turbines and alternators do not supply any information about cost, since every installation is different and complex.
- Lack of detailed hydrological data for the rivers in analisys because no gauging station was installed.
- Scarse availability of agencies and institutions willing to finance projects of rural electrification, because often the payback is not guaranteed.

### 2.1.1. Sites analysis

REA identified nine rivers and agreed with DIT to perform a pre-feasability study and develop the technical and financial proposal for the detailed survey, profile and design of distribution scheme in selected sites. The pre-feasibility study was undertaken and completed by the Dar Es Salaam Institute of Technology in January 2010. To come up with the possible potential sites, consideration was made not only of the technical aspect and its consequent costs including that of the associated transmission lines, but also the accessibility of the project in terms of roads needed during construction and operation. Hence, provisions for this aspect would be possible and at a minimum cost.

Using field measurements, visual observations and engineering judgments the followings are established:

- Out of the 9 river basins visited, 7 were found to have significant potential.
- Possible locations of the weir, forebay, and power house were selected and respective coordinate recorded for all potential sites.
- Maximum available head was determined for each site.
- Catchment and respective hydrology informations were initially assessed and possible data needed for detail design were identified.
- Possible transmission route to the load centre was identified and respective distance estimated for each site.
- Visual observation of the geology and terrain of the site, especially for the power house, were considered in assessing the suitability of construction.

The sites in analisys are the following:

1. **Makete in Ijangala district**: the Tandala diaconical centre of South Central Diocese of the Evangelical Lutheran Church of Tanzania intends to develop available hydropower potential of Ijangala River in Makete District for own consumption and electrifying 19 neighbouring villages. The centre deals with people with various disabilities, orphans and other disadvantaged persons. The centre has been in contact with various church authorities in Germany that have shown interest in sponsoring the project. Extension of grid electricity is not economically feasible to the remote areas like Tandala and the nearby villages.
2. **Mtonya in Namtumbo district**: the site is located 3 $km$ from Namtumbo District town and is accessible just nearby the main road going to Tunduru. The route to the site comprises of a gentle slope which made possible to drive near to the proposed site. The soil nature to the site is rocky and therefore very firm and less prone to erosion. In Namtumbo town there are several important utilities to be supplied by the proposed electrification project, just

to mention a few: the district headquarters, the district hospital, the water and sewerage authority, the NMB bank branch, communication towers of Voda and TTCL, schools and church buildings.

3. **Malindindo in Mbinga district**: the Malindindo small hydropower plant would be located along Wogawoga River in Malindindo village. The main activity of the people in this area is farming, mainly coffee as a source of income. On the other hand, they do cultivate food crops such as corn and cassava. The village has no electrical power and therefore, depends on diesel machines in running milling machines and also kerosene for lighting. The provision of hydroelectric generation is a viable solution to this need in the area.

4. **Madaba in Rural Songea district**: Madaba town is about 120 *km* from Njombe District and 118 *km* from Songea district, located along the Songea-Njombe highway. The proposed site for the mini hydropower plant is about 12 *km* along the road and 3 *km* from the Madaba Livestock and Agricutural Institute (LITI). From the centre of Madaba Town is around 9 *km* from the main road. Madaba is a very big active centre economically. Institutions also exist, like the Madaba LITI, banks, a health centre, primary and secondary schools and some government offices. Commercial businesses are also substantial in number including grain milling machines, residential houses, communication towers and small shops and workshops. These are the load centres which in the detailed study will give the actual load demand. It is interesting also to note that, at the Madaba LITI, there is already a power distribution network which is supplied by the LITI diesel powered generators.

5. **Macheke in Ludewa district**: the Macheke Small Hydropower Plant would be located in Ludewa District, 30 *km* from Mlangali town. The project is in Macheke village surrounded by other villages which can benefit from the project. There is also nearby a Roman Catholic mission with several social services such as a nursery school. Some developments have been made as regards to this project: an access road to the site is under construction, this includes a bridge which was under construction during the site visit. The power transmission line is proposed to originate from the proposed powerhouse location to Mlangali centre 8 *km* away. In the way, there will be tee-off point at Mlangali Roman Catholic church to the neighbouring village of Utiriri. The common load centres are the primary and secondary schools, dispensaries, residential houses, shops and small workshops and garages including communications towers and water pumps.

6. **Isigula in Ludewa district**: the site is located along the road from Njombe to Ludewa districts. The site is in Ludewa District 5 *km* before Mlangali town from Njombe District. The area is characterized by heavy forest. Both the proposed intake and powerhouse are accessible to the main road. The

development of this plant was initially initiated by villagers, indeed there are some developments which were noted during the visit. The research team was led by one of the villagers to locations which were earlier identified for intake and power house. The local initiative went as far as starting a construction for the open channel from the proposed intake to forebay.

7. **Mpando in Njombe district**: the proposed Mpando small hydropower plant is located in Imalinyi Village, Njombe District. The plant is about 30 $km$ from Njombe town and about 5 $km$ from Mangula secondary school. The proposed site was once being used by a failed mini hydroelectric generating plant. The site has a constructed open channel which is about 500 $m$ long, a forebay as well as a power house. The previous power plant was locally fabricated. It was reported that the failure was due to the flooding of the power house which resulted into short circuiting of the generator. The open channel was constructed in such a way that at one section it crosses the river downstream of the intake location as result at one time it was washed away by floods causing also the powerhouse flooding. The power line transmission route will originate from the proposed powerhouse location to the Phillip Mangula Secondary School, about 5 $km$ away. From there, will be a tee-off point to other load centers including the dispensary, village government offices, primary schools and residential houses.

8. **Mugali in Mafinga district**: the proposed Mugali hydro plant is located in Mafinga rural district about 25 $km$ off the main road from Iringa to Mbeya. The idea for installation of the mini hydropower plant was once initiated by the Mafinga municipal council. The plant is expected to serve the nearby villages and the surplus will be connected to the national grid system.

9. **Ruaha in Iringa district**: the proposed site is located about 60 $km$ from Iringa municipality. The site is accessible through two approaches from Iringa municipality. The shortest access with 60 $km$ involves crossing the Little Ruaha river using small local boat at downstream side of the proposed site. The nearest village to this site is about 3 $km$ . Most of the villagers depend on the small irrigation schemes of rice and cattle keeping using water taken from little Ruaha River. As this river flows throughout the year has attracted people to settle along its banks. With this migration, water has been diverted from the little Ruaha river purposely for domestic use and irrigation. The transmission route is proposed to take power to Mboliboli and Itunundu townships. A tee-off point at Pawaga village is proposed to transmit power to Iringa town for connection to the grid.

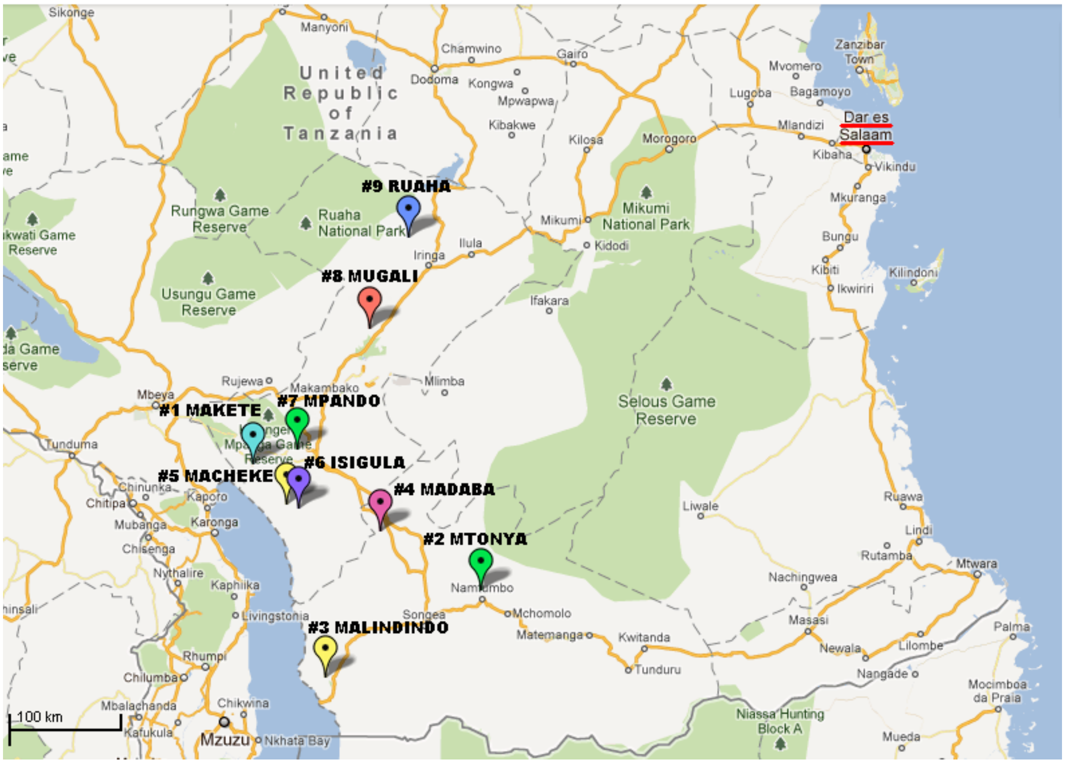


Figure 2.1.: Sites locations

A simulation with the software "Mini hydro plants simulator" will be performed in part IV for four of these sites which have been considered most promising.

## 2.2. Universities partnership

This project arises according to the framework agreement signed in August 2007 between Politecnico di Milano and Dar Es Salaam Institute of Technology for promoting a number of joint activities devoted to upgrade local curricula, joint research and staff exchange.

In this case the exchange experience lasted two month, from $23^{rd}$ October to $23^{rd}$of December 2011, and the work was carried out all within the DIT, with the help of the following lecturers and assistant lecturers:

- Dr. Bonaventure Saanane, PhD. Head Department of Electrical Engineering.
- Dr. Prosper Mgaya, PhD. Department of Civil Engineering.
- Dr. Johnson Malisa, PhD. Department of Civil Engineering.
- Dr. Singo Daudi, MSc. Head of Department of Civil Engineering.

- Godfrey Moshi, MSc. in Electrical Engineering & Renewable Energy Systems.
- Moses Kaswa, MSc. Geographic Information System (GIS) expert.

At the end of the period, a presentation of the work was held in REA offices in Dar Es Salaam to make them aware of the work done and to speak about future developments.

# 3. Tanzania outlook

The United Republic of Tanzania is bordered by Kenya and Uganda on the north, Rwanda, Burundi and the Democratic Republic of the Congo on the west, and Zambia, Malawi and Mozambique on the south. To the east it borders the Indian Ocean. The country is formed by the mainland with 26 regions and the Zanzibar Archipelago composed by numerous small islands and two large ones: Unguja (the main island, informally referred to as "Zanzibar"), and Pemba.

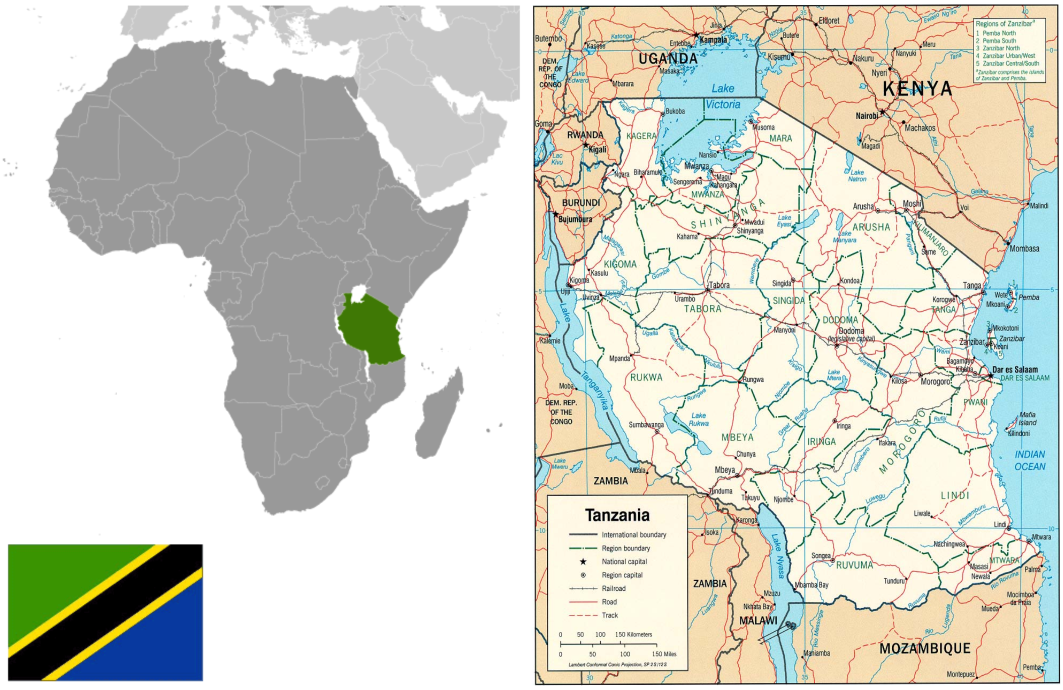


Figure 3.1.: Tanzania maps and national flag

Since 1996, the official capital of Tanzania has been Dodoma, where Parliament and some government offices are located. Between independence and 1996, the main coastal city of Dar es Salaam served as the country's political capital. Today, Dar es Salaam remains the principal commercial city of Tanzania and the seat of most government institutions. It is the major seaport for the country and its neighbours.

The name Tanzania derives from the names of the two states Tanganyika and Zanzibar that united in 1964 to form the United Republic of Tanganyika and

Zanzibar, which later the same year was renamed the United Republic of Tanzania.

The local currency is the Tanzanian Shilling (TZS) and the official languages are Swahili and English.

## 3.1. History

Tanzania is probably one of the oldest known inhabited areas on Earth; fossil remains of humans and pre-human hominids have been found dating back over two million years. More recently, Tanzania is believed to have been populated by hunter-gatherer communities, probably Cushitic and Khoisan speaking people. About 2000 years ago, Bantu-speaking people began to arrive from western Africa in a series of migrations. Later, Nilotic pastoralists arrived, and continued to immigrate into the area through to the $18^{th}$ century. The people of Tanzania are associated with the production of steel. The Haya people of East Africa invented a type of high-heat blast furnace which allowed them to forge carbon steel at 1802 °C nearly 2000 years ago.

Travellers and merchants from the Persian Gulf and western India have visited the East African coast since early in the first millennium BC. Islam was practised on the Swahili Coast as early as the eighth or ninth century BC. Claiming the coastal strip, Omani Sultan Seyyid Said moved his capital to Zanzibar City in 1840. During this time, Zanzibar became the centre for the Arab slave trade. Between 65% to 90% of the population of Arab-Swahili Zanzibar was enslaved.

In the late 19th century, Imperial Germany conquered the regions that are now Tanzania (minus Zanzibar), Rwanda, and Burundi, and incorporated them into German East Africa.

During World War I, an invasion attempt by the British was thwarted by German General Paul von Lettow-Vorbeck, who then mounted a drawn out guerrilla campaign against the British. The post-World War I accords and the League of Nations charter designated the area a British Mandate, except for a small area in the northwest, which was ceded to Belgium and later became Rwanda and Burundi, as well as a small area in the southeast (Kionga Triangle), incorporated to Portuguese East Africa (later Mozambique), the region that was to become Tanzania was called Tanganyika.

After World War II, Tanganyika became a United Nations territory under British control. Subsequent years witnessed Tanganyika started moving gradually toward self-government and independence. In 1954, Julius Nyerere, the future leader of Tanzania, who was then a school teacher and one of only two Tanganyikans educated abroad at the university level, organized a political party, the Tanganyika African National Union (TANU). On 29 March 1961 Britain agreed that Tanganyika would become an independent state on 28 December 1961 (Fig. 3.2). Actually on December 9, 1961 Tanganyika became an autonomous Commonwealth realm, and Nyerere became Prime Minister, under a new constitution. On December 9, 1962, a republican constitution was implemented with Mwalimu Julius

Kambarage Nyerere as Tanganyika's first president.


Figure 3.2.: Nyerere on indipendence day

Zanzibar received its independence from the United Kingdom on December 19, 1963, as a constitutional monarchy under the Sultan. On January 12, 1964, the African majority revolted against the sultan and a new government was formed with Abeid Karume as President of Zanzibar and Chairman of the Revolutionary Council.

Soon after independence, Nyerere's first presidency took a turn to the Left after the Arusha Declaration, which codified a commitment to socialism in Pan-African fashion. After the Declaration, banks were nationalized as were many large industries. After the Zanzibar Revolution overthrew the Arab dynasty in neighbouring Zanzibar, the island merged with mainland Tanganyika to form the United Republic of Tanzania on 26 April 1964.

The United Republic of Tanzania coat of arms, shown in figure 3.3, comprises a warrior's shield which bears a golden portion on the upper part followed underneath by the flag of Tanzania.


Figure 3.3.: Coat of arms of Tanzania

The golden portion represents minerals in the United Republic; the red portion underneath the flag symbolizes the rich fertile soil of Africa; while the wavy bands represent the land, sea, lakes and coastal lines of the United Republic. In the golden part of the flag there appears a burning torch signifying freedom (*uhuru*), enlightenment and knowledge; a spear signifying defence of freedom and crossed axe and hoe being tools that the people of the Tanzania use in developing the country. The shield stands upon the representation of Mount Kilimanjaro. Elephant tusks are supported by a man and a woman, with a clove bush at the feet of the man and a cotton bush at the feet of the woman (whose head is covered with a golden shroud) indicating the theme of cooperation. The United Republic motto *Uhuru na Umoja* is written in Swahili and means "Freedom and Unity".

The union of the two, hitherto separate, regions was controversial among many Zanzibaris (even those sympathetic to the revolution) but was accepted by both the Nyerere government and the Revolutionary Government of Zanzibar owing to shared political values and goals. When in power, Nyerere implemented a socialist economic programme, establishing close ties with China, and also introduced a policy of collectivisation in the country's agricultural system, known as *ujamaa* or "familyhood." Nyerere had tremendous faith in rural African people and their traditional values and ways of life. He believed that life should be structured around the *ujamaa*, or extended family found in traditional Africa. Unfortunately for Nyerere and Tanzania, this *ujamaa* system caused agricultural output to plummet. The deficit in cereal grains was more than 1 million tons between 1974 and 1977. Only loans and grants from the World Bank and the International Monetary Fund in 1975 prevented Tanzania from going bankrupt. At that time, *ujamaa* villages contained 90% of the rural population but only produced 5% of the national agricultural output. Subsequently, the country fell on hard economic times which was exacerbated by a war: in 1979 Tanzania declared war on Uganda. On April 11, 1979 the army took the capital Kampala with the help of the Ugandan and Rwandan guerrillas and Idi Amin (military leader and the President of Uganda) fled into exile.

By the mid-1979 corruption reached epidemic proportions as the economy collapsed. Socialism left the country as one of the poorest and the least developed. Dependency on foreign aid had become one the world's highest and Tanzania went from the largest exporter to the largest importer of agricultural products in Africa.

From the mid 1980s Tanzania's GDP per capita has grown and poverty has been reduced.

## 3.2. Political framework

The Government of the United Republic of Tanzania is a unitary republic based on multiparty parliamentary democracy, whereby the President of Tanzania is both head of state and head of government, and of a multi-party system. Executive power is exercised by the government, legislative power is vested in both the government and parliament while the Judiciary is independent. The President of Tanzania, and the members of the National Assembly, are elected concurrently by direct popular vote for five-year terms.

The party system is dominated by the Chama Cha Mapinduzi (Revolutionary State Party, Fig. 3.4), at present holding about 75% of the seats in the Assembly. Opposition parties are widely considered to have no real chance of gaining power, though the country remains peaceful.

In December 2005, Jakaya Mrisho Kikwete was elected the $4^{th}$ president for a five-year term.

Figure 3.4.: Chama Cha Mapinduzi logo

Figure 3.5.: President Jakaya Mrisho Kikwete

## 3.3. Geography and Climate

At 947300 $km^2$, Tanzania is the world's 31st-largest country. Compared to other African countries, it is slightly smaller than Egypt and comparable in size to Nigeria. Tanzania is mountainous in the northeast, where Mount Kilimanjaro, Africa's highest peak, is situated. To the north and west are the Great Lakes of respectively Lake Victoria (Africa's largest lake) and Lake Tanganyika (the continent's deepest lake, known for its unique species of fish) and to the southwest lies Lake Malawi whose elongated depression forms most of the country's border with Malawi. Central Tanzania comprises a large plateau, with plains and arable land. The eastern shore is hot and humid, with the island of Zanzibar lying just offshore.

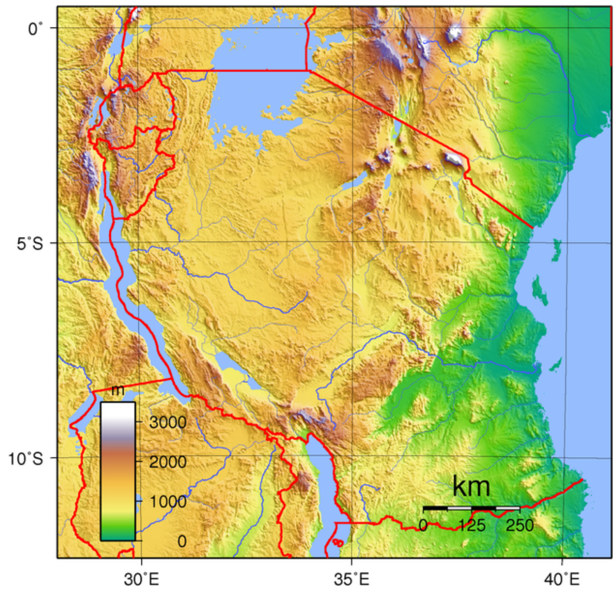


Figure 3.6.: Topographical map of Tanzania

Tanzania contains many large and ecologically significant wildlife parks, including the famous Ngorongoro Crater, Serengeti National Park in the north, and Selous Game Reserve and Mikumi National Park in the south and Gombe National Park in the west.

The climate of Tanzania is tropical, ranging from hot and humid on the coast, to a more temperate climate in the elevated centre of the country. In the highlands, temperatures range between 10 and 20 °C during cold and hot seasons respectively. The rest of the country has temperatures rarely falling lower than 20 °C. The hottest period extends between November and February (25-31°C) while the coldest period occurs between May and August (15-20 °C). Tanzania has two major rainfall seasons, March - May rains are referred to as the long rains (experienced mainly in the north and northern coast), whereas the October - December rains are generally known as short rains (found mainly in the southern and western part of the country).

## 3.4. Tribes

Despite the diversity in the indigenous gene pool, most tribes are very small, as a result none have succeeded in dominating politically or culturally. The vast majority of Tanzanians, about 95%, are of Bantu origin. The most famous include:

**Sukuma** (People in the North) tribe is the largest of Tanzania's more than 120 different ethnic groups. Close to 15% of the population in Tanzania are from the Sukuma tribe. They live around Mwanza and the southern Lake Victoria region. Most Sukuma people are farmers and their lands comprise one of Tanzania's most important agricultural areas. Cattle are also an important source of livelihood. The Sukuma people are closely related to the Nyamwezi, their members are often found in Nyamwezi villages.

**Nyamwezi** are the second-largest group in Tanzania. They live in the northwest central area of the country, between Lake Victoria and Lake Rukwa. The core members of a "domestic group" consisted of the husband, his wife or wives, and any children who still lived with them. In general men did the heavy work, while women did the recurring tasks and much of the everyday agricultural work. Elephant hunters have historically been one of the most prestigious occupations among the Nyamwezi, since the elephant hunters could get very rich from ivory trade. Ironwork came from localized settlements whose products were then traded over wide areas. Most follow a traditional religion, despite conversion attempts by Islam and Christianity.

**Makonde** are an ethnic group in southeast Tanzania and northern Mozambique. The Makonde are traditionally a matrilineal society where children and inheritances belong to women, and husbands move into the village of their wives. The Makonde are best known for their wood carvings (Fig. 3.7): they traditionally carve household objects, figures and masks. After the 1930s, the Portuguese colonizers and other missionaries arrived at the Makonde plateau. They immediately showed great interest and fascination for the Makonde wood carvings and began to order different pieces, from religious until political "eminences". Since the 1950s years the socalled Modern Makonde Art has been developed.

Figure 3.7.: Makonde carvings

**Haya** are said to have settled in the Kagera Region of north western Tanzania during the time of the Bantu expansion. They were organized into small groups which were loosely affiliated with one another and organized in a system similar to feudalism with commoners and nobles as the main participants. They are believed to be some of the earliest inhabitants in the area to practice metal work which allowed them to create various new forms of pottery, particularly they have been linked to one of the greatest scientific breakthroughs of all time: the advent of steel. They were able to create furnaces using mud and grass which when burnt provided the carbon needed to transform the iron into steel. These furnaces were carbon dated and were found to be as old as 2000 years, whereas steel of this calibre did not appear in Europe until several centuries later.

**Maasai** The Maasai are a Nilotic ethnic group of semi-nomadic people located in Kenya and northern Tanzania. They are among the best known of African ethnic groups, due to their distinctive customs and dress (Fig. 3.9) and residence near the many game parks of East Africa (Serengeti, Ngorongoro and Masai Mara). They speak Maa, a member of the Nilo-Saharan language family, and are also educated in the official languages of Kenya and Tanzania: Swahili and English. The Tanzanian and Kenyan governments have instituted programs to encourage the Maasai to abandon their traditional semi-nomadic lifestyle, but the people have continued their age-old customs. Traditional Maasai lifestyle centres around their cattle which constitute their primary source of food. The society is strongly patriarchal in nature, with elder men, sometimes joined by retired elders, deciding most major matters for each Maasai group.

Figure 3.8.: Maasai man with his cattle in Ngorongoro Crater

Figure 3.9.: Maasai tribe

## 3.5. Socio economic framework

In this chapter a socio-economic analisys has been conducted, most of the indicators computed here, will be also useful to carry out the following energy analisys.

The analisys has been conducted taking into account indicators for the following countries:

1. Tanzania
2. Kenya
3. Mozambique
4. South Africa
5. Italy

When possible also a comparison with Low Income group (with GNI value of 1005 $USD$ or less) and Africa Sub Saharan has been done (Ref. [WB2]).

### 3.5.1. Population

Data about population have great importance in energy analisys, because energy consumption for a country is directly proportional to the number of users. Particularly in a developing country the urban population fraction is a more significant index: it accounts the bigger part of energy usage because usually governments meet the needs of urban population, electrifying big cities and leaving out rural areas. Unbridled demographic growth, during the last half century, in developing countries has been often considered as one of the crucial factors causing underdevelopment, because resources are going into saturation since still more people have to exploit them.

At present global urbanization rate is just above 50%, obviously is higher in developed countries, for example in Italy 68% of population lives in urban areas while in Tanzania only 26% does, lower than Sub Saharian countries average (Fig. 3.10). This means that in Tanzania, most of the rest of population living in rural areas (76%), will not have the chance to access electricity and modern fuels, due to the connection problems for villages and rural settlements.

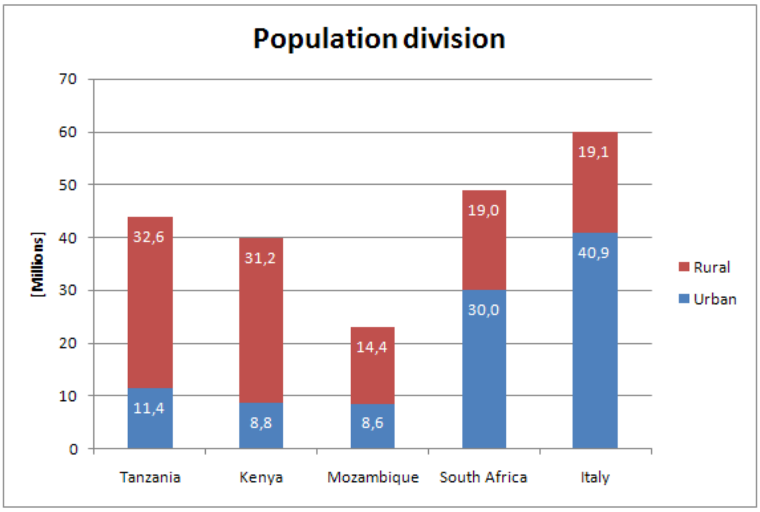


Figure 3.10.: Urban and rural population division in millions, data 2010, [WB2]

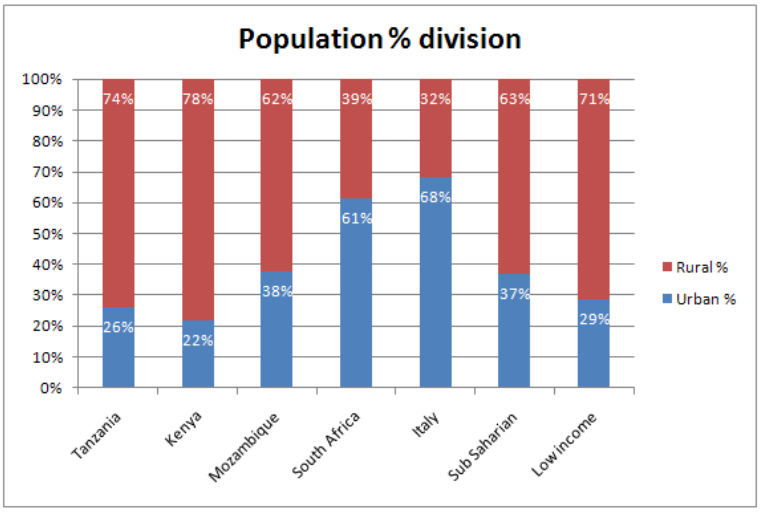


Figure 3.11.: Urban and rural population percentage division, data 2010, [WB2]

Another basic socio-economic index is the population growth rate. As just said, in order to predict the increase in energy demand, is better to consider the urban population growth rate, because the greater part of demand will come from big cities. Demographic growth in urban area in Tanzania has reached an exponential rate of growth 4,7% annual in 2010 (slightly higher than Kenya and Mozambique, respectevely 4% and 4,4%). Total tanzanian population rate of growth was 3% annual in 2010 (Fig. 3.12).

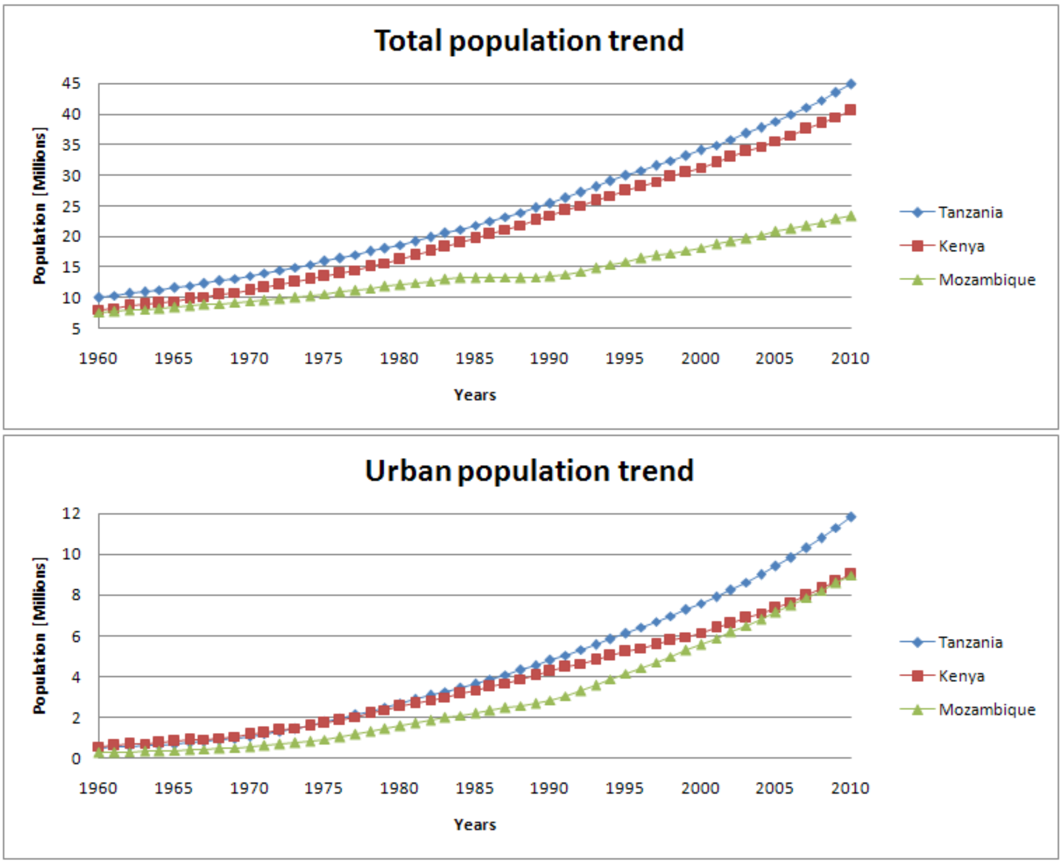


Figure 3.12.: Total and urban population growth, data 2010, [WB2]

### 3.5.2. Gross Domestic Product (GDP) and Gross National Income (GNI)

GDP is the main and most used economic index. It's a macroeconomic quantity expressing the whole value of final goods and services within a Country in a given period of time (usually one year).

GNI is computed summing or subtracting to GDP cash flows between different countries. It represent the sum of value added by all resident producers plus any product taxes (less subsidies) not included in the valuation of output plus net receipts of primary income (compensation of employees and property income) from abroad.

To smooth fluctuations in prices and exchange rates and better compare the relative size of economies, a special Atlas method of conversion is used by the World Bank (Ref. [WB2]) for GNI computation. Economies are divided according to 2010 GNI per capita, the groups are: low income, 1005 *USD* or less; lower middle income, 1006 - 3975 *USD*; upper middle income, 3976 - 12275 *USD*; and high income, 12276 *USD* or more.

Figure 3.14 shows the slightly difference between GDP and GNI (computed with Athlas method), here only Tanzania, Kenya and Mozambique are reported, with GDP value respectively of 23,4, 31,8 and 10,3 billion *USD*. South Africa (305 billion *USD*), Italy (2126 billion *USD*), Low Income (420 billion *USD*) and Sub Saharian group (1014 billion *USD*) can't be shown because the graph would go off-scale.

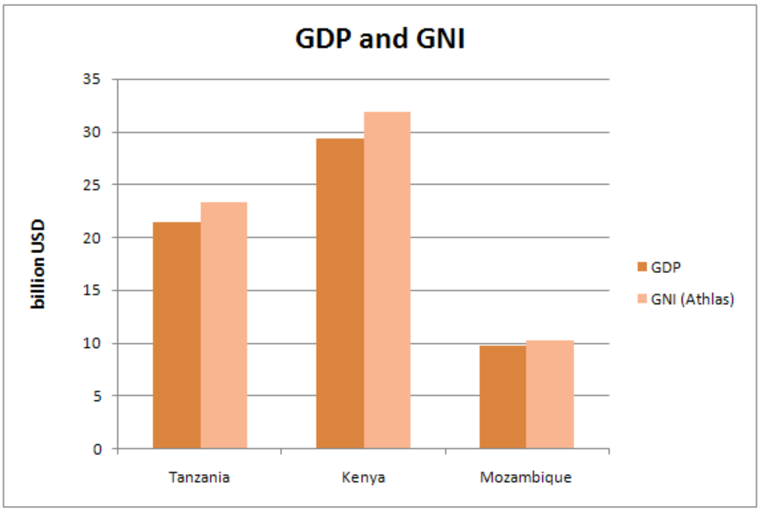


Figure 3.13.: GDP and GNI, data 2011, [WB1]

It's important to notice that GNI increases conconsistently every year in Sub-Saharan countries: the GNI annual growth rate in Tanzania has remained stable around 7% since 2002, while in Italy in the same period it has never gone over 2% [WB2].

The more meaningful GDP and GNI per capita (Fig. 3.14) show the extreme situation of poverty in the three east-african countries, all of them are placed below the Sub Saharian average (1187 *USD*). Tanzania with GNI per capita value of 530 *USD* is on average with the Low Income group (528 *USD*), Mozambique with 440 *USD* is even lower. South Africa GNI per capita (6090 *USD*) is one order of magnitude higher than all the countries and groups aforementioned. The value for Italy, two order of magnitute higher (35150 *USD*), is not even comparable.

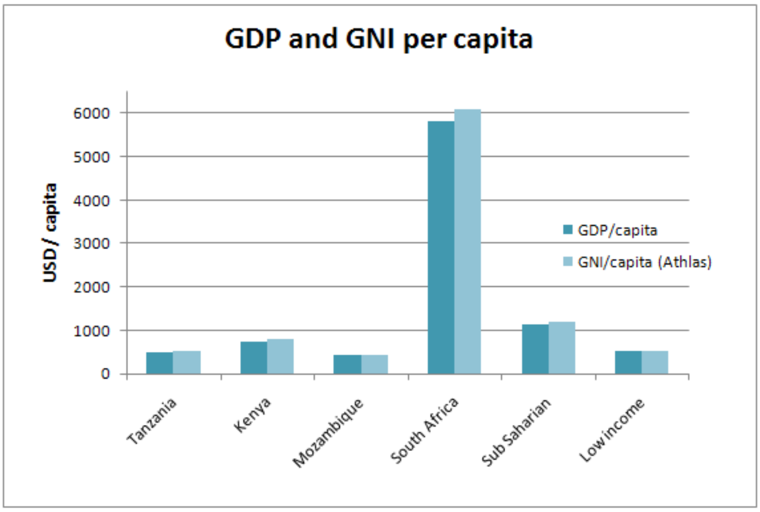


Figure 3.14.: GDP and GNI per capita, data 2011, [WB1]

However sometimes is not sufficient to limit the study to the value of income as an average between the whole population, because wealth is almost never equally distributed, therefore GINI index has been introduced. Gini index measures the extent to which the distribution of income (or, in some cases, consumption expenditure) among individuals or households within an economy deviates from a perfectly equal distribution. A Lorenz curve plots the cumulative percentages of total income received against the cumulative number of recipients, starting with the poorest individual or household. The Gini index measures the area between the Lorenz curve and a hypothetical line of absolute equality, expressed as a percentage of the maximum area under the line. Thus a Gini index of 0 represents perfect equality, while an index of 100 implies perfect inequality (Fig. 3.15).

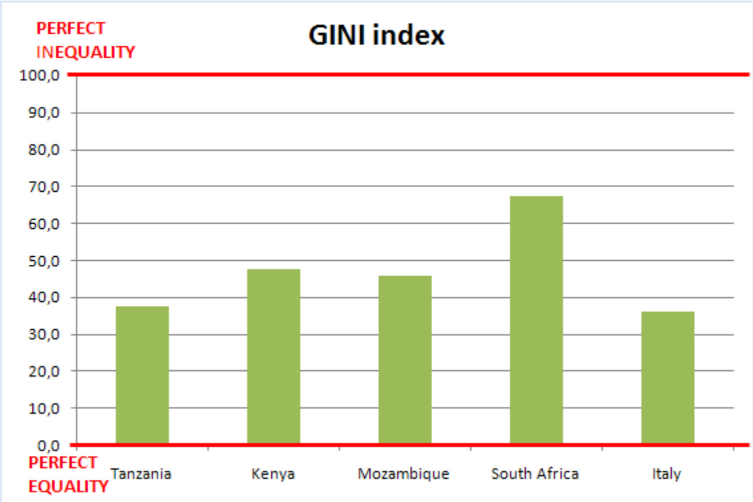


Figure 3.15.: GINI index, data 2000-2008 depending on the availability, [WB1]

It's interesting to notice that, although GNI per capita in South Africa is one order of magnitude higher than Tanzania one, there will probably be a great slice of South Africa population living with an income per capita comparable with the globally poorer Tanzanians.

### 3.5.3. HDI - Human Development Index

The Human Development Index (HDI) is a composite statistic used to rank countries by level of "human development", it was defined in the annual Human Development Reports of the United Nations Development Programme (Ref. [UNDP1]). It is taken as a synonym of the older term standards of living, and distinguish "very high human development", "high human development", "medium human development", and "low human development" countries. The Human Development Index is a comparative measure of life expectancy, literacy, education and standards of living for countries worldwide. It is a standard means of measuring well-being, especially child welfare. It is used to distinguish whether the country is a developed, a developing or an under-developed country, and also to measure the impact of economic policies on quality of life.

HDI combines three dimensions:

- a long and healthy life: Life expectancy at birth
- education index: Mean years of schooling and Expected years of schooling
- a decent standard of living: GNI per capita (PPP USD)

This index shows again (Fig. 3.16) the extreme situation of underdevelopment in East Africa, with Tanzania placed 152nd of 187 countries in the HDI global rank with an HDI value of 0,466. It is line with the Sub Saharian (0,463) and low human development groups (0,456). In the group of countries in analisys only Mozambique, with an HDI value of 0,332, is potioned lower, exactly at the last but three place in the global rank. South Africa lies within the medium human development group with 0,619 (121st place), while Italy, with 0,874, is at the 24th place within the high human development group.

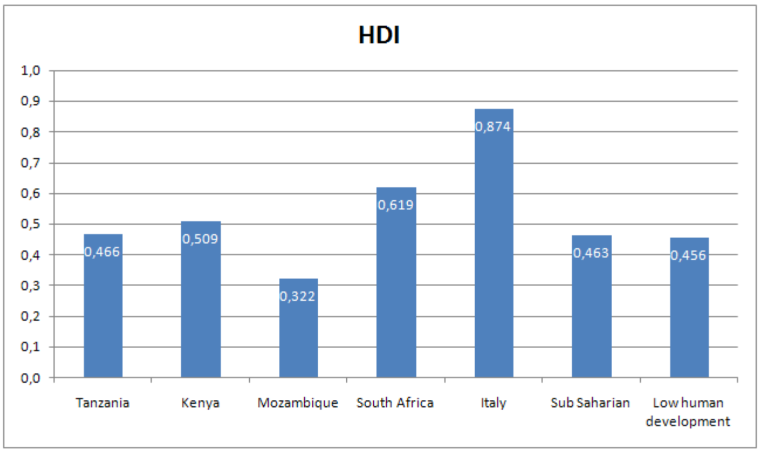


Figure 3.16.: HDI - Human Development Index, data 2011, [WB2]

# 4. Tanzania energy situation

## 4.1. Energy Indicators for Sustainable Development

Energy indicators analysis is conducted according to International Atomic Energy Agency standards, splitting energy indicators in three main dimensions: social, economic and environmental, none of these has priority but they all lay on the same level of importance.

This definition is coherent with the idea of sustainability and requires to face the access to energy problem in developing countries not only as a technical problem, linked to lack of technologies, but also as a social problem, strictly connected to shortage of opportunities.

Energy indicators for sustainable development (EISD) have been defined in the publication "Energy Indicators for Sustainable Development: Guidelines and Methodologies" (Ref. [IAEA]) in April 2005 in Wien, born from an international initiative with the purpose of defining methodologies and guidelines for computation and use of parameters which were universally recognized as suitable to describe the level of development in a country. It was possible to carry out this task successfully thanks to the sharing between some of the most importan non-governative organization like International Atomic Energy Agency (IAEA), United Nations Department of Economic and Social Affairs (UNDESA), International Energy Agency (IEA), Eurostat e European Environment Agency (EEA).

Thematic structures, guidelines, methodologies and energy indicators presented in the report reflect the experience of these agencies acknowledged all over the world as leaders in the energy and environment analysis field. Thanks to this synergic cooperation has been possible to provide users with means to analyze sustainable development which are more understandable and universally accepted.

Is important to be able to measure the status of development of a Country and to monitor its growth or regression through sustainability, and for this goal indicators were introduced. These indicators are not simply data, but rather parameters which highlight some information that otherwise would be hardly detectable through traditional statistic.

Every set of indicators represent different aspects and consequences of energy production and usage and, considered all together, they depict a full picture of the entire system, including interconnections and exchanges between different dimensions of sustainable development and long-term implications of actual decisions. The variation of the indicator value over time highlight progress or lack of progress towards the direction of sustainable development.

Energy indicators for sustainable development (EISD) are globally 30, and they are further divided into 7 themes and 19 sub-themes. Some of them can be included in more than one dimension thanks to the interconnection between different categories. The entire list can be found in the EISD guide by IAEA (Ref. [IAEA]).

The following analisys observes the logical framework suggest by IAEA which divides the EISD into the social economic and environmental sections but only few indicators, which have been considered the most relevant, are computed.

## Social

Availability of energy has a direct impact on poverty, employment opportunities, education, demographic transition, indoor pollution and health, and has gender- and age-related implications. In rich countries, energy for lighting, heating and cooking is available at the flip of a switch. The energy is clean, safe, reliable and affordable. In poor countries, up to six hours a day is required to collect wood and dung for cooking and heating, and this task is usually done by women, who could be otherwise engaged in more productive activities. In areas where coal and charcoal are commercially available, these fuels take up a large portion of the monthly household income. Inadequate equipment and ventilation means that these fuels, burned inside the house, cause a high toll of disease and death through air pollution and fires.

This example serves to illustrate the two themes of the social dimension: Equity and Health. Social equity is one of the principal values underlying sustainable development, involving the degree of fairness with which energy resources are distributed, energy systems are made accessible and pricing schemes are formulated to ensure affordability. Energy should be available to all at a fair price.

The Equity indicators have the sub-themes of Accessibility, Affordability and Disparities. Because of a lack of access to modern energy (for example, by not being connected to the electricity grid), poor households not only spend a larger portion of their income on energy than do the rich, but they often have to pay more in absolute terms per unit of useful energy. A household in an African township often has to pay more for the coal or paraffin needed to cook a meal than one in a European city pays for the electricity to do the same amount of cooking. The lack of electricity limits work opportunities and productivity, as without electricity it is only possible to use the simplest tools and equipment. It also usually means, among other limitations, inadequate illumination, limited telecommunications and no refrigeration.

Limited income (limited affordability) may force households to use traditional fuel and inefficient technologies, and the time needed to find and collect fuelwood is time that cannot be spent cultivating fields or otherwise working. The poor usually have to spend a large share of their income on indispensable energy fuels such as those required for services like cooking and heating.

There may be disparities in access or affordability between regions and between income groups within a region. Disparities within a country or between countries may result from highly uneven income distributions, inadequate energy transport and distribution networks, and major geographical differences among regions.

The Health indicators have the sub-theme of Safety, which covers accident fatalities caused by the extraction, conversion, transmission/distribution and use of energy.

In the following sections some social indices are defined.

### 4.1.1. Access to electricity

It measures the share of population which has a domestic electricity connection. This connection could vary with quantity (availability during the day) or with quality (stability in voltage and frequency).

According to the World Bank data, in 2009 74% of global population have access to electricity but, as usual, considering the world mean is not very meaningful because the great part of this share belongs to the OECD (Organisation for Economic Cooperation and Development) and transition economies, where almost 100% of people has the access. The share in Sub-Saharan Africa is indeed more than two times lower (32,5%) than the global value, and all the considered african countries, except the more developed South Africa, are placed below with percentage share less than 20% (Fig. 4.1).

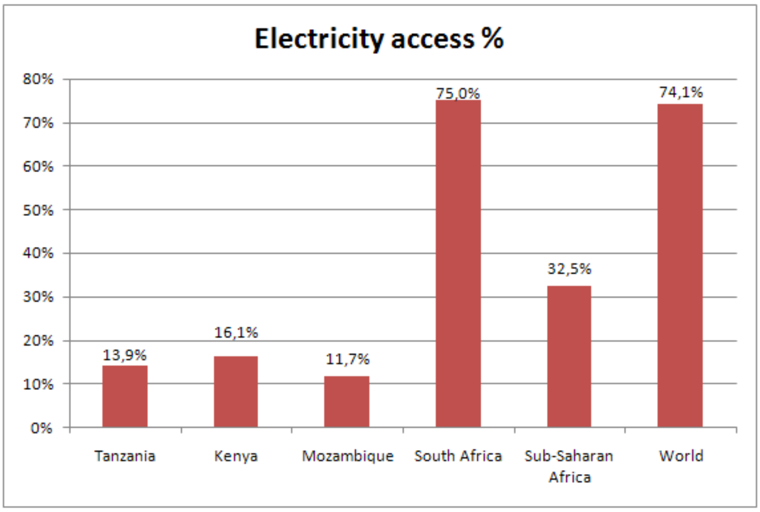


Figure 4.1.: Share of population with access to electricity, data 2009, [WB1]

### 4.1.2. Access to modern fuels

It measures the share of population which use electric energy, liquid or gas fuels as first source for cooking and heating. These fuels include: liquefied petroleum gas (LPG), natual gas, kerosene (including paraffins), ethanol and biofuels, traditional biomass and coal are excluded.

UNDP computes this indicator for a series of countries where access to modern fuels is more limited: the Least Developed Countries (LDCs) and Sub-Saharan Africa, this link include Tanzania, Kenya, Mozambique and South Africa. In developing countries overall, more than 40% of people rely on modern fuels; however, in LDCs and Sub-Saharan Africa, only 9% and 17%, respectively; the access in Tanzania and Mozambique is even limited to 3% of population (Fig. 4.3) The situation improves a bit in Kenya and reaches in the richer South Africa the share of 83%. Of course these mean value will vary sharply within the single country depending on the level of urbanization, for example the access in a rural area of an LCD country is around 3% while in urban areas it reaches 27%; the values for a generic Sub-Saharan country are equal to 5% and 42% for rural and urban area respectively.

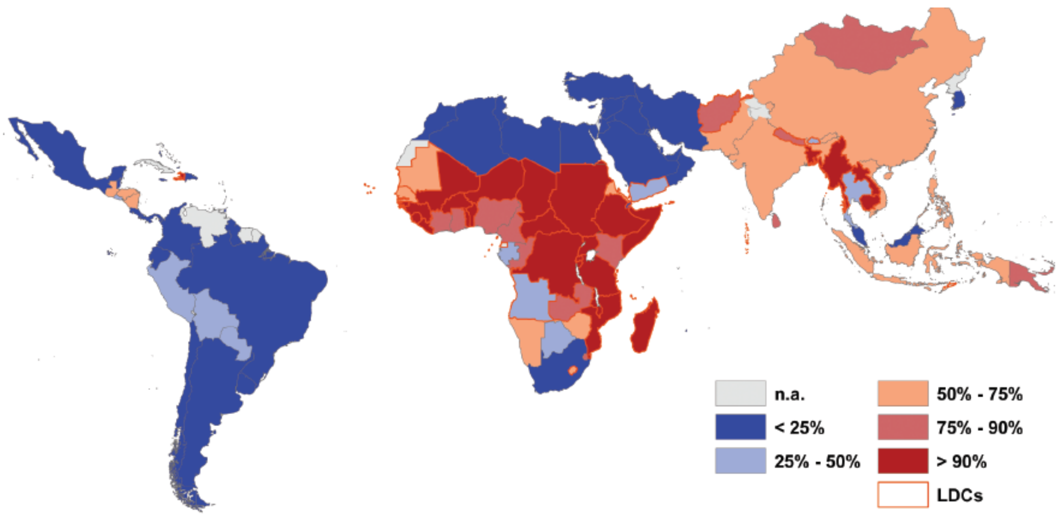


Figure 4.2.: Share of population without access to modern fuels, data 2007, [UNDP2]

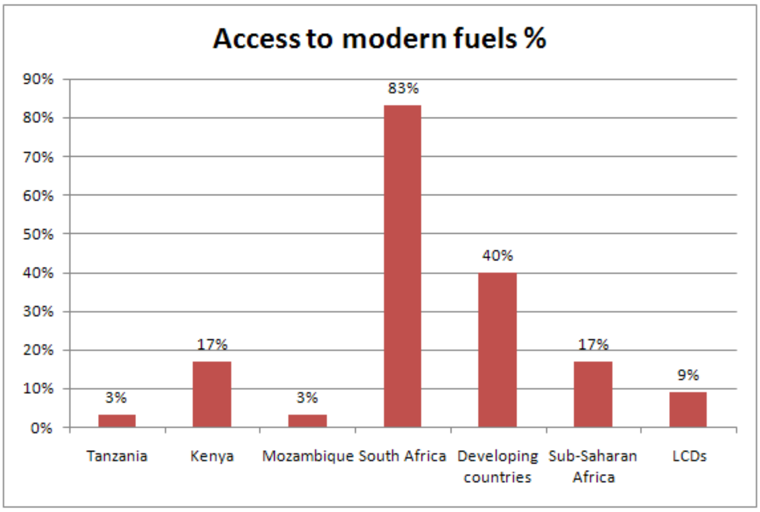


Figure 4.3.: Share of population with access to modern fuels, data 2007, [UNDP2]

### 4.1.3. EDI - Energy Development Index

The International Energy Agency (IEA) defined EDI in order to understand better the energy role in human development. It is and indicator which takes into account the progress in the transition of a country or region towards the use of modern fuels.

The World Energy Outlook (IEA report) publish the Energy Development Index every year, hoping to sensitize the international community on energy poverty problems and to help countries in monitoring their progress towards modern energy.

EDI is computed to reflect the Human Development index defined by UNDP and it's composed by four indicators, each of them captures a specific aspect of potential energetic poverty:

1. Commercial energy use per capita: it indicates the general economic development of a country;

2. Electricity consumption per capita in residential sector: in indicates consumers capability in paying for electric energy services;

3. Share of modern fuels of total in residential sector: indicating the level of efficiency and cleanliness in cooking;

4. Share of population with access to electricity

EDI is then computed as arithmetic mean of these four indices for each country. Similar to HDI, a value near to 1 states a considerable development within the country.

Figure 4.4 (Source [IEA2]) shows EDI, and the four indices composing it, for the four developing countries in analisys:

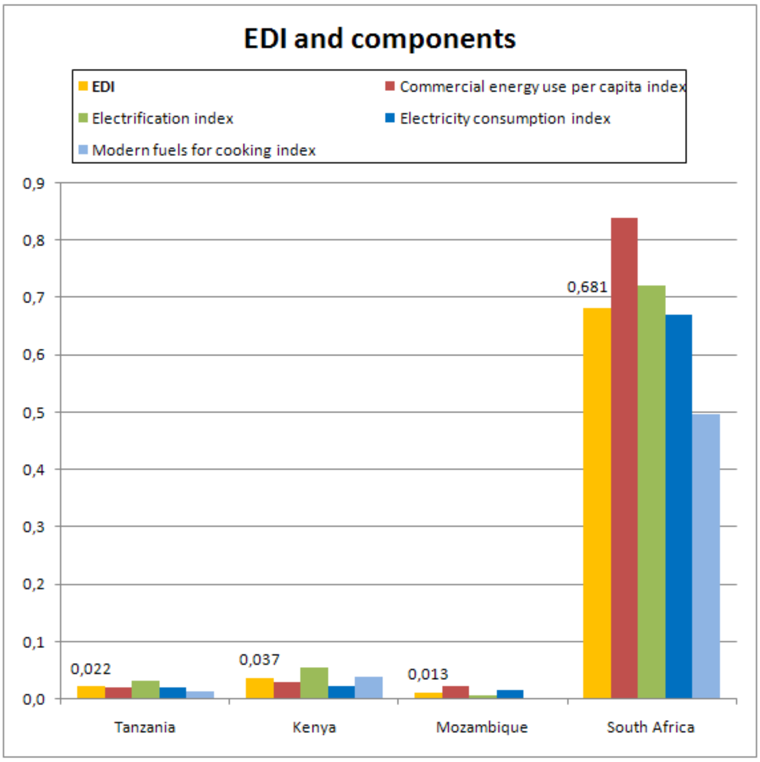


Figure 4.4.: EDI and components, data 2011

In the rank composed by 64 developing countries, Tanzania with an EDI value of 0,022 occupies the $60^{th}$position, with extremely low values of all the sub-indices composing EDI, the only ones placed below are in the order: Myanmar, Ethiopia, Mozambique (shown in the graph with an EDI equal to 0,013) and Democratic Republic of Congo. Kenya is just above Tanzania, in $59^{th}$position with 0,037. The situation in South Africa change significantly, it's characterized by medium-high levels in all the indices which allow the Country to obtain the $11^{th}$place with 0,681.

## Economic

Modern economies depend on a reliable and adequate energy supply, and developing countries need to secure this as a prerequisite for industrialization. All sectors of the economy (residential, commercial, transport, service and agriculture) demand modern energy services. These services in turn foster economic and social development at the local level by raising productivity and enabling local income generation. Energy supply affects jobs, productivity and development. Electricity is the dominant form of energy for communications, information technology, manufacturing and services. The economic indicators have two themes: Use and Production Patterns, and Security. The first has the sub-themes of Overall Use, Overall Productivity, Supply Efficiency, Production, End Use, Diversification (Fuel

Mix) and Prices. The second has the subthemes of Imports and Strategic Fuel Stocks.

Addressing energy security is one of the major objectives in the sustainable development: interruptions of energy supply can cause serious financial and economic losses. To support the goals of sustainable development, energy must be available at all times, in sufficient quantities and at affordable prices. Secure energy supplies are essential to maintaining economic activity and to providing reliable energy services to society. The monitoring of trends of net energy imports and the availability of appropriate stocks of critical fuels are important for assessing energy security.

In the following sections some economic indicators are defined.

### 4.1.4. TPES - Total Primary Energy Supply

TPES is made up of:

$$Indigenous\,Production + Import - Exports - International\,Marine\,Bunkers \pm Stock\,Changes$$

All different energy units are transformed to million tons of oil equivalent.

In 2009 Total Primary Energy Supply in Tanzania was 19,62 $Mtoe$ and, as can be seen from the past trend (Fig. 4.5), it's probably going to increase quite quickly in the coming years.

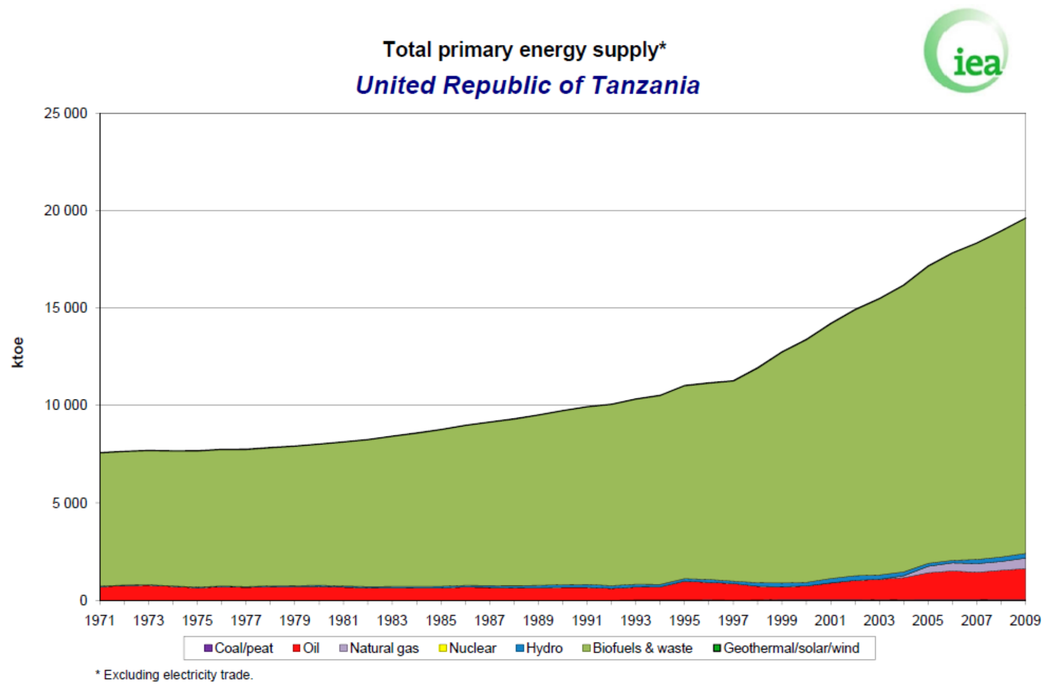


Figure 4.5.: TPES trend in Tanzania, data 2009, [IEA3]

In share of TPES (Fig. 4.6) biomass (wood and charcoal), considered in biofuels and waste slice, covers almost 88%, this is because households, both in rural areas and big cities, haven't got access to modern fuel and so they have to use biomass for cooking. Oil products (8%) are fully imported, gasoline and diesel are used for transport while kerosene is used for electric generations. Gas accounts for 2,8%, it's internal produced and its exploitation is growing in these years. Natural gas is used in gas-fired plants and in industrial processes.

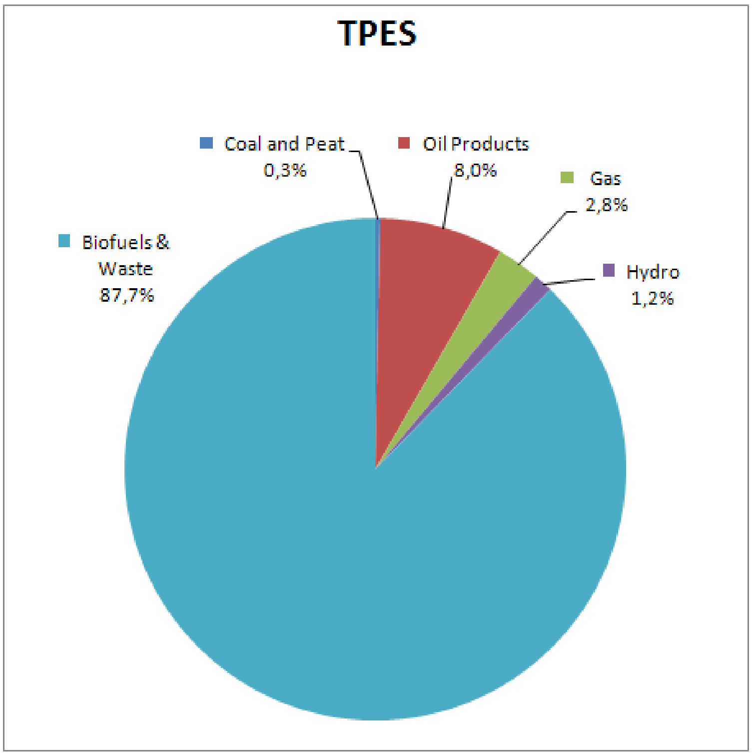


Figure 4.6.: TPES share in Tanzania, data 2009, [IEA3]

As done before with other indicators, to compare different countries, is better to consider the value of the indicator referred to the total population. From figure 4.7 is possible to notice that the mean energy supply of an inhabitant of the Earth is 1,80 *toe/capita*. This value will be of course lower than the request of an inhabitant of a developed country like Italy (2,74 *toe/capita*). The mean for the african continent, equal to 0,67 *toe/capita*, is almost one third of the world average, Tanzania, Kenya and Mozambique are all placed below the african average with similar values, respectively 0,45, 0,47 and 0,43 *toe/capita*, approximately six times lower of an italian resident.

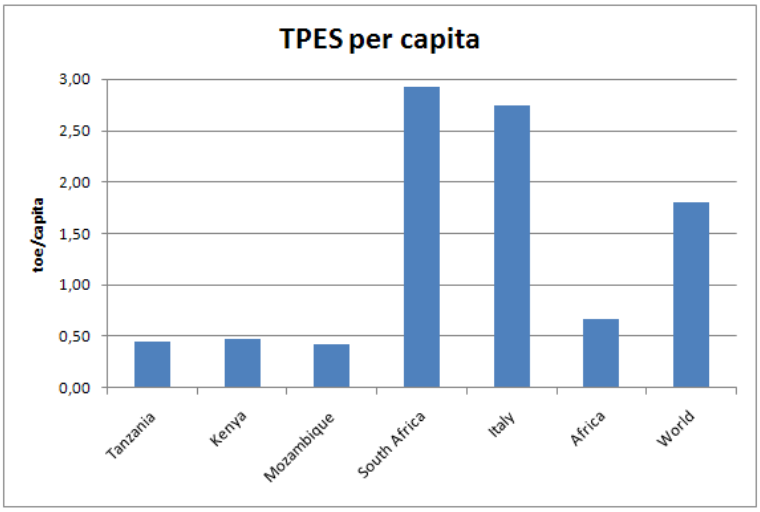


Figure 4.7.: TPES per capita, data 2009, [IEA2]

### 4.1.5. TFC - Total Final Consumption

This indicator is defined as the sum of the energy supplied to the final user for all energy uses. It is provided as total and broken down by sector. All different energy units are transformed to million tons of oil equivalent.

The sectors are:

- Agriculture/forestry
- Commercial/public services
- Residential
- Fishing
- Industry
- Non-energy use
- Non-specified
- Petrochemical feedstocks
- Transport

In Tanzania the Total Final Consumption value is around 17 $Mtoe$, 73% of it is covered by the residential sector as a great amount of wood and charcoal is used for households cooking. Other relevant contributions are to be attributed to Industry (13%) and transport (7%) (Fig. 4.8).

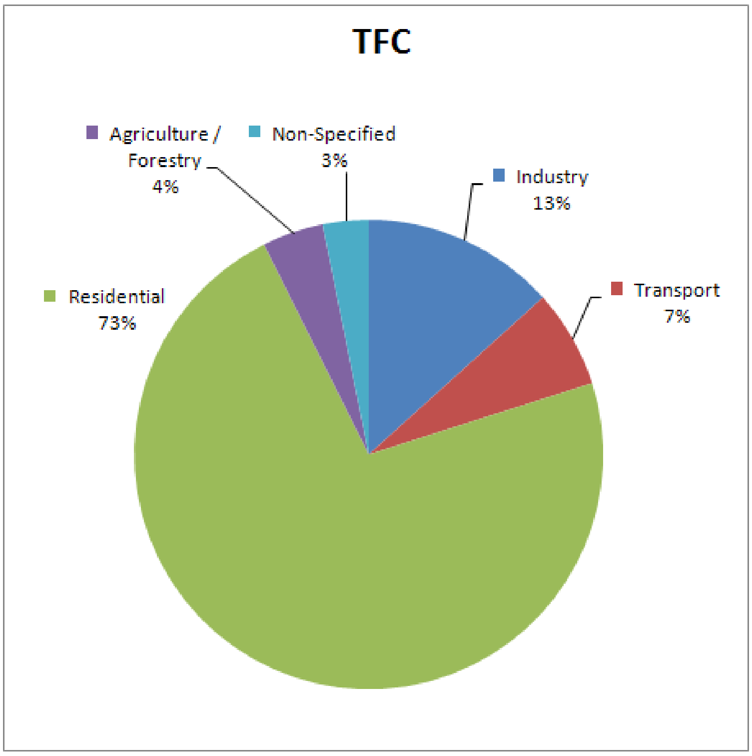


Figure 4.8.: TPES share in Tanzania, data 2009, [IEA3]

### 4.1.6. Energy intensity

Energy intensity is a measure of the energy efficiency and sustainability of a nation's economy. It's computed as unit of energy, in tons of oil equivalent (*toe*), to produce one unit of GDP:

$$EnergyIntensity = \frac{TPES}{GDP}$$

High energy intensities indicate a high price or cost of converting energy into GDP, low energy intensity indicates a lower price or cost.

Many factors influence an economy's overall energy intensity. It may reflect requirements for general standards of living and weather conditions in an economy. It is not atypical for particularly cold or hot climates to require greater energy consumption in homes and workplaces for heating (furnaces, or electric heaters) or cooling (air conditioning, fans, refrigeration). A country with an advanced standard of living is more likely to have a wider prevalence of such consumer goods and thereby be impacted in its energy intensity than one with a lower standard of living. Energy efficiency of appliances and buildings (through use of building materials and methods, such as insulation), fuel economy of vehicles, vehicular distances travelled (frequency of travel or larger geographical distances), better methods and patterns of transportation, capacities and utility of mass transit, energy rationing or conservation efforts, 'off-grid' energy sources, and stochastic economic shocks such as disruptions of energy due to natural disasters, wars, massive power outages, unexpected new sources, efficient uses of energy or energy subsidies may all impact overall energy intensity of a nation. Thus, a nation that is highly economically productive, with mild and temperate weather, demographic patterns of work places close to home, and uses fuel efficient vehicles, supports carpools, mass transportation or walks or rides bicycles, will have a far lower energy intensity than a nation that is economically unproductive, with extreme weather conditions requiring heating and cooling, long commutes, and extensive use of generally poor fuel economy vehicles.

In figure 4.9 is shown the energy intensity index for the five countries in analysis, the whole Africa and the World. It stands out that developed countries like Italy have the lowest values of this index, this means that they will have an highly developed economy that, due to a low amount of energy consumed, can contribute to the growth of the nation.

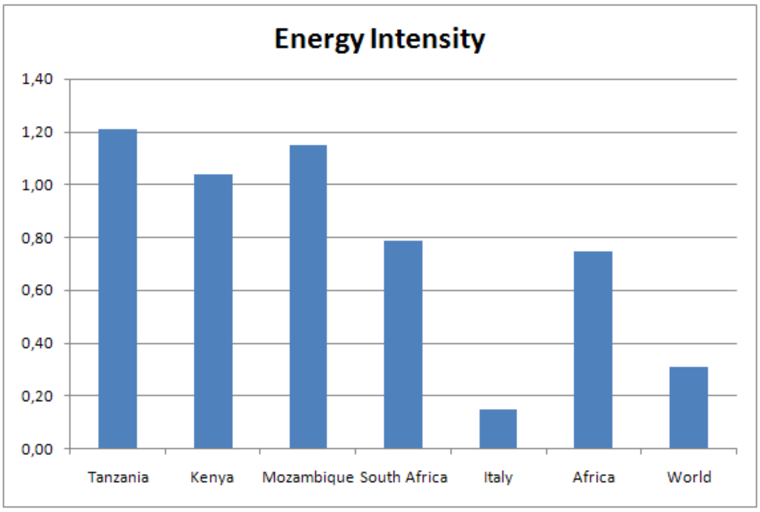


Figure 4.9.: Energy Intensity, data 2009, [IEA2]

Energy intensity in the african continent is 0,75 $toe/thousand2000USD$ , exactly five times higher than Italy. Even higher is the value for the african countries considered, touching the value of 1,21 in Tanzania, which eight times higher than the italian intensity, is therefore remarkable the difficulty in these countries in converting energy into economic activity, measured through GDP.

### 4.1.7. Electric energy consumption

Total net electric energy consumption is defined as follows:

$$EE_{Consumption} = EE_{GrossProduction} + EE_{import} - EE_{export} - EE_{losses} \ [TWh]$$

The pie chart in figure 4.10 explains clearly the situation in the world. Africa accounts only 3% of global electricity consumption and, of this percentage, South Africa takes 40% while all the other african countries together make up the other 60%. The share given by Tanzania, Kenya and Mozambique to the 60% slice is very low, in fact the sum of their percentage contribution is around 3,5% of total african consumption.

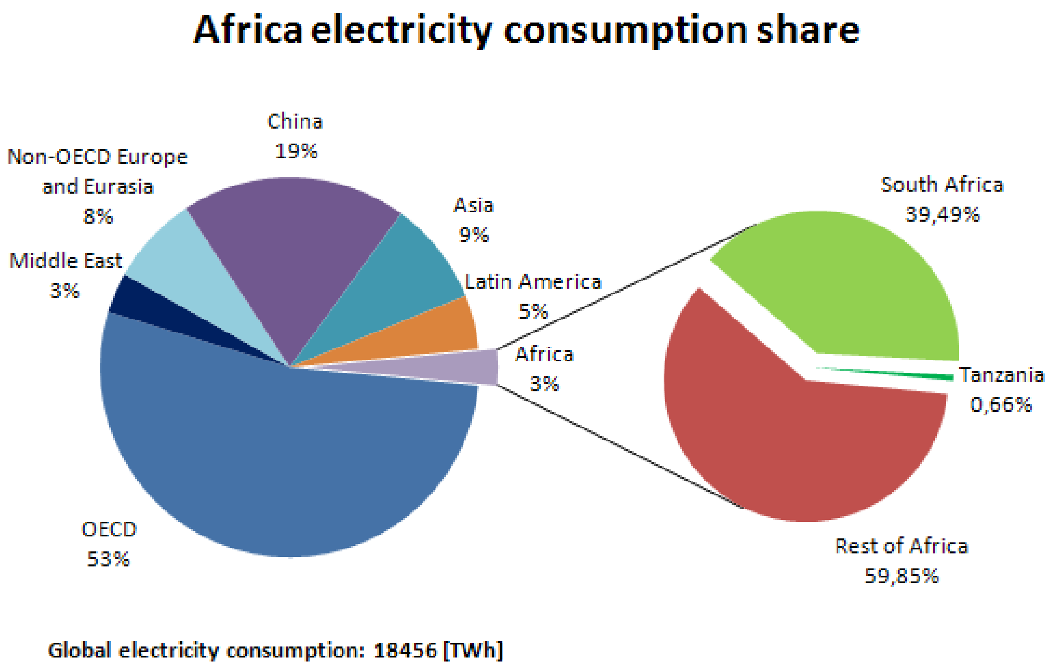


Figure 4.10.: Africa electricity consumption share, data 2009, [IEA2]

Referring to the value of this indicator per capita, measured in $kWh/capita$, is possible to compare the mean consumption for an inhabitant of the Earth with a generic citizen of the considered countries.

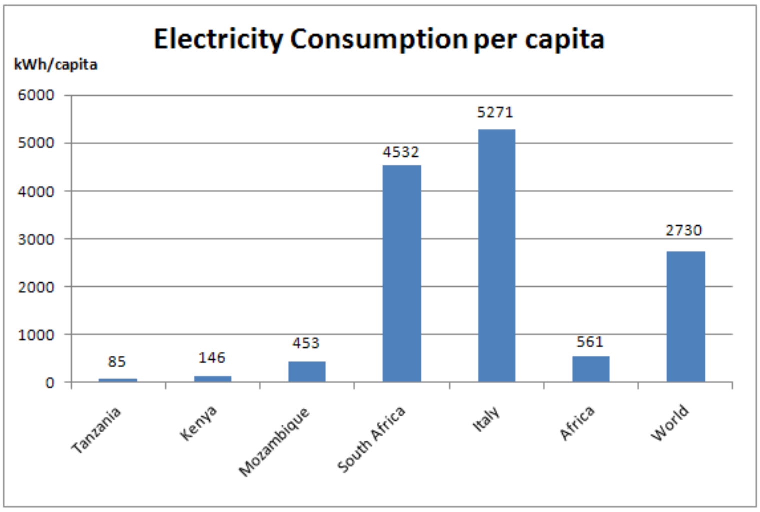


Figure 4.11.: Electricity Consumption per capita, data 2009, [IEA2]

South Africa and Italy stay high above the world average (2730 $kWh/capita$) with respectively 4532 and 5271 $kWh/capita$. The three other african countries lie at the bottom, with lowest values of electric energy consumption, all below the african continent average value of 561 $kWh/capita$. Particularly a Tanzanian citizen, with 85 $kWh/capita$, uses an amount of electricity 32 times lower than the world mean, and 62 times lower than an Italian citizen.

## Environmental

The production, distribution and use of energy create pressures on the environment in the household, workplace and city, and at the national, regional and global levels. The environmental impacts can depend greatly on how energy is produced and used, the fuel mix, the structure of the energy systems and related energy regulatory actions and pricing structures. Gaseous emissions from the burning of fossil fuels pollute the atmosphere. Large hydropower dams cause silting. Both the coal and nuclear fuel cycles emit some radiation and generate waste. Wind turbines can spoil pristine countryside. And gathering firewood can lead to deforestation and desertification.

The Environmental indicators are divided into three themes: Atmosphere, Water and Land.

The sub-themes on the Atmosphere are Climate Change and Air Quality. Priority issues include acidification, the formation of tropospheric ozone and emissions of other pollutants affecting urban air quality. Greenhouse gas emissions are central to the debate on whether humankind is changing the climate for the worse.

Water and land quality are other important themes of the environmental dimension. Land is more than just physical space and surface topography; it is in itself an important natural resource, consisting of soil and water, essential for growing food and providing habitat for diverse plant and animal communities. Energy activities may result in land degradation and acidification that affect the quality of water and agricultural productivity.

Land is also affected by energy transformation processes that often produce solid wastes, including radioactive wastes, which require adequate disposal. Water quality is affected by the discharge of contaminants in liquid effluents from energy systems, particularly from the mining of energy resources.

### 4.1.8. Carbon emission per capita

It measures the amount of carbon dioxide emission of the considered country, distributed on the total population, they result mainly from fossil fuels combustion for electricity production. The unit is $t_{CO_2}/capita$.

Figure 4.12 shows that on the Earth, the larger amount of emissions comes from OECD countries with 9,83 $t_{CO_2}/capita$. This is due to the huge use of fossil fuels for electricity conversion and transport. Global $CO_2tons$ per capita are equal to 4,29, the african one are much lower (0,92 $t_{CO_2}/capita$). South Africa emission are high (7,49 $t_{CO_2}/capita$), more than eight times than the african mean, particularly South Africa emits 40% of total african carbon dioxide emissions (due to the great use of coal for electric energy production). For Tanzania, Kenya and Mozambique the level of emission is less than the african value, this because electricity consumption per capita is very low (see figure 4.11), and the generation is based mainly on renewable energy (hydropower in Tanzania and Mozambique and hydropower and geothermal in Kenya).

However IEA in its 2010 "World Energy Outlook" says that the achievement of universal access to modern energy services by 2030, would result in modest increase in energy demand and $CO_2$ emissions. In 2030, global oil demand would have risen less than 1% and $CO_2$ emissions would be only 0,8% higher, compared with the New Policies Scenario (Ref. [IEA4]).

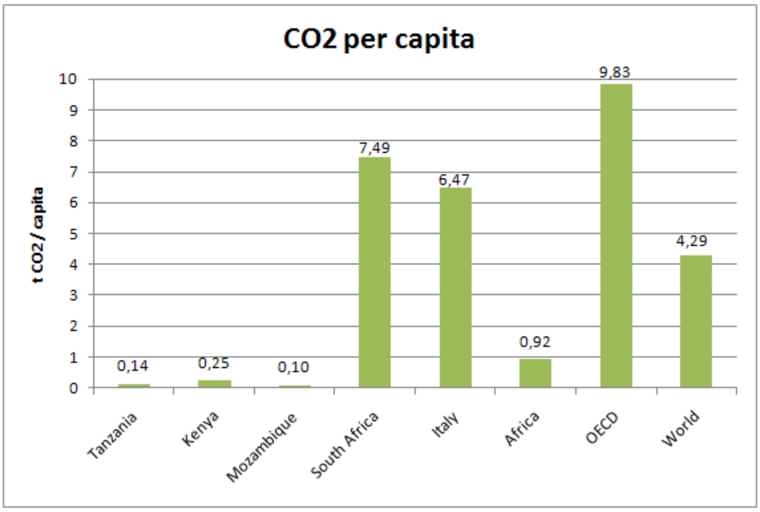


Figure 4.12.: $CO_2$ emission per capita, data 2009, [IEA2]

### 4.1.9. Woodfuel supply and demand balance

Large exploitation of solid biomass for inefficient cooking and heating practices can cause serious land degradation.

There is some localized deforestation, but depletion of forests in a large scale has not been found to be attributable to demand for fuelwood. Fuelwood is more often gathered from the roadside and trees outside forests, rather than from natural forests. Clearing of land for agricultural development and timber are the main causes of deforestation in developing countries. Studies at the regional level indicate that as much as two thirds of fuelwood for cooking worldwide comes from non-forest sources such as agricultural land and roadsides (Ref. [IEA4]). Charcoal, on the other hand, is usually produced from forest resources. Unsustainable production of charcoal in response to urban demand, particularly in sub-Saharan Africa, places a strain on biomass resources. Charcoal production is often inefficient and can lead to localized deforestation and land degradation around urban centers. Scarcity of wood typically leads to greater use of agricultural residues and animal dung for cooking. When dung and residues are used for fuel rather than left in the fields or ploughed back into fields, soil fertility is reduced and propensity to soil erosion is increased. Figure below shows the supply and demand balance of wood resources in East Africa. Red areas represent the risk of environmental impact due to overexploitation. In these areas, the supply of biomass energy resources is insufficient to meet the demand. The red deficit areas in Tanzania, along the border with Kenya, are the result of high consumption of fuelwood and charcoal, due to high population density and low levels of production of woody biomass.

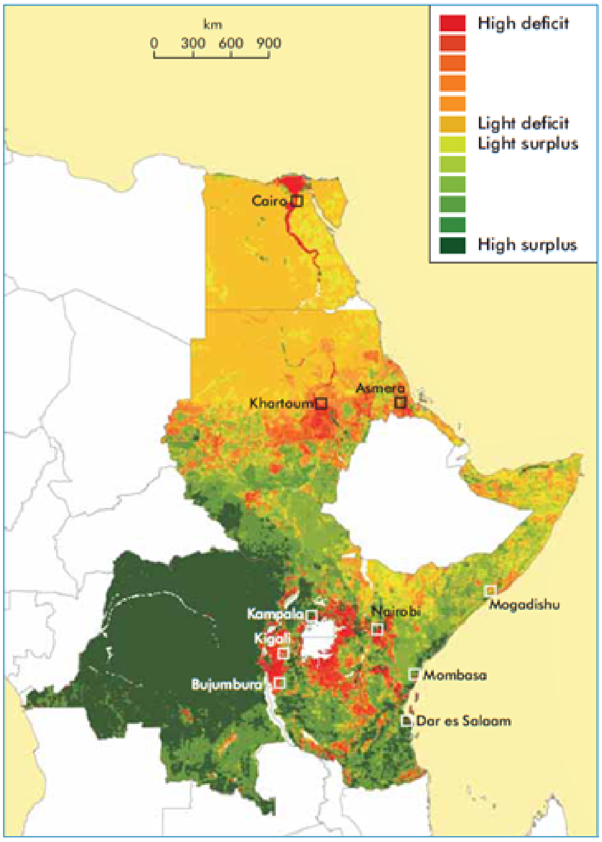


Figure 4.13.: Woodfuel supply and demand balance, data 2005, [FAO]

## 4.2. Energy sources

Tanzania is endowed with diverse energy resources including biomass, natural gas, hydro, coal, geothermal, solar and wind, uranium, much of which is untapped. Following the different sectors are listed with a brief introduction and the SWOT analisys (strengths, weaknesses, opportunities and challenges).

### 4.2.1. Oil

Tanzania has not yet found oil and is, therefore, completely dependent on imported petroleum products, nevertheless the presence of excellent unexploited but potential sedimentary basins has been assumed.

Petroleum sector is categorized into two categories namely upstream and downstream. Upstream activities involves exploration and production activities, while downstream includes importation, storage, transformation, export, inland transportation of crude oil and refined petroleum products, wholesale and retail distribution of petroleum products including liquefied petroleum gas. Exploration and production of petroleum is governed by the Petroleum Act of 1980. Petroleum exploration activities started in the country since early 1950s when British Petroleum (BP) drilled a number of wells along the coast and in the island of Zanzibar and Mafia. Tanzania Petroleum Development Corporation (TPDC) is responsible on behalf of the Government to oversee the development of petroleum exploration and production activities in the country. Currently there are 14 exploration companies operating in the country.

**Strenghts:** high level of interest in exploration in deep sea as well as shallow waters from international petroleum firms; effective health safety environment regulation and technical standard setting by Regulator.

**Weaknesses:** the Petroleum Products Price Setting Rules are inconsistent with Government policy to allow market forces to determine prices in competitive markets; differential fuel taxation, which is intended to assist low income households using kerosene for lighting and cooking, encourages adulteration of gasoline and diesel with kerosene.

**Opportnunities:** reduce landed costs through national procurement of refined products (system for this is nearly in place); produce ethanol in sufficient quantities for it to be introduced as a fuel extender to reduce petrol imports; use compressed natural gas as a transport fuel to reduce petroleum imports.

**Challenges:** ensure economic viability of biofuels and manage displacement impacts on more valuable agricultural crops, products and on rural livelihoods; provide employment, income and energy diversification benefits for local communities; manage environmental effects.

### 4.2.2. Natural gas

Although no liquid hydrocarbons have been discovered, Tanzania has so far made four discoveries of natural gas fields so far in the vicinities of Songo Songo Island (about 250 $km$ South of Dar es Salaam in 1974), Mnazi Bay (about 450 $km$ South of Dar es Salaam in 1982), Mkuranga (about 60 $km$ South of Dar es Salaam in December 2007) and Kiliwani North (about 2,5 $km$ South East of Songo Songo Island in April 2008). Only two gas fields, Songo Songo and Mnazi Bay are producing. Available data indicate that the proven and probable reserves in the Songo Songo gasfield are estimated at 22 billion standard cubic meter, while proven, the probable and possible reserves stand at 29,5 trillion standard cubic meters. The proven, the probable and possible gas reserves in Mnazi Bay vicinities are estimated at 59 trillion standard cubic meter. Four entities are actively carrying out downstream natural gas regulatory activities, are Tanzania Petroleum Development Corporation (TPDC), Songas Limited (Songas), PanAfrican Energy Tanzania Limited (PAT), and Maurel et Prom (M&P). Only TPDC (logo in fig.) with passive roles is licensed, others are contractors operating on their behalf and on behalf of TPDC, as under licensed entities through several agreements between them.

Figure 4.14.: Tanzania Petroleum Development Corporation logo

**Strenghts:** significant deposits, with good prospects for further discoveries; gas available close to good harbours, allowing to be readily traded internationally; positive experience of production sharing agreements with private firms; regulatory framework for downstream industries already established under Regulator (to become fully operational when Gas Act in place).

**Weaknesses:** lack of a national strategy for use of gas; lack of legal framework for gas sector; lack of transmission and distribution networks for gas utilisation (except for the limited network supplying gas to Dar es Salaam).

**Opportnunities:** use gas to consolidate power generation and to substitute more expensive or less desirable forms of energy for process heat, cooking and transportation; use gas as the feedstock of a petrochemicals industry, provided economic viability can be proven; export any surplus gas to regional or international markets.

**Challenges:** maintain a sense of dynamism, so as to ensure the commitment of existing investors and attract new investors; be able to remain effective in regulation of the sector even if it grows rapidly due to additional discoveries.

### 4.2.3. Coal

Coal resources similar in quality to the "Gondwana coals" of southern Africa occur in the Ruhuhu and Songwe-Kiwira basins in the Southwest Tanzania. A total of about 1,5 billion tons in reserves have so far been identified. The country's only coal mine at Kiwira has an average annual output of 35000 *tons*, all of which is consumed mostly locally for power generation.

**Strenghts:** reserves are large and will last the next two generations; multiple uses for electricity generation, industrial energy, process heaters, open fired systems, coke making, steel production; medium sulphur coal (0,7%); needs no special storage facility, easily stored at power plant for long periods of time; poverty alleviation due to economic benefits; not dependent on weather, used as backup for hydro, oil and gas; coal supply routes do not need to be protected at big costs.

**Weaknesses:** low heating values (24,1 $MJ/kg$); high ash content (24%); environmental constraint for mining activity and composition (metals, emissions and waste disposal); lack of infrastructure cause high cost of transportation.

**Opportnunities:** increasing demand of electricity in Tanzania (mining, industries, agriculture, commerce and household); potential use in cement industry after blending with imported low ash coals; switch over from imported coal to washed local coal provides potential costs reduction; potential use in conjunction with the development of the iron and steel industry; advanced technologies for further reduction of pollutants emission and improvement of efficiency; sustainable electric power tariffs.

**Challenges:** uneven quality of coal; technological challenges; coal resources occur in remote areas, infrastructure improvement is needed; lack of political decision making; people's mind set (coal identified with negative images).

### 4.2.4. Renewables

Renewable energy resources are expected to play a significant role in the supply of modern energy services in the country in future and to serve as an engine towards economical and social development of remote areas. This is largely due to their availability, suitability in addressing global concerns on environment and the need to make energy services available to rural and peri-urban areas where most of these resources exist.

At present, the following renewable energy technologies are being developed, promoted and disseminated:

- Small scale hydropower (see section 4.3.6).
- Modern biomass technology (co-generation, improved stoves, improved charcoal production, thermal-chemical gasification, briquettes, liquid biofuel production): biomass and agricultural waste have been recently utilized to generate electrical power in sugar and sisal industries.
- Solar energy: it enjoys almost equal level of sun radiation through out the year, all over the country.
- Wind for mechanical and electrical power: potential sites for eolic energy is in abundance in central and northern part of Tanzania. However, there are

some identified scattered locations in the country which, with average wind speed higher than 5 $m/s$, have potential for wind power developments.

- Development of liquid biofuels to supplement use of petroleum fuels.

**Strenghts:** supportive policy framework; comprehensive regulatory framework for small power (100 $kW$ to 10 $MW$); pilot projects demonstrating renewable energies; renewable energy industry association (TAREA) and growing local industries; tax and VAT exemptions for wind and solar.

**Weaknesses:** lack of comprehensive implementation strategies; lack of regulatory framework above 10 $MW$; uncoordinated initiatives and interventions; incomplete establishment of Quality Assurance system; weak interaction between Research and Development institutions; absence of Codes of Practice.

**Opportnunities:** unresolved problems with nuclear and petroleum fuels; rural electrification through off grid, stand alone RE; Clean Development Mechanism funding opportunities (Kyoto); regional integration promoting collaboration; trained technical personnel; RE training in higher learning institutions; multinational financing institutions proven successful in financing small scale RE; technological advances in conservation and efficiency; huge untapped potential of all RE sources except wood.

**Challenges:** inadequate attention paid to RE; lack of affordable technology for some RE; high up front cost barrier; concerns on the quality of products and services; failure of commercial banks in financing small scale RE; unsustainable use of wood based resources; inadequate attention to climate change and mitigation.

### 4.2.5. Uranium and minerals

Recent reports have indicated that uranium deposits have been discovered in the Tanzania mining sector and this is why several companies are exploring for it. In July 2009 Tanzania Ministry for Energy and Minerals has indicated, through other sources, that there are approximately 24,5 million kilograms of uranium oxide deposits available in the country. As a result of significant successful exploration expeditions as well as government investment incentives, the country's mining sector has become increasingly important to the overall economic standing of the country, which is expecting to welcome to new companies to the mining sector, with the purpose of working with the newly discovered uranium deposits. Overall, the sector is currently being dominated by gold, which is represented by the fact that Tanzania is the third largest producer on the continent of this precious mineral. However, in recent years, Tanzania has been looking to strengthen its position in the mining industry by exploiting its potential with Uranium and Nickel.

## 4.3. Electric energy

### 4.3.1. Electricity market

The electricity market is dominated by the Tanzania Electric Supply Company Limited (TANESCO), a parastatal organisation wholly owned by the government of Tanzania (details in section 4.3.3). Its business include: electricity generation, electricity transmission, electricity distribution and sale of electricity to the Tanzanian mainland and bulk power supply to the island of Zanzibar.

The Ministry of Energy and Minerals (MEM) and the Energy and Water Utilities Regulatory Authority (EWURA) regulate the operations of TANESCO.

The functions of EWURA include among others, licensing, tariff review, monitoring performance and standards with regards to quality, safety, health and environment. EWURA is also responsible for promoting effective competition and economic efficiency, protecting the interests of consumers and promoting the availability of regulated services to all consumers including low income, rural and disadvantaged consumers in the electricity, petroleum, natural gas and water sectors. The Energy and Water Utilities Regulatory Act (chapter 414 of the laws of Tanzania) gives also EWURA the mandate to issue, renew and cancel licenses of companies participating in the electricity industry.

Regarding the economic and technical regulation of the electricity industry, Tanzania's last electricity tariff adjustments occurred in 2008, so generators of power had to soak up increasing costs borne out of inflation or feedstock price rises. In the past, it was extremely difficult for EWURA to allow TANESCO to increase tariffs to profitable levels. The Govern tried to ensure that electricity was affordable to domestic and commercial (non-industrial) end users, who together accounted for 63% of total electricity consumption. The few industrial consumers of electricity who could have afforded higher tariffs accounted for less than 20% of overall consumption, so an across-the-board increase in tariffs would have a pronounced affect on Tanzania's domestic and commercial end users. Attempts at cross-subsidization also had minimal effects on TANESCO's balance sheet.

In recent times, significant growth within the mining industry has resulted in increased electricity demand from the industrial sector. Industrial sector entities, that previously generated their own power, are intent on growing their operations and require the availability of electricity to enable such growth. The stated willingness of the industrial sector to pay higher, but reasonable, tariffs has prompted EWURA to revisit its tariff determination policies. In November 2010, TANESCO sent a multi-year tariff order application to EWURA, requesting average tariff increases of about 26% per annum from 2011 to 2013. In January 2011, EWURA granted TANESCO a 21,3% increase, signifying intent by Tanzania's policy makers to minimise the effect of tariff rises on the industry's operations and growth. In general, tariffs are expected to continue increasing in order to: cover TANESCO's losses, pay for emergency power generation and fund capacity expansion, either directly or indirectly. Actual prices (2012) and the related categories are shown in

Tanzanian Shillings ($TZS$) in the tables below, the conversion rate is: 1 $USD$ = 1700 $TZS$.

| | |
|---|---|
| Domestic low usage tariff (D1) | This category covers domestic customers who on average have a consumption pattern for 50 $kWh$. The 50$kWh$ are subsidized by company are not subjected to service charge. Under the category any unit exceeding 50 $kWh$ is charged a higher rate up to 283,4 $kWh$. In this tariff category, power is supplied at a low voltage, single phase (230 $V$). |
| General usage tariff (T1) | This segment is applicable for customers who use power for general purposes: including residential, small commercial and light industrial use, public lighting, and billboards. In this category the average consumption is more 283,4 $kWh$ per meter reading period. Power is given at low voltage single phase (230 $V$), as well as three phase (400 $V$). |
| Low voltage maximum demand (MD) usage tariff (T2) | Applicable for general use where power is metered at 400 $V$ and average consumption is more than 7500 $kWh$ per meter reading period and demand doesn't exceed 500 $kVA$ per meter reading period. |
| High voltage maximum demand (MD) usage tariff (T3) | Applicable for general use where power is metered at 11 $kV$ and above. |

Table 4.1.: Tariff categories. Source [TAN1]

| | Domestic Low Usage (D1) | General Usage (T1) | Low Voltage Max (T2) | High Voltage Max (T3) | Zanzibar |
|---|---|---|---|---|---|
| Low Energy (0-50 $kWh$) per $kWh$ | 60 | 157 | 94 | 84 | 83 |
| Service charge per month | - | 2303 | 8534 | 8500 | 8534 |
| Demand charge per $kVA$ | - | - | 9347 | 8669 | 4755 |
| Energy charge per $kWh$ | - | 129 | 85 | 79 | 75 |

Table 4.2.: Tariffs. Source [TAN1]

### 4.3.2. Electricity service

In the urban areas 40% of population has access to electricity but 85% of total population lives in rural areas and only 2% of them is connected to the national grid (Fig. 4.15).

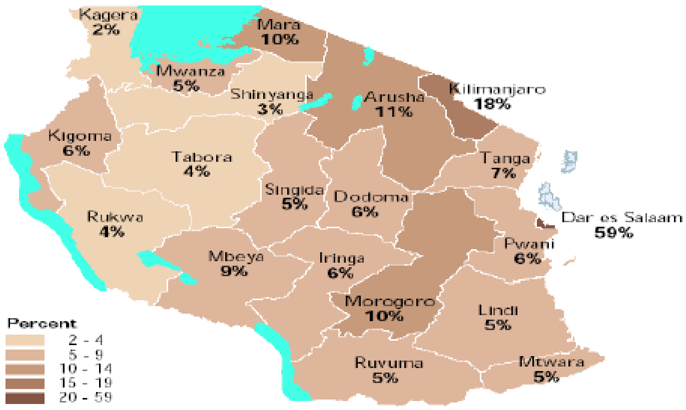


Figure 4.15.: Access to grid electricity, [DIT]

Tanzania, East Africa's second largest economy, is currently experiencing power shortages that are anticipated to restrain the country's potential for economic growth. The power shortages have resulted in up to 12 hours of daily load shedding, leading the International Monetary Fund to adjust Tanzania's 2011 economic growth forecasts from 7,2% down to 6%. The Ministry of Energy and Minerals has developed an ambitious power plan, whose successful implementation will see Tanzania increase its installed electricity capacity by 65% within 12 months at a cost of 318 million $USD$. However, legitimate concerns have been raised by stakeholders over the MEM and TANESCO's ability to supply uninterrupted electricity to Tanzania's key economic sectors.

Much of Tanzania's electricity is generated from four hydro-powered stations, but the increased occurrence and intensity of droughts has significantly reduced Tanzania's generating capacity (to between 25% and 45% during severe droughts). The implications of droughts on the availability of power were forecasted even before 2004, when the first severe drought occurred, but in the last 7 years the Tanzanian electricity industry has achieved limited success in diversifying its energy feedstock mix. Despite this external cause had highly influenced the continuity of the service, TANESCO fully recognizes that its performance in the recent years has not been acceptable: widespread and painful blackouts throughout the grid were strongly influenced by the severe drought but also by its lack of funds to maintain and make even minimal improvements in the distribution facilities and existence of inefficiencies in management and operations. Similarly, its inability to connect new customers for lack of adequate equipment, even though many of these potential consumers had already made the necessary deposits, has caused great dissatisfaction.

The company is designing an ambitious business plan for the coming years, aimed at eliminating its inefficiencies as fast as possible and achieving a sustainable improvement in quality of electricity supply and customer service. However, it will be impossible to achieve improved outcomes unless TANESCO receives a tariff increase that will allow to finance improvements.

The SWOT analisys for the elecricity sector is reported below:

**Strenghts:** skilled personnel in many of the important posts in the state electricity institutions; diversified resources for electric generation; activities of agencies like Rural Energy Agency and EWURA; government policy, legislation and institutions in place to encourage private participation in the electricity sector, especially in small power sector.

**Weaknesses:** monolithic power utility (TANESCO), with insufficient levels of investment to maintain a secure electricity supply for the country; prevailing electricity tariff is not cost reflective; lack of experienced middle level staff; project preparation and prioritisation processes are not being adhered; lack of reserve margin needed to avoid frequent and costly supply interruptions; generation capacity standing idle due to deficient past procurement and present drawn-out legal disputes; very low connection rates and per capita electricity usage, particularly in the rural areas.

**Opportnunities:** achieve more efficient use of electricity through demand side management; achieve financial viability and operational efficiency within the electricity sector; integrate electricity investments at the national and local level with socio-economic development opportunities; connect isolated regions presently supplied by diesel generators to the national grid; take advantage of regional electricity trade opportunities within the South African and East African power pools; achieve a 'greener' electricity sector by paying attention to the environment and renewable generation options.

**Challenges:** obtain public support for substantial electricity tariff increases; create an environment in which consensus can rapidly be achieved on electricity sector restructuring; ensure that future private sector participation in the electricity industry offers sustainable mutual benefits to the nation and the investors; raise more than 18 billion $USD$ required for the implementation of 'Power System Development Plan' up 2033.

### 4.3.3. TANESCO

Figure 4.16.: Tanesco logo

TANESCO is a parastatal organization whole owned by the Government. The main functions are generation, transmission, distribution and sale of electricity to Tanzania mainland and in bulk to the Islands of Zanzibar.

For the first time public electricity was started in 1908 by German colonialists in Tanganyika at Dar es Salaam. In 1920 when Tanganyika was mandated to Great Britain, a Government department was formed to take over and operate the supplies left by the German and so in 1931 the Government handed over the undertaking to private enterprises, one of the companies was Tanganyika Electric Supply Company Ltd (TANESCO) which was established in 1931. After Independence in 1961 the Government bought all the shares of TANESCO. Since Independence TANESCO is planning new power projects in order to meet the increasing industrial, commercial, township and rural power demand. In 1995 the Government embarked on rural electrification starting with regional headquarters, district headquarters and potential rural areas.

In 1999 TANESCO was unbundled vertically and horizontally, separating transmission, generation and distribution. Generation and distribution were also privatized but TANESCO, still state-owned, remains in a leader position, and it is still the responsible of most of the small isolated networks. The gas turbines were born for distillate fuel but afterwards they would be converted to natural gas due to reserves exploitation. TANESCO imports electricity for local supply in two areas that are not connected to the main national grid: from Uganda to the Kagera region and from Zambia to the Mbozi district.

Currently the workforce of TANESCO is about 5000 employees, customers stand at 800000 and plans are on to connect 100000 customers every year.

#### Generation

TANESCO Generation division is responsible for all power generation functions owned by TANESCO. Other sources of generation are from independent power producers (IPPs) which feed the national grid and isolated areas as well. TANESCO generation system consists mainly of hydro and thermal based generation. Hydro contributes the largest share of TANESCO power generation and 73% of total electricity generated from October 2009 up to September 2010 came from this sector

(Ref. [TAN1]). Gas and thermal contributed the remaining amount. During the year 2010 the total amount of energy generated by the grid and isolated plants was 4938 GWh. The hydro-plants operated by TANESCO are all interconnected with the national grid system and their total installed capacity of 561 MW is divided as described in table 4.3.

| Power plant | Region | Gross head $[m]$ | Discharge capacity $[m^3/s]$ | Generating capacity $[MW]$ | Number of units | Annual productivity $[GWh]$ | Start year |
|---|---|---|---|---|---|---|---|
| Kidatu | Iringa | 175 | 140 | 204 | 4 | 800 | 1981 |
| Kihansi | Iringa | 852 | 24 | 180 | 3 Pelton | 1000 | 2000 |
| Mtera | Dodoma | 106 | 96 | 80 | 2 | 300 | 1980 |
| Pangani | Tanga | 170 | 46 | 68 | 2 Francis | 367 | 1994 |
| Hale | Tanga | 70 | 38 | 21 | 2 Francis | 91 | 1964 |
| Nyumba ya Mungu | Kilimanjaro | 27 | 34 | 8 | 2 Francis | 35 | 1969 |

Table 4.3.: TANESCO hydropower plants. Source [DIT]

TANESCO has been implementing power generation mix program, whereby a substantial amount of generation comes from thermal generation through own generation and independent power plants (IPPs). Own thermal generation comes from the Ubungo 100 $MW$ gas fired plant in Dar es Salaam (Fig. 4.18) and a new 45 $MW$ gas fired power plant located at Tegeta in Dar es Salaam entered the grid system.

By the end of year 2008 IPPs contributed a total installed capacity of 282 $MW$. IPPs powering the national grid include the Independent Power Tanzania Ltd (IPTL) with 100$MW$ (diesel based) installed capacity and SONGAS (Songo Songo gas to electricity project) which by the end of 2007 had 182 $MW$ capacity. There are also several diesel generating stations connected to the national grid in Dar es Salaam, Mwanza, Tabora, Dodoma, Musoma and Mbeya. These have installed capacity of 80 $MW$ but the only operational grid diesel based station is Dodoma which contributes about 5 $MW$ and the rest are due for disposal due to obsolescence and high maintenance costs. However a short term plan is being implemented to replace the retired capacity by a 60 $MW$ plant at Nyakato, Mwanza by 2011.

The other regions, districts and townships namely, Kigoma, Mafia, Mpanda, Tunduru, Songea, Liwale, Ikwiriri, Masasi, Mbinga, Ludewa, Ngara, Bihalamulo, and Kilwa Masoko (Fig. 4.17) are dependent on isolated diesel – based generators with a total installed capacity of 31 $MW$. Mtwara and Lindi are supplied by M/S

Artumas Group Ltd, an IPP based in Mtwara. The total capacity of Artumas power plant is 8 $MW$ using gas from Mnazi Bay gas wells in Mtwara.

TANESCO also imports a total of 10 $MW$ of electric power for Kagera Region from Masaka substation in Uganda while Sumbawanga, Tunduma and Mbozi districts receive about 3 $MW$ from neighbouring Zambia.


Figure 4.17.: Townships dependent on isolated diesel

Figure 4.18.: Ubungo gas plant

The total installed capacity in the main grid system amounts 1092 $MW$. The system is hydropower dependent, constituting about 51% of total installed capacity. Thermal generating capacity forms the rest, mainly from IPPs (Fig. 4.19).

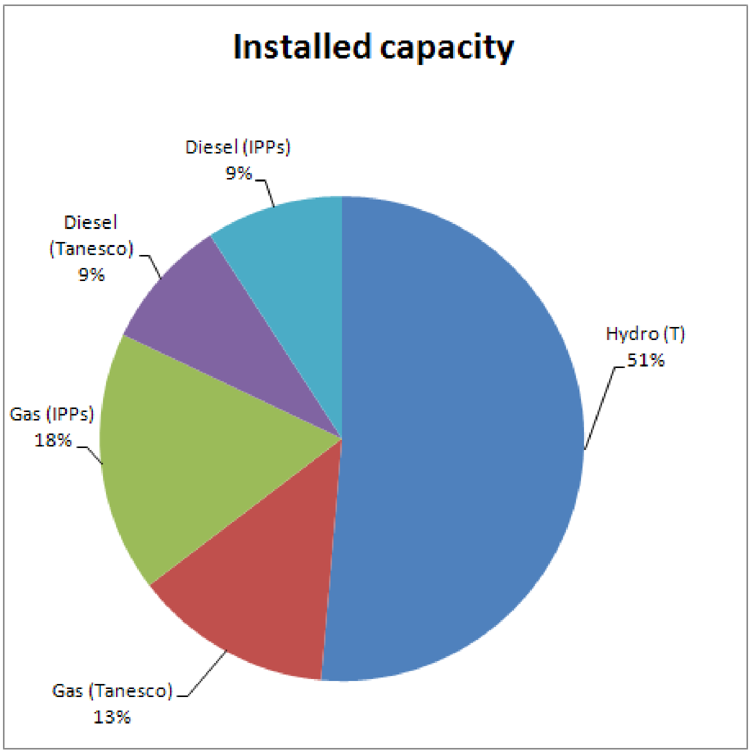


Figure 4.19.: Installed capacity [$MW$]. Source [DIT]

### Transmission

TANESCO owns interconnected power grid made up of generation system transmission and distribution system. Transmission system comprises of 38 grid substations interconnected by transmission lines. The transmission lines comprise of 2732 $km$ of system voltages 220 $kV$; 1538 $km$ of 132 $kV$; and 546 $km$ of 66 $kV$, totaling to 4817 $km$ by the end of September, 2009. Transmission lines use pylons made of steel. Almost all the transmission lines are radial single circuit lines. The system is all alternating current and the system frequency is 50 $Hz$.

The Main grid system demand of 2009 was 755,41 $MW$ as recorded on November 16th, 2009 at 20hrs. By August 9th, 2010 the highest grid system demand was 802 $MW$ at 21 hrs. The Transmission system losses is in the range of 5% to 6% (5,16% record of 2008 and 6,10% as recorded in august 2009). Including also distribution losses a value of 19% is reached [WB2].

TANESCO operates the grid system by dispatching all available generation plants in order to service the load required by its customers and to maintain the required high voltage levels in a bid to maintain the required power quality, reliability and the appropriate safety standards. To achieve the above, TANESCO utilizes high tech equipment at its Grid Control Centre (GCC) and its numerous substations all around the country. To ensure sustainability in the generation and transmission capacity, TANESCO prepares plans for the short, medium and long-term and continuously seek for funding to implement generation and transmission addition projects as well as for maintaining the current infrastructure.

### 4.3.4. Rural energy agency

Rural Energy Agency (REA) is an autonomous body under the Ministry of Energy and Minerals of the United Republic of Tanzania. Its main role is to promote and facilitate improved access to modern energy services in rural areas of mainland Tanzania for social and economic development. REA became operational in October 2007.

The majority of rural tanzanians have no access to modern energy services. The government maintains that rural Tanzania cannot be transformed into a modern economy, and that rural tanzanians' livelihoods can't be improved significantly without a dramatic improvement in their access to modern energy services.

The National Energy Policy 2003 sets national energy objectives to ensure availability of reliable and affordable energy supplies, and to promote efficient energy use in order to support national development goals. The policy recognizes that, the main thrust has to be based on private initiatives and investments for exploitation of local energy sources. The policy sets an entirely new approach to modern energy in rural areas of Tanzania and the government has committed itself to develop and implement the new strategy to address modern energy needs of over 85% of Tanzanians living in rural areas.

An improved energy supply in the rural areas through public and private sector participation, will contribute significantly in improvement of the livelihoods of the rural population and the attainment of sustainable economic growth. For these reasons, the Rural Energy Board (REB), the Rural Energy Agency (REA), and the Rural Energy Fund (REF) were established and entrusted with the role of promoting, stimulating and facilitating improved access to modern energy services in rural areas through empowering both public and private sector initiatives. In fact REA works in partnership and collaboration with private sector, Non Governmental Organizations, Community Based Organizations, and Government agencies.

The main functions of REA are the following:

- promote, stimulate, facilitate and improve modern energy access for productive uses in rural areas in order to stimulate rural economic and social development
- promote rational and efficient production and use of energy, and facilitate identification and development of improved energy projects and activities in rural areas
- pinance eligible rural energy projects through REF
- prepare and review application procedures, guidelines, selection criteria, standards and terms and conditions for grants allocation

- build capacity and provide technical assistance to project developers and rural communities
- facilitate preparation of bid documents for rural energy projects

### The Rural Energy Fund

The Rural Energy Fund (REF) was established by The Rural Energy Act, 2005 for the purpose of providing grants to qualified project developers.

The Fund Provides resources for:

- grants towards the capital costs of projects implemented by private and public entities, co-operatives, and local community organizations
- the provision of technical assistance, training and other forms of capacity building to qualified developers by qualified experts related to the planning and preparation of a project prior to an application for a grant
- the provision of financial assistance. Co-financing investments in innovative pilot and demonstration projects and applications for renewable energy when development partners make special purpose funds available for that purpose

The Fund does not provide grants towards the operating or debt service costs of any project or developer.

The sources of income for the Fund consist of monies as may be provided:

- by Government, in an annual budgetary allocation
- as contributions from international financial organizations, multilateral and bilateral agencies and other development partners
- from levies of up to five percent (5%) on the commercial generation of electricity to the national grid
- as fees in respect of programmes, publications, seminars, consultancy services and other services provided by the REA
- as development partners' contributions for rural energy
- as interest or return on investments

A trust agent, currently Tanzania Investment Bank (TIB), is responsible for disbursement of grant payments from the Fund and ensuring that any pre-conditions set by the Board for making a grant payment are met by developers.

### The Rural Energy Board

Both the Rural Energy Agency and the Rural Energy Fund are governed by the Rural Energy Board (REB). The Rural Energy Board consist of the following members:

- a representative from the Ministry responsible for energy
- a representative from the Ministry of Finance
- a representative from the Ministry responsible for regional administration and local government;
- a representative of the Private Sector
- a representative of the Tanzanian Bankers' Association
- a representative of a civic society; a representative of the Development Partners
- a representative of consumers

Subject to the overall direction of the Rural Energy Board, REA is headed by the Director General who is the chief executive officer for the Agency as well as the Rural Energy Fund. REA has a lean management structure comprising of two directorates; one responsible for Finance and Administration, and the other for Technical Services.

## 4.3.5. Other energy players

Other main players in the energy sector are:

- The Ministry of Energy and Minerals (MEM) has still the overall governance of the electricity industry.
- The Energy and Water Utilities Regulatory Authority (EWURA), born in 2001 when the Government pushed to create a single agency for the regulation of the water and energy sectors.
- The monopoly and vertical integrated Zanzibar State Fuel and Power Corp. (ZSFPC) is the only responsible of Zanzibar supply.
- Indipendent Power Producers (IPP), mainly the Independent Power Tanzania Limited (IPTL), which owns and operates diesel generating plant at Tegeta in Dar es Salaam, and the Songas Limited.

### 4.3.6. Hydropower

Tanzania has basins draining towards the three oceans in the east, west and north of the African continent. The oceans and seas are the Indian, Atlantic and Mediterranean. Some river basins drain eastward into the Indian Ocean, for example the Rufiji river basin. Others drain northward into the Mediterranean Sea through the Nile basin. Others drain westward into the Atlantic Ocean through Lake Tanganyika's basin.

Tanzania has the highest peak of Africa namely Kilimanjaro which used to be covered by ice throughout the year. The Kilimanjaro ice and natural springs are the a source of the Pangani river, home to hydropower plants. Tanzania has the largest hydropower potential in East African Community (Kenya, Tanzania, Uganda, Rwanda and Burundi), it has about 5 $GW$, with only about 10% tapped.

Tanzania has the two highest head hydropower projects in Africa. Lower Kihansi (850 $m$, Fig. 4.20) which became operational in late 1999 and Rumakali (1200 $m$) which is studied to a feasibility level. The East African Rift system that influences hydropower potential traverses in Tanzania with eastern and western branches.

Figure 4.20.: Lower Kihansi dam

#### Small and Mini Hydropower

Potential small scale hydropower sites are situated in remote isolated areas (Fig.4.21), their development is expected to serve as an engine towards economical and social development of the remote tanzanian communities which are supplied by isolated diesel powered stations.

Operation of diesel stations in the remote isolated systems depends on the expensive imported fuel which is a cost to the national economy. This fact opens a challenge to develop small hydropower to supply cheap and environmentally friendly electricity to the isolated communities.

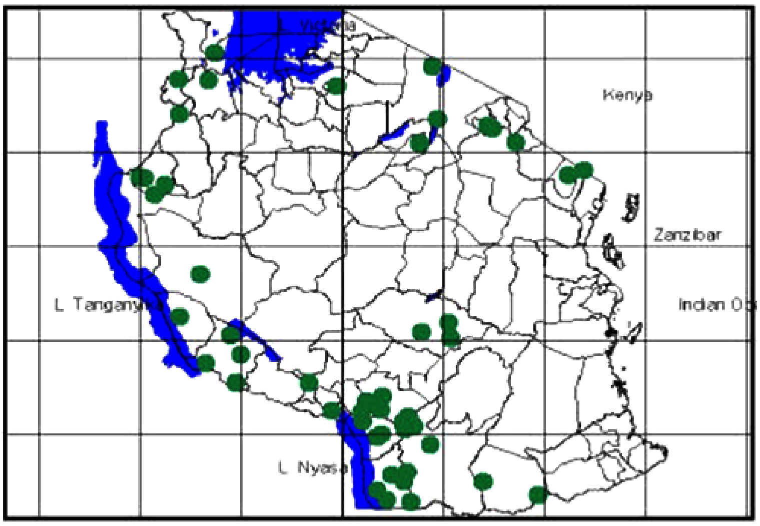


Figure 4.21.: Small hydropower potential, [DIT]

The government policy on small hydropower is to develop small sites in areas which are not supplied with power from the national grid or to replace diesel generation in isolated areas. Based on this policy, several small scale hydropower development activities have been initiated by the government in cooperation with local and foreign agencies.

The government underscores the advantages of investing in hydro electricity generation for those sites which have been evaluated and proved to be viable. Following the recent reforms of the power sector (trade liberalisation, opening doors to private investors, privatisation of public utilities, etc) it is anticipated that private firms will also increase their interest to invest in hydro electricity generation.

## 4.4. Energy strategy

There are several options to alleviate poverty in relation to sustainable energy. Some of them are:

**Rural electrification** through extension of the national electricity grid to boost small and medium enterprises and other productive activities in rural areas.

**Energy efficiency** which can reduce the demand for biomass for several activities.

**Promotion of appropriate (environmentally sound) energy technologies** for mechanized agriculture, water pumping, agro-processing, educational and health facilities.

**Agro forestry** with multipurpose tree growing.

Tanzania's strategy as regards to energy poverty reduction include (Ref. [MINE]):

- Promoting affordable and reliable energy supplies in the whole country.
- Reforming the market for energy services and establish an adequate institutional framework.
- Enhancing the development and utilisation of indigenous and renewable energy sources and technologies.
- Taking adequate account of environmental concerns in all energy activities.
- Promoting energy efficiency and conservation in all sectors.
- Increasing energy education and building gender-balanced capacity in energy planning, implementation and monitoring.
- Capacity building in terms of skills for managing appropriate energy technologies and financial resources.
- Substantive involvement of the local people in energy and poverty planning aspects.
- Improving the availability and access to energy services, including promotion of utilisation of renewable energy technologies at grassroots level.
- Promoting more efficient and sustainable utilisation of traditional fuels for income generating activities at grassroots levels.
- Information and awareness creation on the possibilities and options available in increasing energy services.

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# Part II.

# Mini hydro technology

# 5. Mini hydro schemes

There is no consensus among the different countries on the mini hydro power size definition, the upper limit can range from the 1,5 $MW$ of Sweden to the 20 $MW$ of UK. For the purposes of this text any scheme with an installed capacity of 10 $MW$ or less will be considered as mini.

## 5.1. Run-of-river

Run-of-river schemes are where the turbine generates electricity as and when the water is available and provided by the river. When the river dries up and the flow falls below some predetermined amount or the minimum technical flow for the turbine, generation ceases. Medium and high head schemes use weirs to divert water to the intake, it is then conveyed to the turbines via a pressure pipe or penstock. Penstocks are expensive and consequently this design is usually uneconomic. An alternative is to convey the water by a low-slope canal, running alongside the river to the pressure intake or forebay and then in a short penstock to the turbines. If the topography and morphology of the terrain does not permit the easy layout of a canal, a low pressure pipe can be an economical option. At the outlet of the turbines, the water is discharged to the river via a tailrace.

## 5.2. Existing dam

A small hydropower scheme cannot afford a large reservoir to operate the plant when it is most convenient, the cost of a relatively large dam and its hydraulic appurtenances would be too high to make it economically viable. But if the reservoir has already been built for other purposes, such as flood control, irrigation, water abstraction for a big city, it may be possible to generate electricity using the discharge compatible with its fundamental use or the ecological flow of the reservoir. The main issue is how to link headwater and tail water by a waterway and how to fit the turbine in this waterway. If the dam already has a bottom outlet, the powerhouse could be installed at its exit.

Provided the dam is not too high, a siphon intake can be installed. Integral siphon intakes provide an elegant solution in schemes, generally, with heads up to 10 $m$ and for units up to about 1000 $kW$. The turbine can be located either on top of the dam or on the downstream side. The unit can be delivered pre-packaged from the works, and installed without major modifications to the dam.

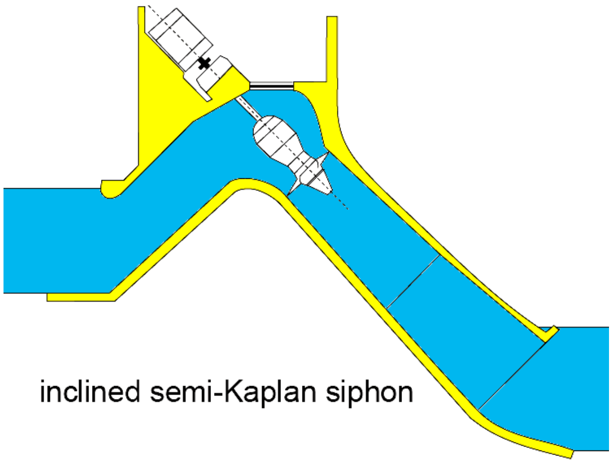


Figure 5.1.: Siphon scheme

## 5.3. Schemes integrated within a canal

In the design phase the canal is enlarged to accommodate the intake, the power station, the tailrace and the lateral bypass. The lateral bypass is needed to safeguard the water supply for irrigation and in case of shutdown of the turbine. This kind of scheme should be designed at the same time as the canal, as additional works while the canal is in full operation can be a very expensive option.

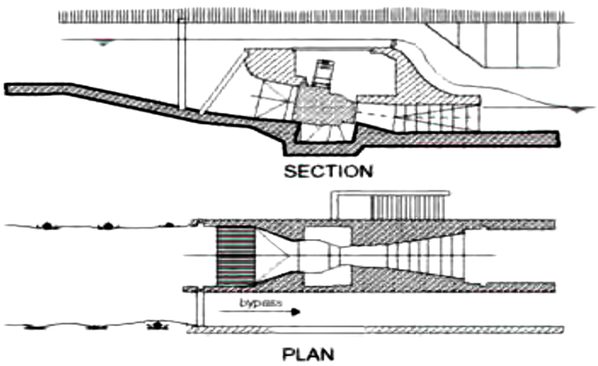


Figure 5.2.: Integrated within canal scheme

# 6. Evaluating streamflow

All hydroelectric generation depends on falling water. This makes hydropower extremely site dependent. First of all, a sufficient and dependable stream flow is required. Secondly, the topographic conditions of the site must allow a sufficient head for power generation. This head can be created by dams, weirs or by leading the water in parallel to the river in a waterway with low head losses compared to the natural stream, or very often by a combination of both.

## 6.1. Discharge records

When a site has been identified as topographically suitable for hydropower, the first task is to investigate the availability of an adequate water supply. Unfortunately, it is rather unusual for regular gauging to have been carried out in the stretch of river where the development of a small hydro scheme is proposed. Whether or not regular gauging has taken place, the first step is to do some research, to ascertain if there are stream flow records for the stretch of river in question. If not, then in other stretches of the same river or a similar nearby river that permits the reconstitution of the time series for the referred stretch of river.

### 6.1.1. World Meteorological Organisation

The United Nations organisation 'World Meteorological Organisation' provides an hydrologic information service 'Infohydro' whose aim is to promotes water-resources assessment and provides the forecasts needed to plan water storage, agricultural activities and urban development. Further information can be obtained at the website:
'http://www.wmo.int/pages/prog/hwrp/INFOHYDRO/infohydro_index.html'

### 6.1.2. Food and Agriculture Organization

The United Nation organisation FAO provides a software named 'New_LocClim' (Local Climate Estimator) containing a large database of rainfall patterns through which is possible to compute an approximate hydrograph, if better data are not available. The software can be freely downloaded at the following link:
'http://www.fao.org/NR/climpag/pub/en3_051002_en.asp'

## 6.2. Discharge measurements

If appropriate stream flow time series cannot be found, the discharge should preferably be directly measured for at least a year. A single measurement of instantaneous flow in a watercourse is of little use. To measure the discharge several methods are available.

### 6.2.1. Velocity-area method

This is a conventional method for medium to large rivers, involving the measurement of the cross sectional area of the river and the mean velocity of the water through it. It is a useful approach for determining the stream flow with a minimum effort. An appropriate point must be selected on a relatively straight, smoothly flowing portion of the river to be gauged. The method involves three different steps:

1. Creation of a 'Rating curve' that links the river discharge to the gauged river depth, that permits the estimation of the river discharge by reading the river stage.
2. A river cross section measurement, by dividing the watercourse into a series of trapezoids and measuring the trapezoid sides with marked rulers.
3. Gauge the mean section velocity by mechanical current-meter, electro-magnetic current-meter or diluation methods.

### 6.2.2. Weir method

If the watercourse being developed is reasonably small then it may be possible to build a temporary weir. This is a low wall or dam across the river to be gauged with a notch through which all the water may be channelled. Many studies have established accurate formulae for the discharge through such notches. A simple linear measurement of the difference in level between the upstream water surface and the bottom of the notch is sufficient to quantify the discharge. However, it is important to measure the water surface level some distance back from the weir and to keep the notch free of sediment and the edge sharp on the downstream side of the notch.

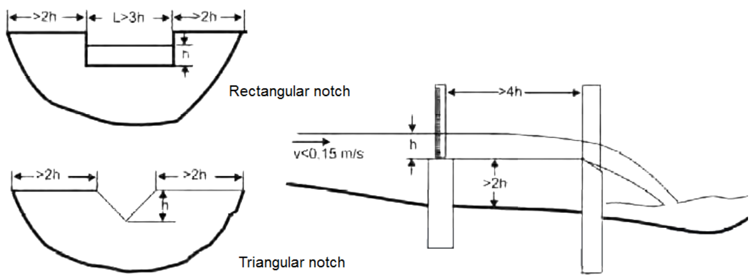


Figure 6.1.: Weir method

### 6.2.3. Slope-area method

This method depends on some hydraulic principles and is useful for high flows where other methods are impractical. It presupposes to use pegs or other temporary elevation marks to measure the water surface level during flow gauging. These marks can be used to establish the water slope ($S$). Cross sectional measurements are taken to establish the area ($A$) and hydraulic radius of the section ($R$). Once these parameters are known the discharge ($Q$) is computed by the Manning formula:

$$Q = \frac{A * R^{2/3} * S^{0,5}}{n}$$

Where $n$ is the Manning's roughness coefficient. This method is sometimes criticised because of its dependence on the value of $n$. Since $n$ for natural streams is about 0,035, an error in $n$ of 0,001 gives an error in discharge of 3%.

## 6.3. Discharge data organization

### 6.3.1. Hydrograph

Once the flow data has been collected they can be organized in different ways.

Plotting them sequentially the 'Hydrograph' is obtained, which shows discharge against time, in chronological order. The hydrograph distribution shows very different aspects, depending on the frequency of the registered data. If a computerized gauging station exists, usually the data are collected with a daily frequency and their aspect is similar to the one shown in figure 6.2.

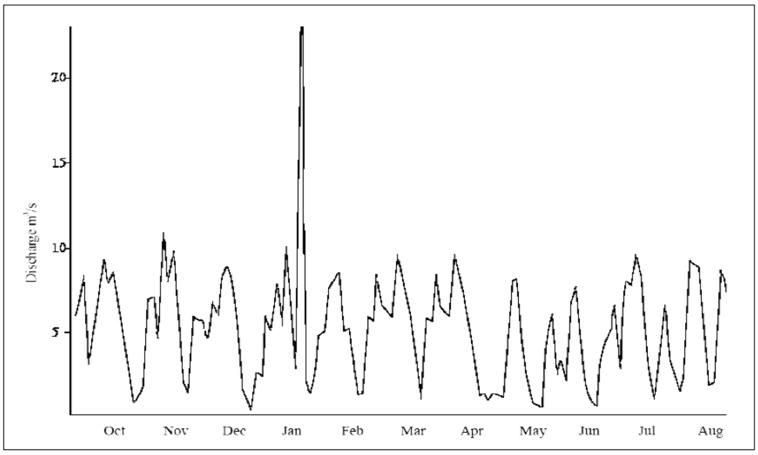


Figure 6.2.: Hydrograph sample

### 6.3.2. Flow duration curve

Another way of organising discharge data is by plotting a 'Flow Duration Curve' (FDC). An FDC shows for a particular point on a river the proportion of time during which the discharge there equals or exceeds certain values. It can be obtained from the hydrograph by organising the data by magnitude instead of chronologically. The figure below shows an example of flow duration curve:

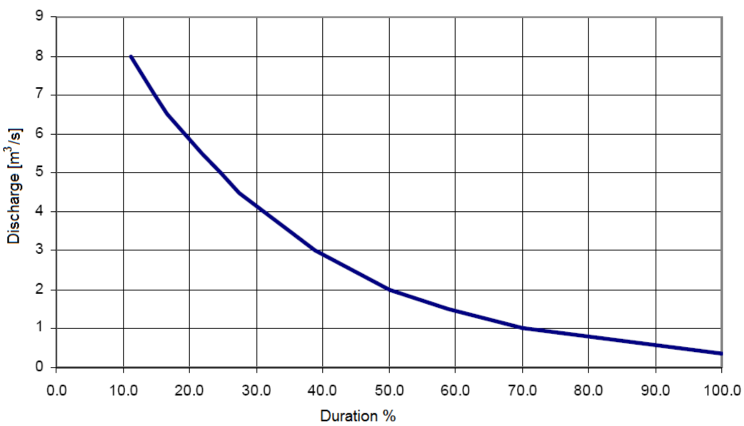


Figure 6.3.: Flow duration curve sample

### 6.3.3. Residual flow

Uncontrolled abstraction of water from a watercourse, passing it through a turbine, even if it is returned to the stream close to the intake, could lead to sections of the watercourse being left almost dry with serious impacts on aquatic life. To avoid this happening, permission to divert water through a hydro turbine or a licence to abstract from a river or stream will almost always specify that a certain residual flow should remain. The residual flow is sometimes called other names, depending on the country, or authority responsible: 'reserved flow', 'prescribed flow' and 'compensation flow' are terms commonly used. This residual flow should be carefully evaluated since a flow that is too small would cause damage to aquatic life in the stream. On the other hand an unnecessarily large flow effects the power production and especially so in periods of low flow, thus reducing the benefits of the installation.

### 6.3.4. Available flow

The river flow minus the residual flow, called 'Available flow', can be used to run the machine(s); even the FDC is corrected to show the available flow.

The corrected FDC can be used to size the turbine over the available water flow. By sizing the turbine over a low value of duration, the available flow will be able to run the turbine for almost the year, with only few stops due to water shortage. On the other side by sizing the turbine over an high value of duration, the electric productivity will be higher during the high flow periods, while the stops frequency will increase. Following this trade-off, usually the water flow that corresponds to the 90-95% value of duration in the corrected FDC is used as the nominal turbined flow ($GD_{nom}$).

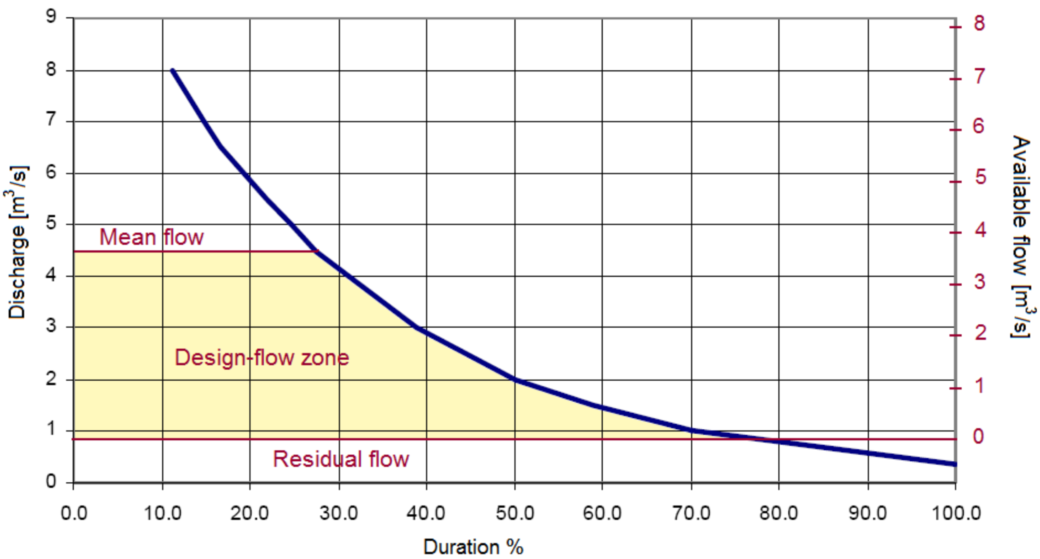


Figure 6.4.: Corrected FDC sample

The stream flow is the fuel of the plant, but stream flow in the form of floods is also a potential threat to all structures built in rivers. Therefore the hydrological investigation must address not only water availability for production, but also frequency and severity of floods so as to design flood protection and control into the scheme.

## 6.4. Water pressure or head

The objective of a hydropower scheme is to convert the potential energy of a mass of water, flowing in a stream with a certain fall to the turbine, termed the 'Head', into electric energy at the lower end of the scheme, where the powerhouse is located. The power output from the scheme is proportional to the flow and to the head. Schemes are generally classified also according to the 'Head':

**High head:** 100 $m$ and above.

**Medium head:** from 30 to 100 $m$.

**Low head:** from 2 to 30 $m$.

These ranges are not rigid but are merely means of categorizing sites.

The gross head ($GH$) is the vertical distance that the water falls through in giving up its potential energy (between the upper and lower water surface levels). Field measurements of gross head are usually carried out using surveying techniques. Nowadays with digital theodolites, electronic digital and laser levels and especially with the electronic total stations the job has been simplified. Surveying by Global Positioning Systems (GPS) is now used widely and a handheld GPS receiver is ideal for field positioning, and rough mapping.

Having established the gross head available, it is necessary to make estimations for the losses, from trash racks, pipe friction, bends and valves. The gross head minus the sum of all the losses equals the net head ($NH$), which is available to drive the turbine.

# 7. Hydraulic structures

## 7.1. Dam

Dams and weirs are primarily intended to divert the river flow into the water conveyance system leading to the powerhouse. Dams also produce additional head and provide storage capacity. The choice of dam type depends largely on local topographical and geotechnical conditions. In the Nordic countries the ice age has left us with wide and open valleys and moraine material in abundance. Not surprisingly the vast majority of dams are embankment dams with a central core of moraine. South of the Alps natural clays suitable for dam core are not in abundance and the topography in many locations favour concrete dams.

According to the ICOLD (International Committee of Large Dams), a dam is considered "small" when its height, measured from its foundation level to the crest, does not exceed 15 $m$, the crest length is less than 500 $m$ and the stored water is less than 1 million $m^3$. These parameters can be important, because of the complicated administrative procedures often associated with the construction of large dams.

### 7.1.1. Embankment dams

World wide, embankment dams are the more common partly due to the following characteristics, which they possess:

- Can be adapted to a wide range of foundation conditions.
- Construction uses natural materials, which can often be found locally, limiting needs for long transportation.
- The construction process can be continuous and highly mechanized.
- The design is extremely flexible in accommodating different fill materials.

Disadvantages with embankment dams are that they are sensitive to overtopping and leakage, and erosion in the dam body and its foundation. There is a higher mortality rate among embankment dams as compared to concrete dams.

Embankment dams can be classified by their structure type:

**Homogeneous dams:** these dams are used for low embankments and often as secondary dams. For dam safety reasons, some type of drainage is almost always provided.

**Zoned embankment dams:** these are used for dam heights from 4 $m$ and up. Constructions are extremely sensitive to the engineering design and construction, and it is therefore vital to engage highly skilled consultants and contractors require experienced site-supervision engineers.

**Embankments dams with membrane:** the membranes can be of different types and be located either at the upstream front of the embankment or vertically in the centre of the embankment. Membranes can be made from concrete, asphalt or in the form of a geomembrane on the upstream slope.

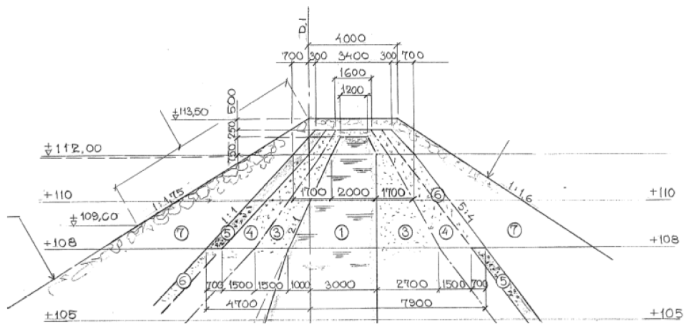

Figure 7.1.: Zoned embankment dam

### 7.1.2. Concrete dams

Concrete dams on the other hand have drawbacks that correspond to the pros of the embankment, but presents several advantages:

- They are suitable for most ranges of topography that is for wide and narrow valleys, provided that foundation conditions are right.
- They are not very sensitive to overtopping.
- A spillway can be placed at the crest, and if required over the entire length of the dam.
- Chambers or galleries for drainage, tubing and ancillary works can readily be housed within the dam body.
- Powerhouses can be placed right at the toe of the dam.

Concrete dams can be classified by their structure type:

**Gravity dams:** these are dependent on their own mass for stability. Their cross-section is basically triangular in order to provide adequate stability and stress distribution across the foundation plane. The upper part is normally rectangular in order to provide adequate crest width for installation and transportation. Design issues include stability analysis (sliding and overturning), stress control, temperature control during construction to avoid cracking, control of uplift pressures under the dam, etc.

**Buttress dams:** these dams consist of a continuous upstream face that is supported by buttresses at regular intervals. The upstream face is normally divided into vertical sections by dilatation joints, each section being supported by a buttress. Cross-sections are similar to those of gravitation dams.

Figure 7.2.: Buttress dam

**Arch and Cupola dams:** These dams function structurally as horizontally laid out arches that transfer the water pressure on the upstream face into the abutments rather than into the foundation. Arch dams can be designed with a constant radius over the dam height, varying radii cupola dams are obtained. Arch dams with a constant radius have a vertical and straight cross-section. These dams will be subject to considerable vertical strain forces since the deformation of the dam will tend to be greatest in the vertical centre of the dam. This requires that the dam be heavily reinforced to avoid cracking with accompanying leakage. The Cupola dam is designed to have only compression forces for all directions and at all sections. This requires the radius of the curvature to vary over the dam height, which produces a curved vertical cross-section. The arch and cupola dams are structurally efficient and greatly reduce the required volume of concrete. They require, however, a narrow valley topography and strong foundation rock in the abutments.

Figure 7.3.: Arch dam

## 7.2. Weir

The large majority of small hydro schemes are of the run-of-river type, where electricity is generated from discharges larger than the minimum required to operate the turbine. In these schemes a low diversion structure is built on the streambed to divert the required flow whilst the rest of the water continues to flow over it. Such a structure is commonly known as a 'Weir', whose role is not to store the water but to increase the level of the water surface so the flow can enter into the intake. Weirs and spillways can be subdivided into fixed and mobile structures. Smaller fixed structures are generally referred to as weirs, whereas larger structures are often referred to as spillways. Spillways are often divided into ungated and gated spillways, corresponding to fixed and mobile structures, the ungated spillway in fact being a large-scale weir.

### 7.2.1. Fixed weir

Fixed storage structures, such as weirs and ungated spillways have the advantage of security, simplicity, easy maintenance, and are cost effective. However, they cannot regulate the water level and thus both the water level and energy production fluctuates as a function of discharge.

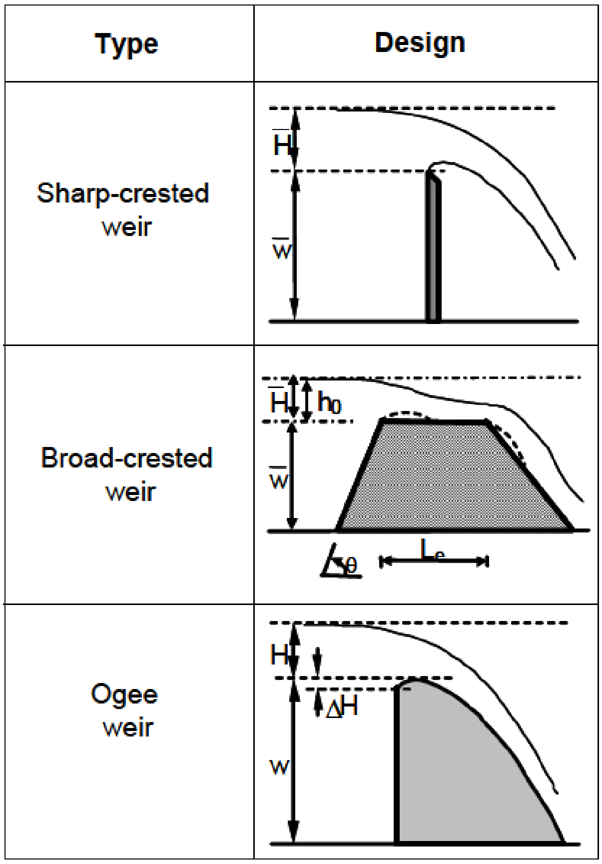


Figure 7.4.: Fixed weirs

**Sharp-crested weir** is easy to construct and relatively cost-effective. Its discharge is defined by means of a coefficient $C_d$. Special attention has to be paid to the shape of the downstream face of the upper part of the weir in order to obtain sufficient aeration between the lower nappe of the jet and the structure. If the lower nappe of the jet sticks to the structure, vibrations may be transferred from the flow to the structure.

**Broad-crested weir** is often applied for temporary structures or for structures of secondary importance, such as in case of temporary flow diversion. Its design is simple and cost-effective. The hydraulic conditions are far from optimal, expressed by a low discharge coefficient and the presence of under-pressures along the weir crest and downstream face. The discharge depends on the form of the structure.

**Ogee weir** is hydraulically the most ideal solution giving the highest discharge coefficient. Its curved shape is defined by the jet trajectory that would appear for the design discharge. For lower or higher discharges, over or under pressures will appear along the downstream face. For discharges much higher than the design discharge, these under pressures may lead to cavitation and damage to the downstream concrete face. Recent work suggests fortunately that separation will not occur until the river flow is three times the project one.

Figure 7.5.: Ogee weir

### 7.2.2. Mobile weir

Mobile storage structures such as gated spillways can regulate the water level such that it stays more or less constant for most incoming flow conditions. Depending on gate configuration and discharge capacity they may also be able to flush accumulated sediment downstream. These structures are generally more expensive than fixed structures, for both construction and maintenance, and their functioning is more complicated. Gate operation needs permanent maintenance and an external energy source. As a result, there is a risk that the gate remains blocked during floods.

The most used types of gates are flat and radial. Depending on the type of gate, the possible gate movements are rotating, sliding or turning. The discharge through the gates depends not only on the type of gate and the relative gate opening and gate lip angle, but also on the shape of the supporting weir.

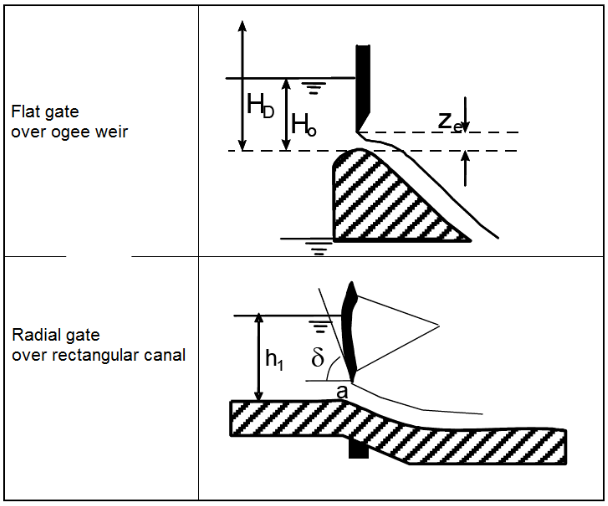


Figure 7.6.: Mobile weirs

## 7.3. Intake

A water intake must be able to divert the required amount of water into a power canal or into a penstock without producing a negative impact on the local environment and with the minimum possible head losses. Also, a major challenge consists of handling debris and sediment transport. The location of the intake depends on a number of factors, such as submergence, geotechnical conditions, environmental considerations (especially those related to fish life) sediment exclusion and ice formation, where necessary. The orientation of the intake entrance to the flow is a crucial factor in minimising debris accumulation on the trashrack, a source of possible future maintenance problems. The best disposition of the intake is with the screen at right angles to the spillway so, that during flood seasons, the flow pushes the debris over its crest. The intake should not be located in an area of still water, far from the spillway, because the eddy currents common in such waters will accumulate trash at the entrance. The intake should be equipped with a trashrack to minimise the amount of debris and sediment carried by the incoming water.

### 7.3.1. Power intake

The intake supplies water directly to the turbine via a penstock. These intakes are often encountered in lakes and reservoirs and transfer the water as pressurized flow. Analyses of cost & benefits suggests that the best design is that of a compact intake with a slopingroof and converging walls (Fig. 7.7), whilst the length of the intake is unlikely to be the major factor contributing to the overall loss coefficient. The $k$ coefficient of this transition profile is 0,19. The head loss ($HL$ [$m$]) in the intake is given by:

$$HL = 0,19 * \frac{V^2}{2 * g}$$

Where $V$ is the velocity in the penstock $[m/s]$.

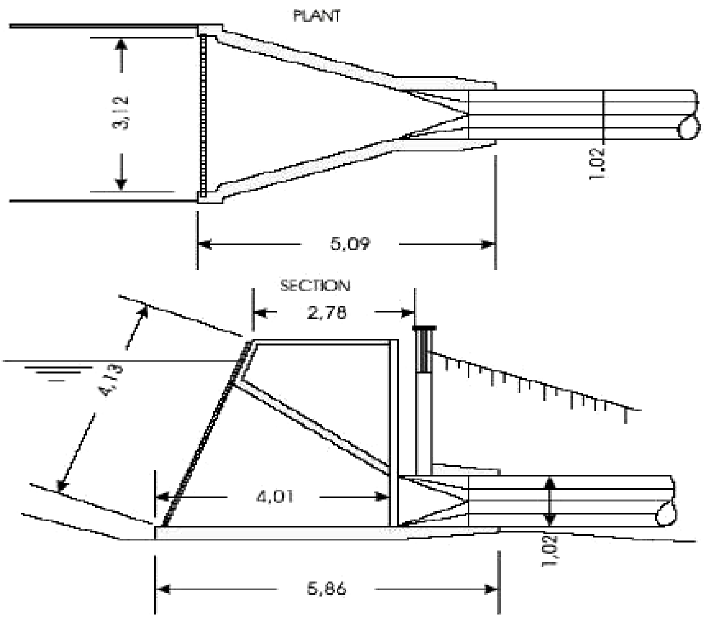


Figure 7.7.: Power intake

### 7.3.2. Trashrack

One of the major functions of the intake is to minimise the amount of debris and sediment carried by the incoming water, so trashracks are placed at the entrance to the intake to prevent the ingress of floating debris and large stones. A trashrack is made up of one or more panels, fabricated from a series of evenly spaced parallel metal bars. The trashrack is designed so the approach velocity ($V_0$) remains between 0,60 $m/s$ and 1,50 $m/s$. The maximum possible spacing between the bars is generally specified by the turbine manufacturers. Typical values are 20-30 $mm$ for Pelton turbines, 40-50 $mm$ for Francis turbines and 80-100 $mm$ for Kaplan turbines.

Head losses due to the trashrack ($HL$ $[m]$) depend on spacing ($b$), thickness ($t$) and shape of the bars ($k$), orientation of the trashrack compared to the flow ($\gamma$) and eventual obstruction due to debris, as shown in the formula:

$$HL = k * (\frac{t}{b})^{4/3} * (\frac{V^2}{2 * g}) * sin(\gamma)$$

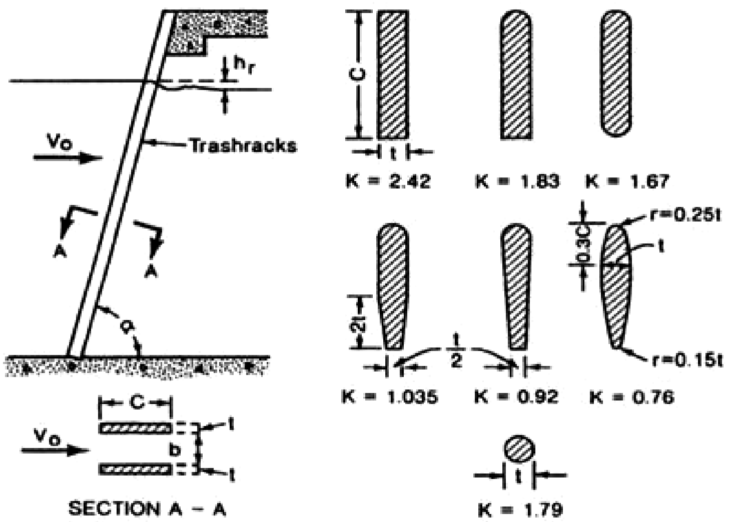


Figure 7.8.: Trashrack bars

### 7.3.3. Conveyance intake

The intake supplies water to other waterways (power canal, flume, tunnel, etc.) that usually end in a power intake. These are most frequently encountered along rivers and waterways and generally transfer the water as free surface flow.

**Lateral intake** uses a gravel deposition canal in front of the intake in order to prevent both bed and suspended load from entering the intake. The channel makes use of a small gravel weir, furthermore its slope should be at least 2%, preferably 5%. The channel bottom has to be protected against abrasion (using high quality concrete, stones, etc.). A partially submerged wall is installed in order to prevent debris from entering the intake. The main elements of the lateral intake structure are presented in figure 7.9: weir, gravel deposition channel and intake with trashrack.

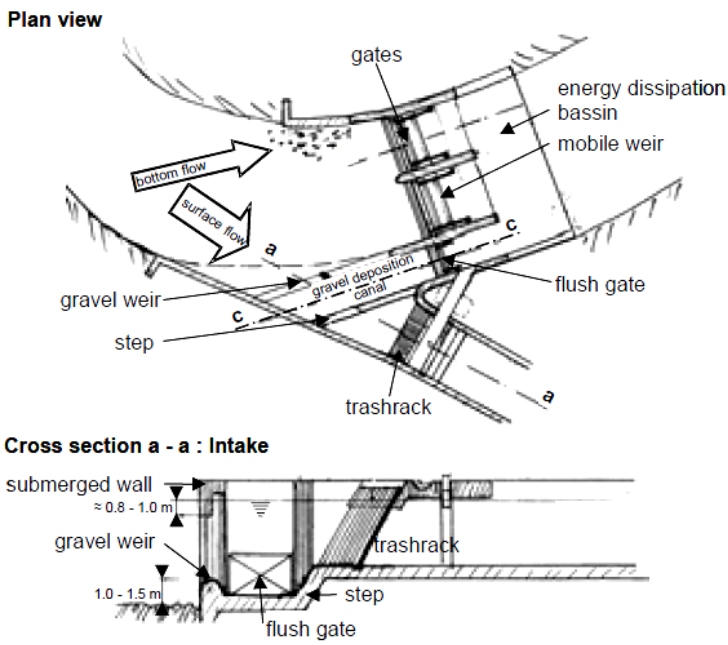


Figure 7.9.: Lateral intake

**Frontal intake** is always equipped with a gravel deposition tunnel and is well adapted for rectilinear river reaches. The deposition tunnel has to be flushed in a continuous manner and the maximum river width is 50 $m$. A major advantage of this type of intake is its ability to handle large quantities of both bed and suspended load. However, this needs continuous flushing and thus large losses of water. The frontal intake is largely applied in regions with very large bed and suspended loads, such as for example in India and Pakistan. In Europe, its application is largely restricted.

**Drop intake** is generally used in steep sloped rivers, such as torrents, and for rectilinear reaches. The 'French drop intake' is essentially a canal built in the streambed, stretching across it and covered by a trashrack with a slope greater than the streambed slope. The trashrack bars are oriented in the direction of the streamflow.

Figure 7.10.: Drop intake

**Coanda intake** is an advanced concept of the drop intake, incorporating the 'Coanda effect', well known in the ore separation industry, to separate fish and debris from clean water. Essentially it consists of a weir with a downward sloping profiled surface of stainless steel wire screen mesh on the downstream side and a flow collection channel below the mesh, as in the drop intake. The mesh wires are held horizontal, unlike the drop intake, and are of triangular section to provide an expanding water passage. Water drops through the mesh with debris and fish carried off the base of the screen. The screen is capable of removing 90% of the solids as small as 0,5 $mm$, so a silt basin and sediment ejection system can be omitted.

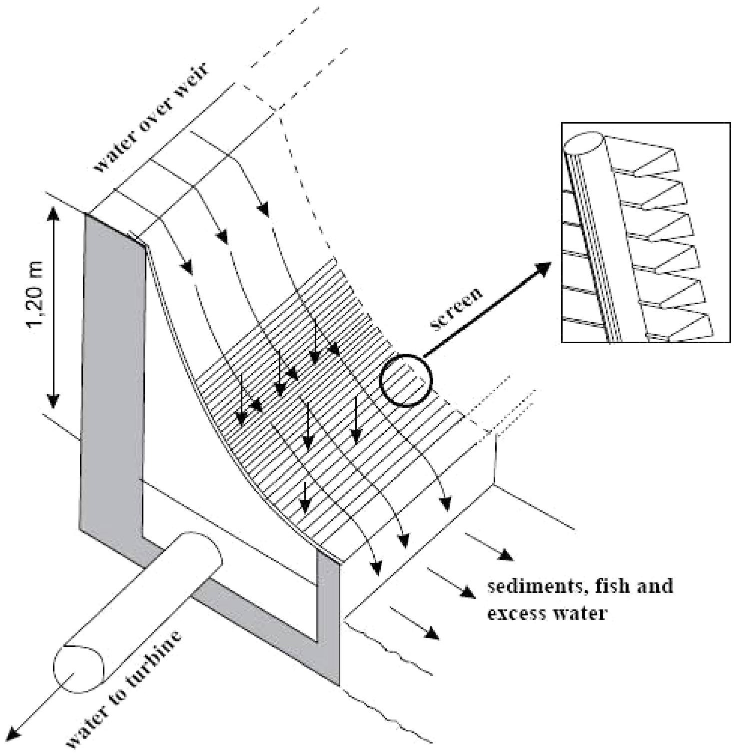


Figure 7.11.: Coanda intake

## 7.4. Channel

The flow conveyed by a canal ($Q$) is a function of its cross sectional profile ($A$), its slope ($S$), and its roughness ($n$). Natural channels are normally very irregular in shape, and their surface roughness changes with distance and time. The application of hydraulic theory to natural channels is more complex than for artificial channels where the cross section is regular in shape and the surface roughness of the construction materials like earth, concrete, steel or wood is well documented; so that the application of hydraulic theories yields reasonably accurate results.

The channels can be divided according to their lining material, as shown in the following table:

| Type of channel | Manning's coefficient |
|---|---|
| **Excavated earth channels** | |
| Clean | 0.022 |
| Gravelly | 0.025 |
| Weedy | 0.030 |
| Stony, cobbles (or natural streams) | 0.035 |
| **Artificially lined channels** | |
| Brass | 0.011 |
| Steel, smooth | 0.012 |
| Steel, painted | 0.014 |
| Steel, riveted | 0.015 |
| Cast iron | 0.013 |
| Concrete, well-finished | 0.012 |
| Concrete, unfinished | 0.014 |
| Planed wood | 0.012 |
| Clay tile | 0.014 |
| Brickwork | 0.015 |
| Asphalt | 0.016 |
| Corrugated metal | 0.022 |
| Rubble masonry | 0.025 |

Figure 7.12.: Lining materials

In small hydropower schemes the flow in the channels is in general in the rough turbulent zone and the Manning equation can be applied:

$$Q = \frac{A^{5/3} * S^{1/2}}{n * P^{2/3}}$$

Where $n$ is Manning's coefficient, which in the case of artificial lined channels may be estimated with reasonable accuracy, $S$ is the hydraulic gradient, which normally is the bed slope, and $P$ is the wetted perimeter.

The above equation shows that for the same cross sectional area $A$ and channel slope $S$, the channel with a smaller wetted perimeter $P$, delivers a larger discharge, then is the most efficient hydraulically. Semicircular sections are consequently the most efficient. A semicircular section however, unless built with prefabricated materials, is expensive to build and difficult to maintain. The most efficient trapezoidal section is the half hexagon. Strictly, this is only true if the water level reaches the level of the top of the bank. Actual dimensions have to include a certain freeboard (vertical distance between the designed water surface and the top of the channel bank) to prevent water level fluctuations overspilling the banks. Minimum freeboard for lined canals is about 10 $cm$, and for unlined canals this should be about one third of the designed water depth with a minimum of 15 $cm$. One way to prevent overflow of the canal is to provide spillways at appropriate intervals; any excess water is conveyed, via the spillway, to an existing streambed or to a gully.

Figure 7.13.: Lateral spillway

In conventional hydropower schemes and in some of the small ones, especially those located in wide valleys where the channels must transport large discharges, the excavated ground is used to build the embankments, not only up to the designed height but to provide the freeboard. An appropriate lining provides bank protection. Possible materials to be used for protection are vegetation, rock blocks with or without mortar, bituminous material, or concrete.

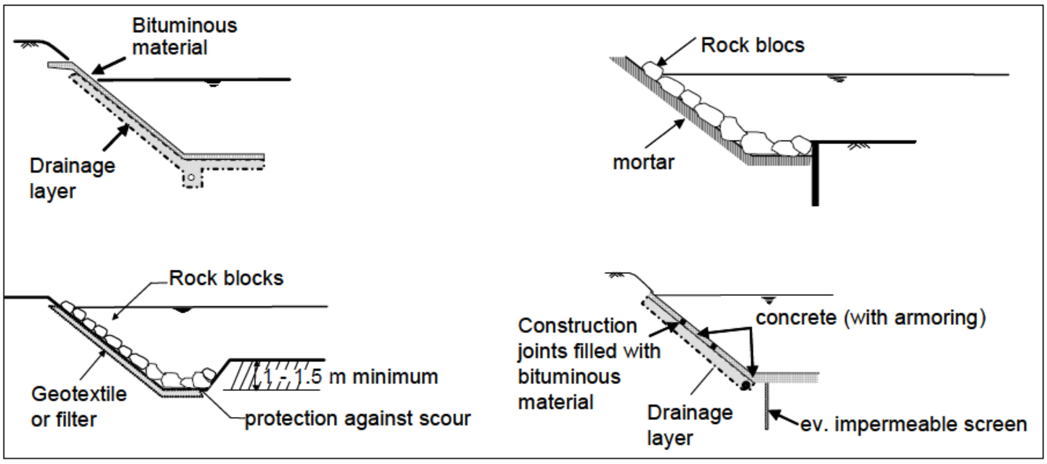


Figure 7.14.: Lining samples

## 7.5. Penstock

The purpose of a penstock is conveying water from the intake to the powerhouse.

Penstocks can be installed over or under the ground, depending on factors such as the nature of the ground itself, the penstock material, the ambient temperatures and the environmental requirements. A flexible and small diameter PVC penstock for instance, can be laid on the ground, following its outline with sand and gravel surrounding the pipe to provide good insulation. Small pipes installed in this way do not need anchor blocks and expansion joints. Larger penstocks are usually buried, as long as there is only a minimum of rock excavation required. Buried penstocks must be carefully painted and wrapped to protect the exterior from corrosion, but provided the protective coating is not damaged when installed, further maintenance should be minimal. From the environmental point of view the solution is optimal because the ground can be returned to its original condition, and the penstock does not constitute a barrier to the movement of wildlife.

A penstock installed above ground can be designed with or without expansion joints. Variations in temperature are especially important if the turbine does not function continuously, or when the penstock is dewatered for repair, resulting in thermal expansion or contraction. Usually the penstock is built in straight or nearly straight lines, with concrete anchor blocks at each bend and with an expansion joint between each set of anchors.

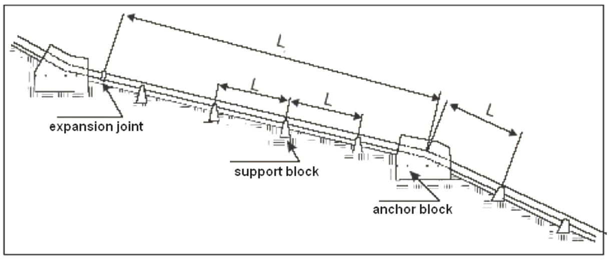


Figure 7.15.: Penstock

The anchor blocks must resist the thrust of the penstock plus the frictional forces caused by its expansion and contraction, so when possible they should be founded on rock. If, due to the nature of the ground, the anchor blocks require large volumes of concrete, thus becoming rather expensive, an alternative solution is to eliminate every second anchor block and all the expansion joints, leaving the bends free to move slightly. In this case it is desirable to lay the straight sections of the penstock in steel saddles, made to fit the contour of the pipe and generally covering 120 degrees of the invert.

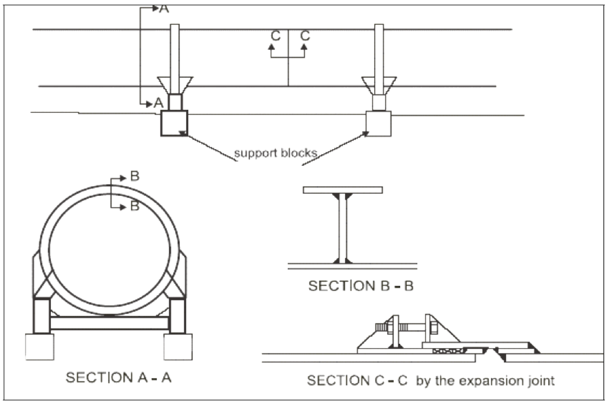


Figure 7.16.: Penstock with concrete anchor blocks and expansion joints

Today there is a wide choice of materials for penstocks. For the larger heads and diameters, fabricated welded steel is probably the best option. At medium and low heads steel becomes less competitive, because the internal and external corrosion protection layers do not decrease with the wall thickness and because there is a minimum wall thickness for the pipe. Polyethylene or PVC pipes are a very attractive solution for medium heads because they are often cheaper, lighter and more easily handled than steel and do not need protection against corrosion.

Different material's characteristics are shown in the figure below:

| Material | Young's modulus of elasticity E(N/m$^2$)E9 | Coefficient of linear expansion a (m/m $^0$c)E6 | Ultimate tensile strength (N/m$^2$)E6 | n |
|---|---|---|---|---|
| Welded Steel | 206 | 12 | 400 | 0.012 |
| Polyethylene | 0.55 | 140 | 5 | 0.009 |
| Polyvinyl Chloride (PVC) | 2.75 | 54 | 13 | 0.009 |
| Asbestos Cement | n/a | 8.1 | n/a | 0.011 |
| Cast iron | 78.5 | 10 | 140 | 0.014 |
| Ductile iron | 16.7 | 11 | 340 | 0.013 |

Figure 7.17.: Materials characteristics

## 7.6. Power house

In a small hydropower scheme the role of the powerhouse is to protect the electromechanical equipment that convert the potential energy of water into electricity, from the weather hardships. The number, type and power of the turbo-generators, their configuration, the scheme head and the geomorphology of the site determine the shape and size of the building.

The following equipment will be included in the powerhouse: inlet gate or valve, turbine, speed increaser (if needed), generator, control system, condenser, switchgear, protection systems, DC emergency supply, power and current transformers.

The first picture in figure 7.18 is a schematic view of an integral intake indoor powerhouse suitable for low head schemes. The substructure is part of the weir and embodies the power intake with its trashrack, the vertical axis Kaplan turbine coupled to the generator, the draft tube and the tailrace. The control equipment and the outlet transformers are located in the generator forebay. In order to mitigate the environmental impact the powerhouse can be entirely submerged, in this way the level of sound is sensibly reduced and the visual impact is nil.

In medium and high head schemes, powerhouses are more conventional (second picture) with an entrance for the penstock and a tailrace. Although not usual, this kind of powerhouse can be underground.

Some turbines configurations allow for the whole superstructure itself, to be dispensed with, or reduced enclosing only the switchgear and control equipment. Integrating the turbine and generator in a single waterproofed unit that can be installed directly in the waterway means that a conventional powerhouse is not required (bulb or siphon units).

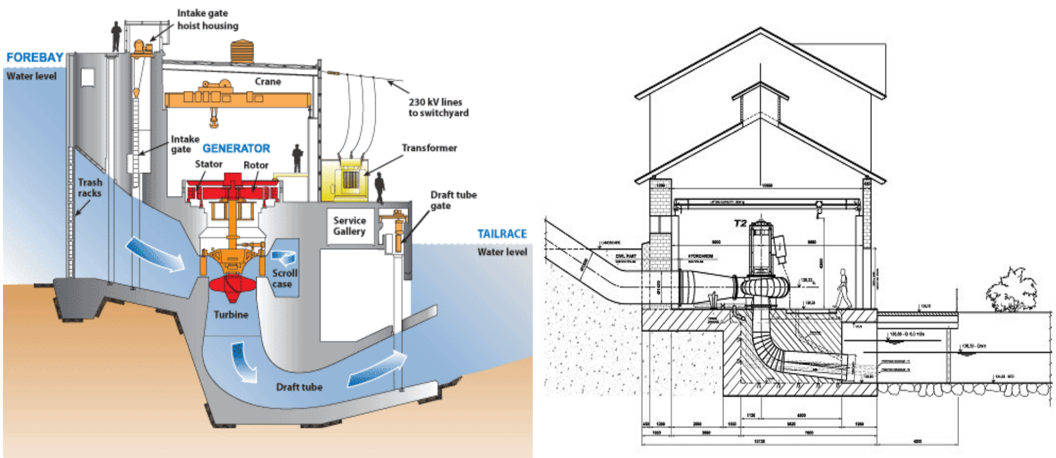


Figure 7.18.: Powerhouses, low and medium heads

# 8. Electro mechanical equipment

## 8.1. Turbine

The purpose of a hydraulic turbine is to transform the water potential energy to mechanical rotational energy.

### 8.1.1. Types and configuration

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

- 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. Francis and Kaplan turbines belong to this category.

- 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. The most usual impulse turbine is the Pelton. This chapter describes each turbine type, presented by decreasing head and increasing nominal flow. The higher the head, the smaller the flow.

The hydraulic power at disposition of the turbine is given by:

$$P_h = \rho Q * gH$$

Where:
$P_h$ is the hydraulic power $[W]$, $\rho Q$ is mass flow rate $[kg/s]$, $\rho$ is the water specific density $[Kg/m^3]$ , $Q$ is the discharge $[m^3/s]$, $gH$ is specific hydraulic energy of machine $[J/kg]$.
The mechanical output of the turbine is given by:

$$P_{mec} = P_h * \eta$$

Where:
$P_{mec}$ is the hydraulic power $[W]$, while $\eta$ is the turbine efficiency [-].

### 8.1.2. Pelton turbines

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 water through a nozzle with a needle valve to control the flow. They are only used for high heads from 60 $m$ to more than 1000 $m$. The axes of the nozzles are in the plan of the runner. In case of an emergency stop of the turbin, the jet may be diverted by a deflector so that it does not impinge on the buckets and the runner cannot reach runaway speed. In this way the needle valve can be closed very slowly, so that overpressure surge in the pipeline is kept to an acceptable level. As any kinetic energy leaving the runner is lost, the buckets are designed to keep exit velocities to a minimum.

One or two jet Pelton turbines can have horizontal or vertical axis, three or more nozzles turbines usually have vertical axis (Fig. 8.1). The maximum number of nozzles is 6 (not usual in small hydro).

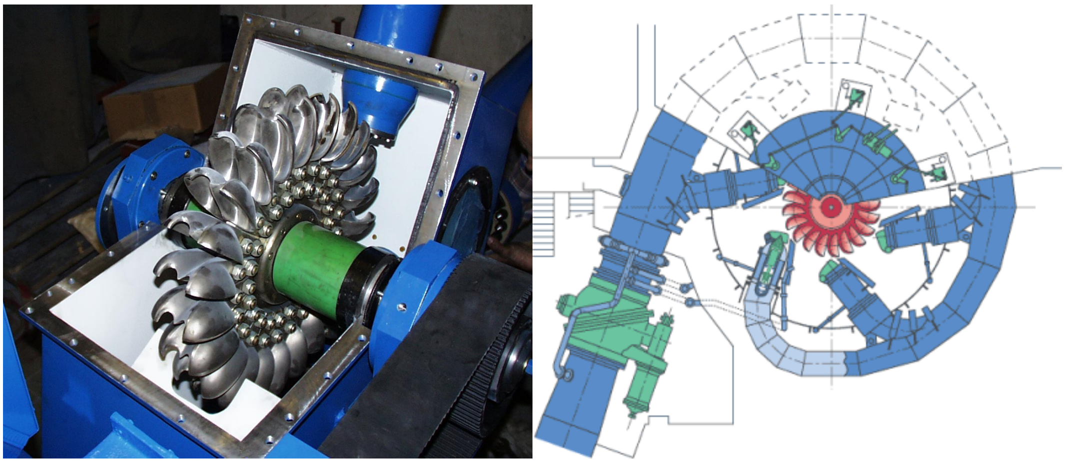

Figure 8.1.: Pelton, horizontal and vertical axis

The turbine runner is usually directly coupled to the generator shaft and shall be above the downstream level. The turbine manufacturer can only give the clearance. The efficiency of a Pelton is good from 30% to 100% of the maximum discharge for a one-jet turbine and from 10% to 100% for a multi-jet one.

### 8.1.3. Turgo turbines

The Turgo turbine can operate under a head in the range of 50-250 $m$. Like the Pelton, it is an impulse turbine, however its buckets are shaped differently and the jet of water strikes the plane of its runner at an angle of 20º. Water enters the runner through one side of the runner disk and emerges from the other (Fig. 8.2). It can operate between 20% and 100% of the maximal design flow.

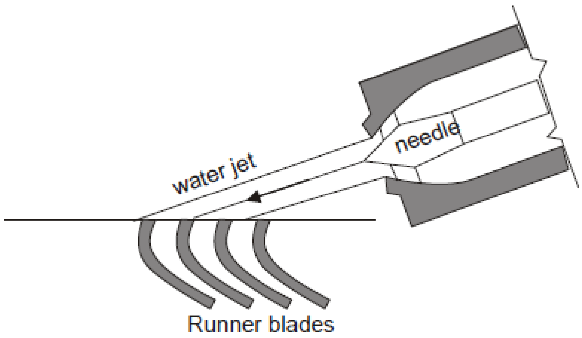


Figure 8.2.: Principle of a Turgo turbine

Compared to the Pelton, a Turgo turbine has a higher rotational speed for the same flow and head. A Turgo can be an alternative to the Francis when the flow strongly varies or in case of long penstocks, as the deflector allows avoidance of runaway speed in the case of load rejection and the resulting water hammer that can occur with a Francis.

The drawback is that the efficiency is lower than for the Pelton and Francis turbines.

### 8.1.4. Cross-flow turbines

This impulse turbine, also known as Banki-Michell is used for a wide range of heads overlapping those of Kaplan, Francis and Pelton. It can operate with heads between 5 and 200 $m$.

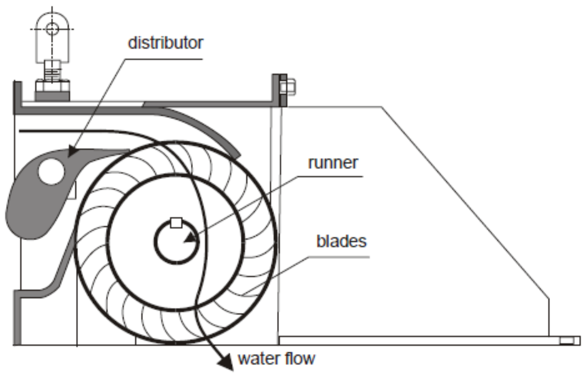


Figure 8.3.: Principle of a Cross-flow turbine

Water enters the turbine, directed by one or more guide-vanes located upstream of the runner and crosses it two times before leaving the turbine. This simple design makes it cheap and easy to repair in case of runner brakes due to the important mechanical stresses. The Cross-flow turbines have low efficiency compared to other turbines and the important loss of head due to the clearance between the runner and the downstream level should be taken into consideration when dealing with low and medium heads. Moreover, high head cross-flow runners may have some troubles with reliability due to high mechanical stress. It is an interesting alternative when one has enough water, defined power needs and low investment possibilities, such as for rural electrification programs.

### 8.1.5. Francis turbines

Francis turbines are reaction turbines, with fixed runner blades and adjustable guide vanes, used for medium heads. In this turbine the admission is always radial but the outlet is axial. Their usual field of application is from 25 to 350 $m$ head. As with Peltons, Francis turbines can have vertical or horizontal axis, this configuration being really common in small hydro.

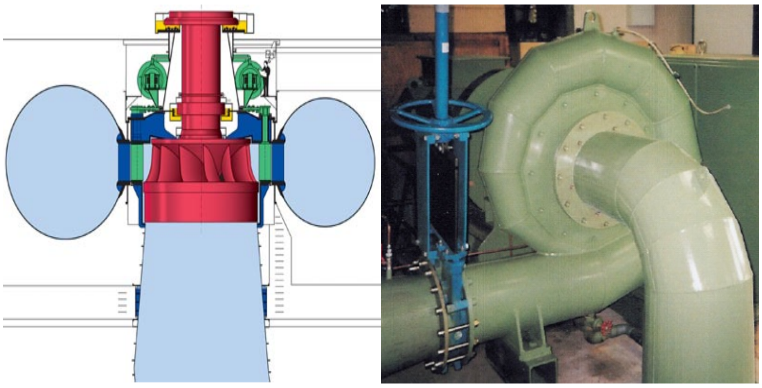

Figure 8.4.: Francis turbine

Francis turbines can be set in an open flume or attached to a penstock. For small heads and power open flumes were commonly employed, however nowadays the Kaplan turbine provides a better technical and economical solution in such power plants.

The water enters the turbine by the spiral case that is designed to keep its tangential velocity constant along the consecutive sections and to distribute it peripherally to the distributor. As shown in figure 8.5, this one has mobile guide vanes, whose function is to control the discharge going into the runner and adapt the inlet angle of the flow to the runner blades angles. They rotate around their axes by connecting rods attached to a large ring that synchronise the movement off all vanes. They can be used to shut off the flow to the turbine in emergency situations, although their use does not preclude the installation of a butterfly valve at the entrance to the turbine.

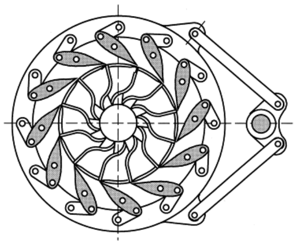

Figure 8.5.: Francis distributor guide vanes

Small hydro runners are usually made in stainless steel castings. Some manufacturers also use aluminium bronze casting or welded blades, which are generally directly coupled to the generator shaft. The draft tube of a reaction turbine aims to recover the kinetic energy still remaining in the water leaving the runner. As this energy is proportional to the square of the velocity one of the draft tube objectives is to reduce the turbine outlet velocity.

### 8.1.6. Kaplan and propeller turbines

Kaplan and propeller turbines are axial-flow reaction turbines, generally used for low heads from 2 to 40 $m$. 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". Fixed runner blade Kaplan turbines are called propeller turbines. They are used when both flow and head remain practically constant, which is a characteristic that makes them unusual in small hydropower schemes. The double regulation allows, at any time, for the adaptation of the runner and guide vanes coupling to any head or discharge variation. It is the most flexible Kaplan turbine that can work between 15% and 100% of the maximum design discharge.

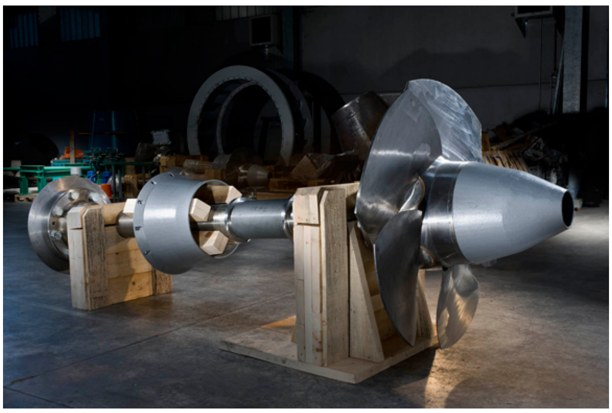

Figure 8.6.: Kaplan runner

The double-regulated Kaplan illustrated in figure 8.7 is a vertical axis machine with a spiral case and a radial guide vane configuration. The flow enters in a radial manner inward and makes a right angle turn before entering the runner in an axial direction. The control system is designed so that the variation in blade angle is coupled with the guide-vanes setting in order to obtain the best efficiency over a wide range of flows and heads.

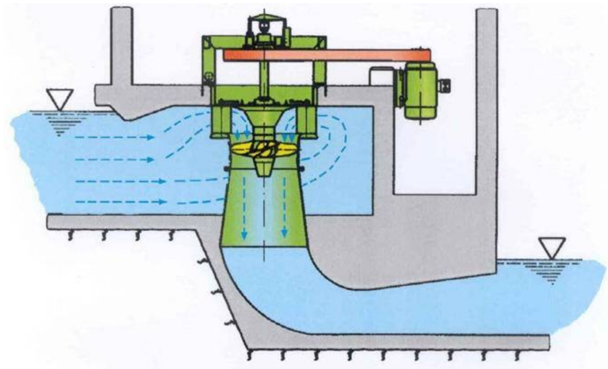

Figure 8.7.: Cross section of a double regulated Kaplan turbine

Bulb units are derived from Kaplan turbines, with the generator contained in a waterproofed bulb submerged in the flow. Figure 8.8illustrates a turbine where the generator (and gearbox if required), cooled by pressurised air, is lodged in the bulb. Only the electric cables, duly protected, leave the bulb.

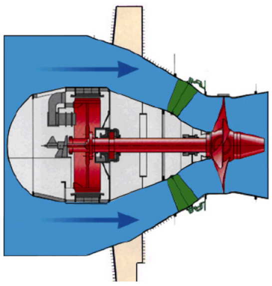

Figure 8.8.: Cross section of a double regulated bulb turbine

### 8.1.7. Cochlea screws

Hydraulic Cochlea is know since ancient times, as Archimede's wheel or snail. A new method of use, which consist in the inversion of the functioning, converts Archimede's snail pump into a turbine. With a given head, water falls flowing into the screw rotor and sets it in motion. I can be used with heads up to 10 $m$ and discharges up to 5,5 $m^3/s$ (Ref. [ATRO]). Moreover its efficiency is higher than other water wheels and small traditional turbines, and it remains more stable.

Construction costs are extremely cheaper than a traditional turbine, this makes this machine suitable for low cost project of rural electrification. Moreover its efficiency is higher than other water wheels and small traditional turbines, and it remains more stable.

Moreover Cochlea screw is robust, wear resistant and requires very short manteinance periods. It's highly tolerant to fish fauna, this is way the trashrack, which would introduce relevant head loss, is not needed.

Figure 8.9.: Coclea screws

## 8.2. Generator

Generators transform mechanical energy into electrical energy. Although most early hydroelectric systems were of the direct current variety to match early commercial electrical systems, nowadays only three-phase alternating current generators are used in normal practice. Depending on the characteristics of the network supplied, the producer can choose between:

**Synchronous generators:** They are equipped with a DC electric or permanent magnet excitation system associated with a voltage regulator to control the output voltage before the generator is connected to the grid. They supply the reactive energy required by the power system when the generator is connected to the grid. Synchronous generators can run isolated from the grid and produce power since excitation is not grid-dependent.

**Asynchronous generators:** They are simple squirrel-cage induction motors with no possibility of voltage regulation and running at a speed directly related to system frequency. They draw their excitation current from the grid, absorbing reactive energy by their own magnetism. Adding a bank of capacitors can compensate for the absorbed reactive energy. They cannot generate when disconnected from the grid because are incapable of providing their own excitation current. However, they are used in very small stand-alone applications as a cheap solution when the required quality of the electricity supply is not very high.

Below 1 $MW$, synchronous generators are more expensive than asynchronous generators and are used in power systems where the output of the generator represents a substantial proportion of the power system load. Asynchronous generators are cheaper and are used in stable grids where their output is an insignificant proportion of the power system load. The efficiency should be 95 % for a 100 $kW$ machine and can increase to 97% towards an output power of 1 $MW$. Efficiencies of synchronous generators are slightly higher. In general, when the power exceeds some $MVA$ a synchronous generator is installed.

| Rated power [kW] | Best efficiency |
|---|---|
| 10 | 0.910 |
| 50 | 0.940 |
| 100 | 0.950 |
| 250 | 0.955 |
| 500 | 0.960 |
| 1000 | 0.970 |

Figure 8.10.: Typical efficiencies of small generators

## 8.3. Control group

Turbines are designed for a certain net head and discharge. Any deviation from these parameters must be compensated for by opening or closing the control devices, such as the wicket-gates, vanes, spear nozzles or valves, to keep either the outlet power, the level of the water surface in the intake, or the turbine discharge constant.

In schemes connected to an isolated network, the parameter that needs to be controlled is the turbine speed, which controls the frequency. In an off grid system, if the generator becomes overloaded the turbine slows-down therefore an increase of the flow of water is needed to ensure the turbine does not stall. If there is not enough water to do this then either some of the load must be removed or the turbine will have to be shut down. Conversely if the load decreases then the flow to the turbine is decreased or it can be kept constant and the extra energy can be dumped into an electric ballast load connected to the generator terminals.

In the first approach, speed (frequency) regulation is normally accomplished through flow control; once a gate opening is calculated, the actuator gives the necessary instruction to the servomotor, which results in an extension or retraction of the servo's rod. To ensure that the rod actually reaches the calculated position, feedback is provided to the electronic actuator. These devices are called "speed governors".

In the second approach it is assumed that, at full load, constant head and flow, the turbine will operate at design speed, so maintaining full load from the generator, this will run at a constant speed. If the load decreases the turbine will tend to increase its speed. An electronic sensor, measuring the frequency, detects the deviation and a reliable and inexpensive electronic load governor, switches on pre-set resistance and so maintains the system frequency accurately.

The controllers that follow the first approach do not have any power limit. The electronic load governors, working according to the second approach rarely exceed 100 $kW$ capacity.

## 8.4. Transmission grid

There are three basic technical approaches to bring electricity to remote areas:

A first option is simply to extend the national grid. In many countries, however, extending the national grid can be extremely costly. Rural areas are normally located far from the national grid, therefore the high cost of extending the transmission lines usually make these projects unfeasible. The terrain also increases expansion costs significantly. Mountainous areas with difficult access for machinery require more time and resources to install transmission lines. A third factor, the size of the demand, determines the cost per $kWh$ of expanding the grid. A critical mass is necessary for a project to be viable but rural areas are generally small in size and their use of energy limited.

The second approach goes through the so called Energy Home System (EHS). The selection of this technology will depend mainly on the dispersion of the households and the types of load required. A village often can support the installation of its own small power system, but the transmission grid costs represent a big share of the project and its feasibility. Therefore a scattered population, covering a large area will entail higher connection costs, due to longer transmission lines. In these cases, stand-alone systems can be a better solution.

A third option is an electricity mini-grid, which can provide centralized electricity generation at the local level, using a village-wide distribution network. Mini grids provide capacity for both domestic appliances and local businesses, and have the potential to become the most powerful technological approach for accelerated rural electrification. Mini grids also offer an optimal solution for utilizing localized renewable energy resources. Many locations offer excellent natural conditions for the use of solar photovoltaic, wind or small hydropower.

Today, conservative calculations of life-cycle costs show that hybrid mini grids, powered chiefly by renewable energy with a generator set, normally working on diesel fuel , are usually the most competitive technical solution. However, translating this great technical potential into real success stories on the ground has turned out to be extremely challenging. Deployment of hybrid mini grids involves complex financial and organizational questions. The concerns for the sustainable success of mini-grids are not the technologies, but financing, management, business models, maintenance, sustainable operations, and socio-economic conditions. Each community presents a cluster of characteristics and interests which will define the best technical solution according to local financial, social, and environmental terms.

# Bibliography


[ARE] “Hybrid mini-grids for rural electrification”, 2011 - Alliance for Rural Electrification (ARE).

[ATRO] “Viti perpetue a forza idraulica” - ANDRITZ Atro GmbH.

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# Part III.

# Mini hydro plants simulator

# 9. Plant design

The aim of this part of the document is to explain in detail the computation process behind sizing, productivity, costs estimation of the hydropower plant, and profitability of the investment. To do that the main logical thread behind the software has been followed without connection to the software scheme, that instead is explained in the last chapter. The main logical tread can be summarized in the following steps:

1. Determination of the river features.
2. Sizing of the hydropower plant (Power group, Electrical equipment, Weir and intake, Channel and penstock).
3. Computation of the plant productivity.
4. Cost valuation of the hydropower plant components.
5. Estimation of the utilities capacity.
6. Development of an economic analysis.

During the whole software developing the main reference document has been the "Guide on How to Develop a Small Hydropower plant" (2004) of the 'European Small Hydropower Association' (Ref. [ESHA]).

## 9.1. Hydropower plant scheme

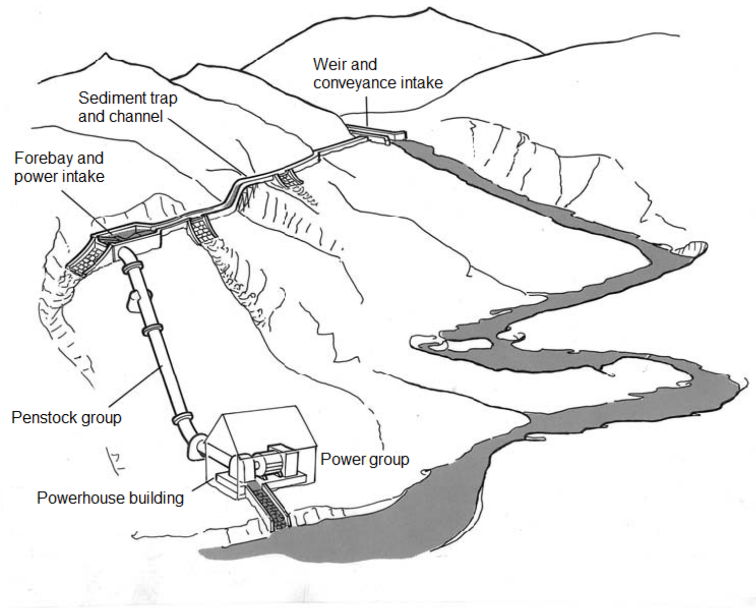


Figure 9.1.: Hydropower plant scheme

Each site configuration can hold an original design of power plant that best fits the terrain features. However for the software purpouse it has been necessary to choose a standard scheme of hydropower plant. The choice has been made following the criteria of adaptability and simplicity of realization. The resulting scheme is divided into different parts and each part is also divided into different components. The following list summarizes the parts and components of the hydropower plant that are described in detail in the next sections:

**Power group:** is the set of turbines used to produce electricity. The software is able to handle up to six parallel turbines of the same size. This is a limitation of the software capacity, but simulating different size parallel turbines results in an excessive computation complexity for the chosen mean. The single unit of the power group is named 'Turbine group' and is composed by:

1. Turbine
2. Alternator
3. Regulator system

**Electrical equipment:** is the set of the devices necessary to deliver electrical energy from the power house to the main distribution centre of loads. The border of the model is the step down transformer(s) that can be one or more depending on the location of the main utilities over the transmission grid. The different devices are:

1. Step up transformer
2. Transmission grid
3. Step down transformer(s)

**Weir and intake:** the weir increases the gross head and diverts the required water from the river to the channel, the conveyance intake stops the bigger debris carried by the river with a trashrack while the sediment trap cleans water from dangerous sand particles. The water flow diverted to the turbine can also be stopped by a gate to permit maintenance or cleaning operations. Components taken into consideration are:

1. Weir structure
2. Conveyance intake structure
3. Sediment trap

**Channel and penstock:** this set conveys the water to the power group. The penstock group includes the different penstocks, one for each parallel turbine, besides each penstock ends with a power valve that allows to stop one machine running the others. The powerhouse is sized to hold the power group and admits maintenance and displacement of the machines. Simulated components:

1. Channel
2. Forebay
3. Power intake structure
4. Penstock group
5. Powerhouse building

## 9.2. List of acronyms

In the following chapters many different parameters are used in functions and algorithms. To avoid the burdening of writing, typing all the units of measure, $m^3/s$ for flow parameters, $kW$ for power, $MWh$ for energy and $m$ for length parameters have been used, unless otherwise specified.

Besides the main parameters with their acronym have been collected in the tables .

| Term | Acronym | Term | Acronym |
|---|---|---|---|
| **River features** | | **Power group sizing** | |
| Hydrograph $[m^3/s]$ | $HY_{(t)}$ | Turbine number | $TN$ |
| Annual mean flow $[m^3/s]$ | $MF$ | Nominal turbine discharge $[m^3/s]$ | $TD_{nom}$ |
| Rainfall $[l/m^2]$ | $RA_{(t)}$ | Turbine discharge $[m^3/s]$ | $TD_{(t)}$ |
| Rainfall annual average $[l/m^2]$ | $AR$ | Turbine flow rate ratio | $fr_T$ |
| Corrective factor | $CF$ | Turbine efficiency | $\eta_{T(fr_T)}$ |
| Flow Duration Curve $[m^3/s]$ | $FDC$ | Alternator organic and electrical efficiency | $\eta_O$ |
| Gross project head $[m]$ | $GH$ | Global efficiency | $\eta_{G(fr_T)}$ |
| Project head loss | $hl_{nom}$ | Mean specific speed | $n_{QE}$ |
| Net project head $[m]$ | $NH$ | Main turbine dimension | $D_{max}$ |
| Hydropower potential $[kW]$ | $HP_{(t)}$ | Turbine speed $[rpm]$ | $TS$ |
| | | Turbine suction head $[m]$ | $SH$ |
| **Electrical equipment sizing** | | Nominal power group electrical power $[kW]$ | $GP_{nom}$ |
| Cable electrical resistance $[\Omega/km]$ | $R_{cable}$ | Nominal power group discharge $[m^3/s]$ | $GD_{nom}$ |
| Grid length $[km]$ | $L_{grid}$ | | |
| Utilities access points | $UA$ | **Weir and intake sizing** | |
| | | Residual flow $[m^3/s]$ | $RF_{(t)}$ |
| **Channel and penstock sizing** | | Excess flow $[m^3/s]$ | $EF_{(t)}$ |
| Channel length $[m]$ | $L_C$ | Extra head $[m]$ | $EH_{(t)}$ |
| Lining thickness $[m]$ | $t_L$ | Flood extra head $[m]$ | $FH$ |
| Forebay volume $[m^3]$ | $V_F$ | Size coefficient | $sc$ |
| Forebay filling time $[s]$ | $T_f$ | Hydraulic gradient $[m/m]$ | $S$ |
| Penstock diameter $[m]$ | $D_P$ | Manning's roughness coefficient | $n$ |
| Turbine group width $[m]$ | $W_{TG}$ | Water depth $[m]$ | $D_W$ |
| Turbine group length $[m]$ | $L_{TG}$ | Shape factor | $k$ |
| Powerhouse foundation thickness $[m]$ | $T_P$ | Trashrack approach velocity $[m/s]$ | $V_T$ |
| | | Component head loss $[m]$ | $HL_{component}$ |
| | | Gate thickness $[m]$ | $t_G$ |
| | | Trap deposition velocity $[m/s]$ | $V_D$ |

Table 9.1.: Table of acronyms I

| Term | Acronym | Term | Acronym |
|---|---|---|---|
| **Hydropower plant productivity** | | **Hydropower plant costs** | |
| Power group flow rate ratio | $fr_G$ | Corrective cost factor | $cf$ |
| Power group discharge $[m^3/s]$ | $GD_{(t)}$ | Transport cost factor | $tf$ |
| Operative turbines | $OT$ | Nominal turbine power $[kW]$ | $TP_{nom}$ |
| Global equivalent efficiency | $\varepsilon_{(fr_G)}$ | Turbine specific cost [€$/kW$] | $SC_{turbine}$ |
| Available river flow $[m^3/s]$ | $AF_{(t)}$ | Cost function 1st coefficient | $c_1$ |
| Available head $[m]$ | $AH_{(t)}$ | Cost function 2nd and 3rd coefficients | $c_2$ ; $c_3$ |
| Overflowing water $[m^3/s]$ | $OF_{(t)}$ | Transformer component cost $[USD]$ | $CC_{transformer}$ |
| Power group electrical power $[kW]$ | $GP_{(t)}$ | Steel pipe specific cost $[USD/m]$ | $SC_{s.p.}$ |
| Power factor $[kW/kVA]$ | $pf$ | Polyethilene pipe specific cost $[USD/m]$ | $SC_{p.p.}$ |
| Dissipated power over grid $[kW]$ | $DP_{(t)}$ | Valve component cost $[USD]$ | $CC_{valve}$ |
| Net power $[kW]$ | $NP_{(t)}$ | Operation and maintenance yearly cost $[USD]$ | $MC$ |
| Monthly productivity $[MWh]$ | $MP_{(t)}$ | Investment cost $[USD]$ | $IC$ |
| Working hours $[h]$ | $WH_{(t)}$ | Operation and maintenance cost percentage | $mc$ |
| | | Metal sheet specific cost $[USD/m^2]$ | $SC_{gate}$ |
| **Utilities** | | Grid specific cost $[USD/km]$ | $SC_{grid}$ |
| Utilities load factor | $LF_{utilities}$ | Building material specific cost $[USD/m^3]$ | $SC_{building\,m.}$ |
| Utilities minimum power $[kW]$ | $UMP$ | Lining material specific cost $[USD/m^2]$ | $SC_{lining\,m.}$ |
| Utilities peak power $[kW]$ | $UPP$ | Bars specific cost $[USD/m]$ | $SC_{bars}$ |
| Monthly utilities consumption $[MWh]$ | $UC_{(t)}$ | | |
| Monthly productivity $[MWh]$ | $MP_{(t)}$ | **Economic analysis** | |
| Monthly sold energy $[MWh]$ | $SE_{(t)}$ | Power plant cost $[USD]$ | $PC$ |
| Annual productivity $[MWh]$ | $AP$ | Engineering, consultation and commissioning cost | $ecc$ |
| Equivalent hours $[h]$ | $Eh$ | Estimated service life $[y]$ | $SL$ |
| Operative hours $[h]$ | $Oh$ | Discount rate | $r$ |
| Power plant load factor | $LF_{plant}$ | Specific plant cost $[USD/kW]$ | $SC_{power\,plant}$ |
| First year revenues $[USD]$ | $RE$ | Net present value $[USD]$ | $NPV$ |
| Energy price valuation $[USD/kWh]$ | $EP$ | Pay back time $[y]$ | $PBT$ |
| Connection price for preferential loads $[USD/kW]$ | $PCP$ | Levelized energy cost $[USD/kWh]$ | $LEC$ |
| Connection price for standard loads $[USD/kW]$ | $SCP$ | Internal rate of return | $IRR$ |

Table 9.2.: Table of acronyms II

## 9.3. Project flow

The 'Nominal power group electrical power' ($GP_{nom}$) has been chosen as a free parameter of optimization. It means that the whole power plant sizing depends on its value, so it's possible to refer to this parameter as the software 'key parameter'.

The flow chart 9.2 helps to understand the logical thread behind software computations:

- Red border boxes contain input parameters, as the design choices.
- Green border boxes contain main parameters, as the parameters that link different part of the project.
- Blue border boxes contain computed parameters, as intermediate parameters that are used to compute main parameters.

Moreover each chapter provides a detailed flow chart to help the understanding of its computation algorithms, following the same conventions on the coloured boxes.

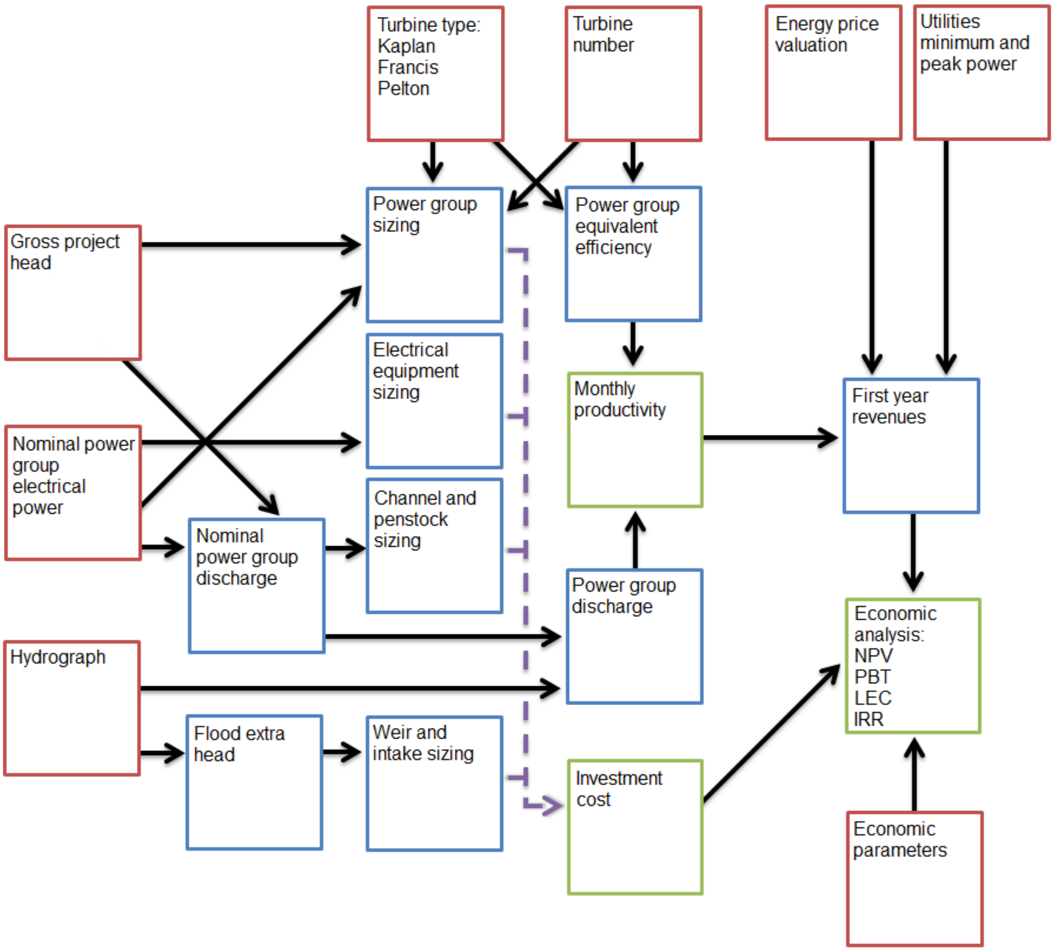


Figure 9.2.: Project flow chart

# 10. River features

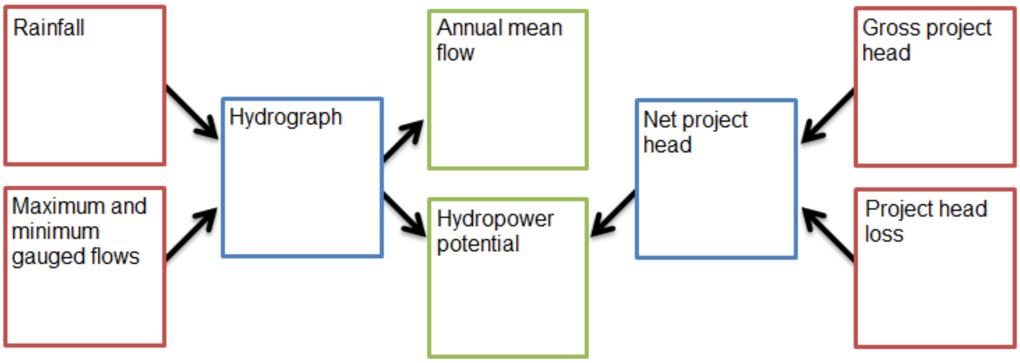


Figure 10.1.: 'River features' flow chart

## 10.1. Water flow

### 10.1.1. Hydrograph

The first challenge in rural areas application is to obtain available and complete data about the river flow. To do that it is necessary to gauge the flow at least for one year, recording the measurements. The collected values are recorded in the 'Hydrograph' ($HY_{(t)}$) as a time sequence, usually daily discretized. In most interesting sites gauging stations don't exist and the flow measurements are taken during periodical surveys, so the single value gauged during the survey has to be taken as the monthly mean value. That's why the software is developed with a monthly discretization of the hydrograph, that is its main weakness.

### 10.1.2. Rainfall to hydrograph

In many cases neither a monthly survey is possible, so it has been developed an algorithm able to estimates the hydrograph distribution knowing: the maximum and minimum flow and their gauging period, the rainfall patterns of the area obtainable by local gauging station or by triangulation of near gauging stations.

The main idea is that the hydrograph distribution follows the rainfall patterns with a month of delay. So for example, the ratio between flow value in February ($HY_{(2)}$) and its mean yearly value ($MF$) is equal to the ratio between the rainfall value in January ($RA_{(1)}$) and its mean yearly value ($AR$), raised to a corrective factor ($CF$).

$$\frac{HY_{(t)}}{MF} = (\frac{RA_{(t-1)}}{AR})^{CF}$$

From this main equation the following algorithm is obtained. Knowing the maximum ($HY_{max}$) and minimum ($HY_{min}$) river flow from two different surveys, and the complete rainfall patterns, the 'Corrective factor' ($CF$) and the 'Annual mean flow' ($MF$) are computed from the formula 10.1, that moreover, simulates the whole hydrograph distribution ($HY_{(t)}$). Notice that the 'Rainfall' value $RA_{(t)}$ $[l/m^2]$ must be always greater than zero to make the algorithm working.

**Algorithm 10.1** Rainfall to Hydrograph

$$MF = \frac{HY_{(t)}}{(RA_{(t-1)}/AR)^{CF}}$$

$$HY_{(t)} = MF * (\frac{RA_{(t-1)}}{AR})^{CF}$$

Figure 10.2 shows the result of a comparison test on the Pangani river in Tanga region, between the hydrograph data and the estimated hydrograph obtained with the algorithm 10.1. The comparison gives a mean error of 11,47% and a maximum error of 35,65%, comparable with yearly hydrograph fluctuations.

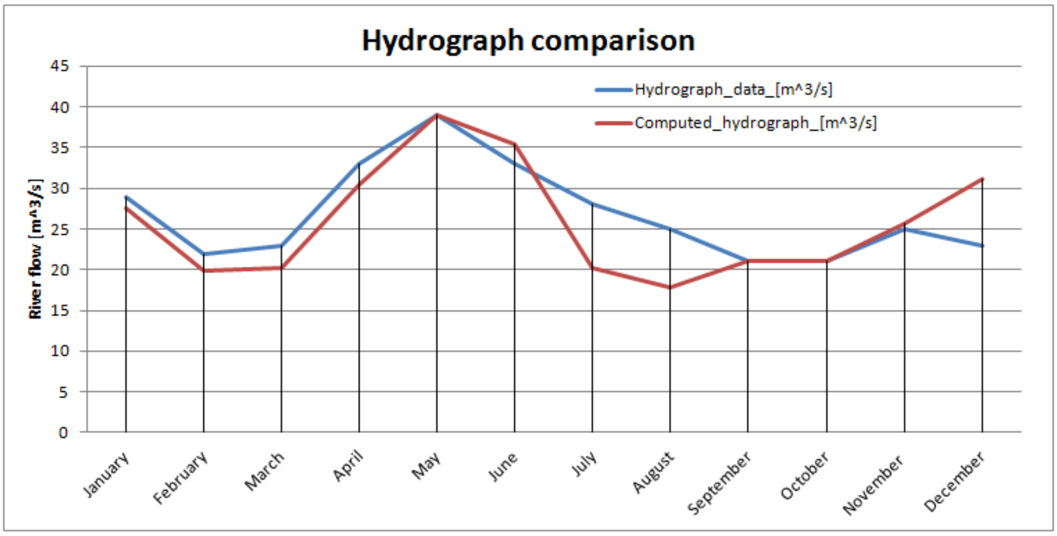


Figure 10.2.: Hydrograph comparison

Once the hydrograph distribution has been obtained, it can be rearrenged to generate the flow duration curve ($FDC$).

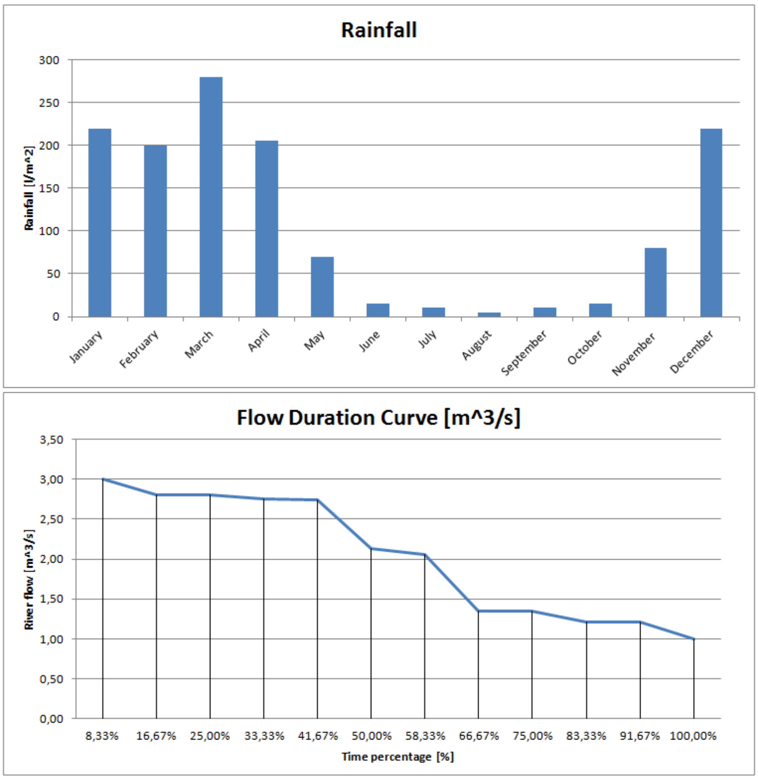


Figure 10.3.: Rainfall data and Flow Duration Curve (examples)

## 10.2. Head

'Gross project head' ($GH$) indicates the gap between the top of the weir and the project discharge water level ($DL$).

'Project head loss' ($hl_{nom}$) is the desired head loss due to channel, trashracks, intake and penstock, during the nominal operating, as a percentage of the gross head. It is fixed as a design parameter to compute the corresponding penstock diameter: the bigger the project head loss, the smaller is the penstock diameter and its cost. Usually the project of the power plants follows a trade-off between investment cost and productivity to select the best option, but a range between 2% and 12% can be used in most applications (the longer the penstock, the bigger the head loss coefficient).

Net head ($NH$) is then computed from gross head and project head loss as:

$$NH = (1 - hl_{nom}) * GH$$

These heads are computed as project values and the components of the power plant are sized on them, but during the power plant operation they can increase due to the overflow.

## 10.3. Hydropower potential

The 'Hydropower potential' ($HP_{(t)}$) is an estimation of the gross power obtainable by the whole river flow, as the hydrograph is monthly discretized. It's computed by the following formula:

$$HP_{(t)} = HY_{(t)} \cdot g \cdot \rho \cdot GH$$

The water density value $\rho$ is assumed equal to 1000 $kg/m^3$, the gravity costant $g$ is assumed equal to 9,81 $m/s^2$. In parallel to the maximum ($HY_{max}$) and minimum ($HY_{min}$) river flow, the maximum ($HP_{max}$) and minimum ($HP_{min}$) hydropower potentials are computed to set the power range of the hydropower plant.

# 11. Power group sizing

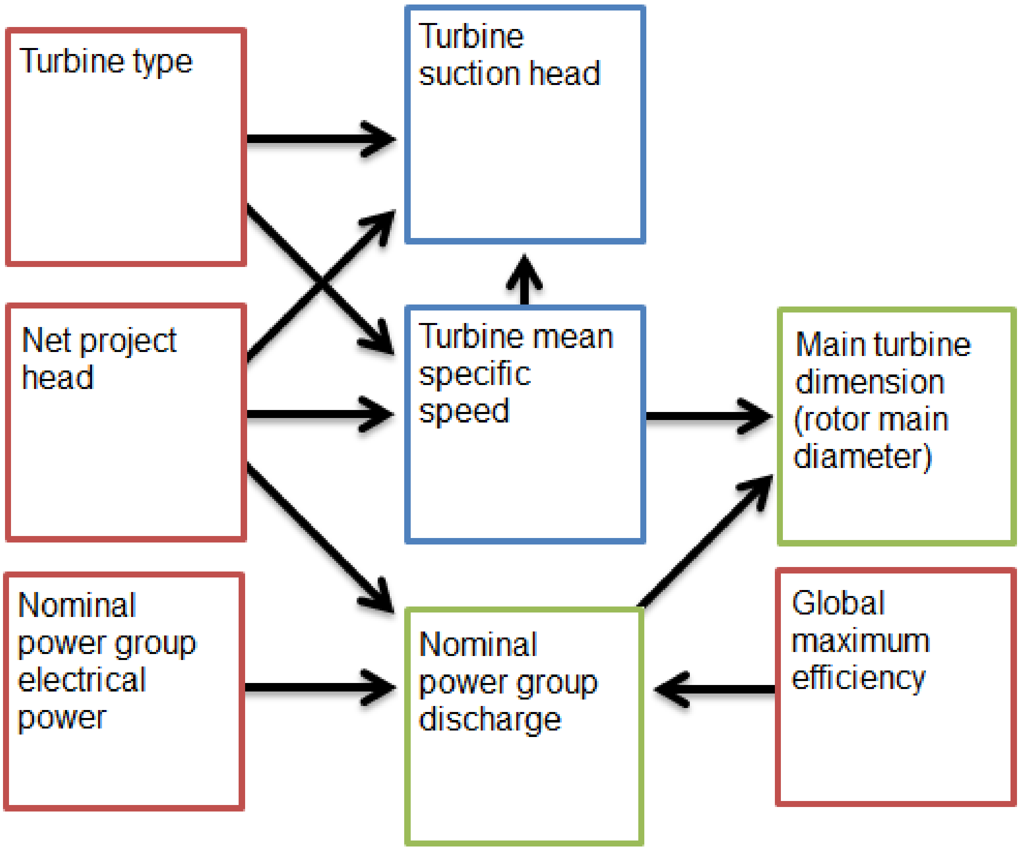


Figure 11.1.: 'Power group sizing' flow chart

## 11.1. Turbine choice

The turbine type choice mainly depends on the river gross head, but sometimes two different solutions are possible. In that case, the choice could depend by parameters like availability, logistic, and price. The program works on the main turbine types: Francis, Kaplan and Two nozzles Pelton. Other turbine types miss the reliability of informations, like efficiency curves and cost functions, so are not considered.

The 'Turbine number' ($TN$) choice is linked to the desired service continuity, virtually a power plant with two or more turbines can work for 8760 hours during the year, if the maintenance on the machines take place in different periods and the riverflow is able to satisfy at least one turbine minimum flow, even in the dry season. Also some logistic problems could be solved dividing the total power in two or more smaller machines.

To provide a tool that can help the user to choose the turbine type, a database of several mini hydro power plants installed among Europe and North America has been collected. The gross head varies between 2 to 340 $m$ and the turbine power between 25 to 2000 $kW$, that is the power range around which the software and its algorithms have been developed (Sources [Andritz, Canadian hydro, Canyon, Dependable, Dulas, TAMANINI, Wiki]).

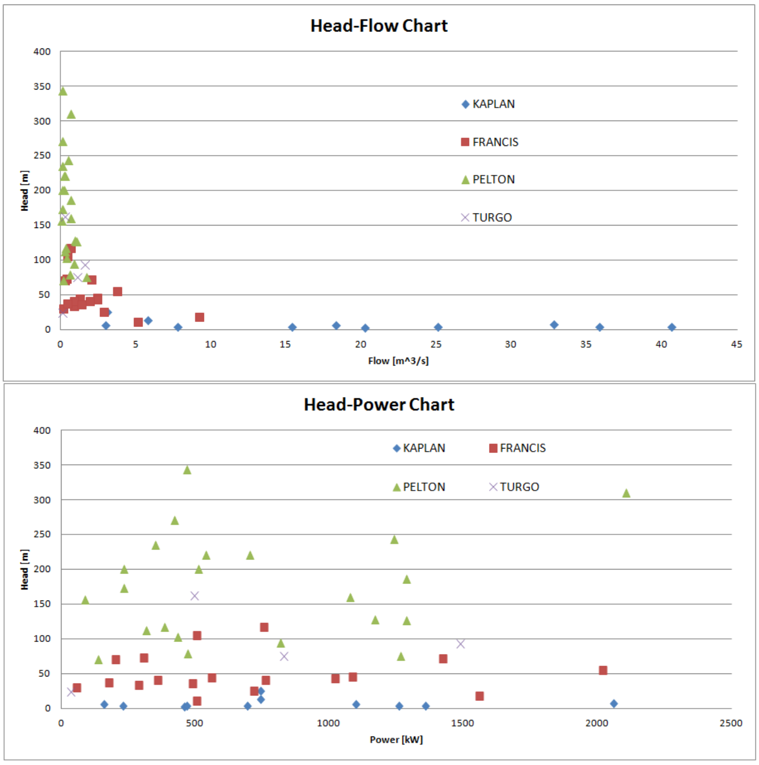


Figure 11.2.: Minihydro turbine database

## 11.2. Turbine efficiency

First of all a list of definitions, that helps to understand the following sections, is presented:

- $TD_{nom}$ 'Nominal turbine discharge' is the water flow through the single turbine, in nominal operation condition, that is the maximum flow allowable.
- $TD_{(t)}$ 'Turbine discharge' is the water flow through the single turbine, in non

nominal operation condition.

- $fr_T$ 'Turbine flow rate ratio' is the ratio between $TD_{(t)}$ and $TD_{nom}$ .
- $\eta_{T,max}$ is the 'Turbine maximum efficiency'.
- $\eta_{T(fr_T)}$ is the 'Turbine efficiency' as function of the turbine flow rate.

All technical information about turbine like maximum efficiency and efficiency trend as function of flow rate ($\eta_{T(fr_T)}$), are taken from the theory for well designed and state of art technologies (Ref. [ESHA]).

The organic and electric efficiency of the alternator ($\eta_O$) is assumed to remain at the costant value of 0,95. Then the global efficiency ($\eta_G$) is computed as a product between the turbine efficiency and the alternator efficiency, giving respectively $\eta_{G,max}$ and $\eta_{G(fr_T)}$. In the following sections $\eta_{max}$ and $\eta_{(fr_T)}$ will be used to refer to the global efficiency. Notice that a turbine could have the maximum efficiency at a flow rate minor than 100% so: $\eta_{(100\%)} < \eta_{max}$, as shown in the figure 11.3.

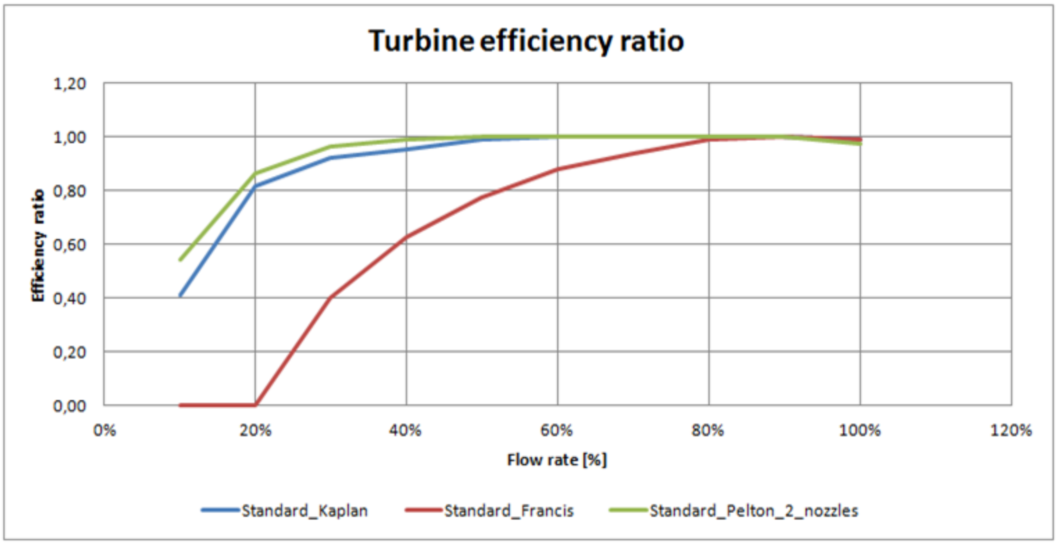


Figure 11.3.: Turbine efficiency ratio

## 11.3. Turbine dimensions

For each turbine type empiric coefficients ($c_1$, $c_2$) have been obtained (Ref. [Schweiger & Gregori, Lugaresi & Massa, Siervo & Lugaresi]), they are used in the following formula to compute a 'Mean specific speed' ($n_{QE}$):

$$n_{QE} = \frac{c_1}{NH^{c_2}}$$

The main turbine dimensions are also computed from empirical functions that return really approximate values, so it's dangerous to use these values to project the turbine, even this is'nt the aim of the software. Still the main turbine dimension can be used as an indicative value to size the powerhouse that has to hold these machines.

The computation of the 'Main turbine dimension' ($D_{max}$) through the 'Mean specific speed' takes different steps, here (Alg. 11.1) the Francis turbine formulas are explained, for the other turbines only the numerical coefficients change (Ref. [Siervo & Leva 1, Siervo & Leva 2, Siervo & Lugaresi]). $TS$ is the 'Turbine speed' in $rpm$, while $TD_{nom}$ is the 'Nominal turbine discharge' in $m^3/s$.

**Algorithm 11.1** Main turbine dimension

$$n_{QE} = \frac{1,924}{NH^{0,512}}$$

$$TS = 60 * n_{QE} * (g * NH)^{3/4} * TD_{nom}^{-0,5}$$

$$D_3 = 84,5 * (0,31 + 2,488 * n_{QE}) * \frac{NH^{0,5}}{TS}$$

$$D_1 = (0,4 * \frac{0,095}{n_{QE}}) * D_3$$

$$D_2 = \frac{D_3}{(0,96 + 0,3781 * n_{QE})}$$

The dimensions $D_3$, $D_1$, $D_2$ are respectively the outlet diameter, the inlet minimum diameter and the inlet maximum diameter of the Francis rotor. $D_{max}$ is the maximum value between them.

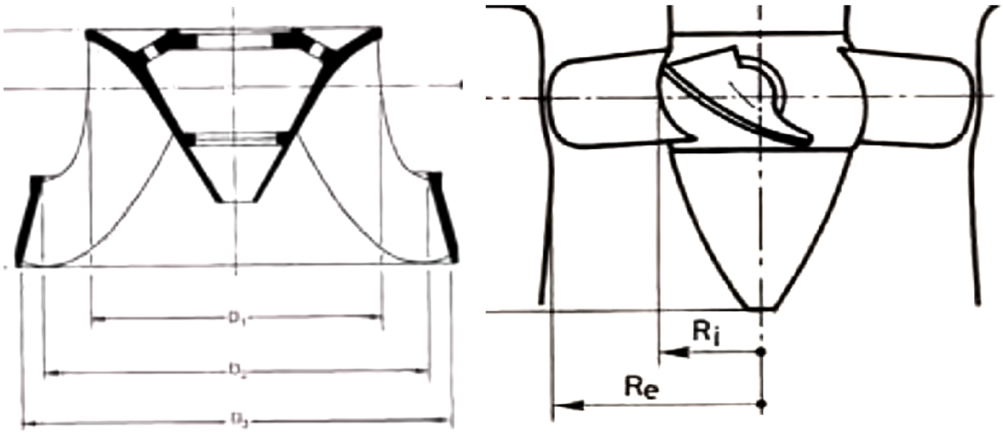


Figure 11.4.: Dimensions of Francis and Kaplan turbines

## 11.4. Turbine suction head

Another parameter that is possible to compute through empirical functions is the suction head ($SH$). It's important to know the suction head value to correctly locate the powerhouse and avoid cavitation problems inside the machine. If the gross head is low and the plant location is close to the sea level, the turbine can be located over the discharge water level ($DL$) of some meters. If the gross head is high and the power plant altitude is over 1000 $m$ on the sea level, it may be necessary to bury in part the powerhouse in order to locate the turbine behind the discharge water level.

**Algorithm 11.2** Suction head (Francis sample)

$$\sigma = 1,2715 * n_{QE}^{1,41} + \frac{V^2}{(2 * g * NH)}$$

$$SH = \frac{(P_{atm} - P_v)}{\rho * g} + \frac{V^2}{(2 * g)} - \sigma * NH$$

Suction head is computed from the specific speed ($n_{QE}$) and the Thoma's sigma ($\sigma$), its value indicates the necessary gap between turbine axis and discharge water level, expressed in meters (Ref. [Siervo & Leva 1, Siervo & Leva 2]). It affects Francis and Kaplan turbines, positive values means that the turbine can be located over the discharge water level, negative values mean that the turbine must be located under the discharge water level. As previously, only the Francis sample is reported (Alg. 11.2).

For $P_{atm}$a formula to compute the atmosferic pressure as function of the powerhouse altitude over sea level has been used. For $V$, water discharge velocity, a standard value of 2 $m/s$ has been considered, while vapour pressure $P_v$ has been taken at 20 Celsius degrees.

## 11.5. Power group discharge

The 'Nominal power group electrical power' ($GP_{nom}$) is the sum of the gross electrical power produced by all the installed machines in nominal operation conditions, like head level on weir top, 100% water flow through all turbines, machines new and clean. It has been chosen as a free parameter of optimization. It means that the whole power plant sizing depends on this value. So it's possible to refer to this parameter as the software 'key parameter'.

The 'Nominal power group discharge' ($GD_{nom}$), that is the water flow arriving to the turbine(s) via channel and penstock(s), is computed on the 'Nominal power group electrical power' as follows:

$$GD_{nom} = \frac{GP_{nom}}{(g * NH * \eta_{(100\%)})}$$

The nominal turbine discharge is immediatly computed as the ratio between power group discharge and turbine number:

$$TD_{nom} = \frac{GD_{nom}}{TN}$$

The $GD_{nom}$ is the water flow that the channel has to be able to deliver from the weir to the powerhouse, so most of the hydraulic components are sized on this value.

# 12. Electrical equipment sizing

For the electrical equipment some standards have been chosen to simplify the model.

The model uses one step up transformer from the power plant to the 11 $kV$ transmission grid, and one or more step down transformer(s) from the 11 $kV$ grid to the 0,4 $kV$ distribution grid that, as a first attempt sizing, share the total power.

For the transmission grid a wood-pole line with three-fase 100 $mm^2$ ACSR cables have been considered. That cable is a good choice for a MV transmission grid, furthermore the cable type have a small impact on the grid total cost. The adopted electrical resistance ($R_{cable}$) of a single fase cable is 2,733 $\Omega/km$.

Parameters like 'Grid length' ($L_{grid}$) and 'Utilities access points' ($UA$), that is the number of step down transformers, need a previus feasability study that maps the main utilities location and find out the optimum layout. So different scenarios could be analized, changing the reached utilities.

The choice of adopting standards represents a limit, but at the end the cost variation linked to these parameters has a neglectable impact on the whole power plant cost. Moreover these standards are consistent with the software power range in most results (Sources [DIT2, POLIMI3]).

# 13. Weir and intake sizing

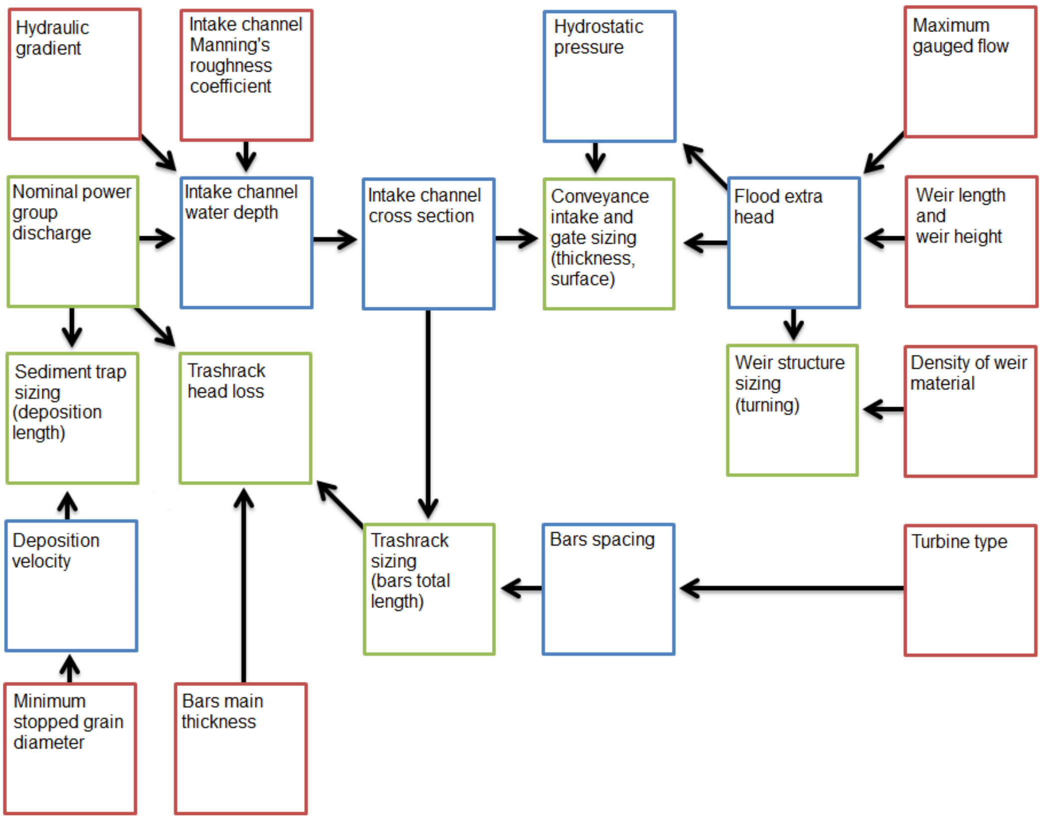


Figure 13.1.: 'Weir and intake sizing' flow chart

## 13.1. Weir structure

### 13.1.1. Flood extra head

The main aim of the weir is to divert the river flow to the intake, but it also must hold on when submitted to the most critical condition: the flood. A broad crested, trapezoid section weir has been chosen for the software (Source [DIT3]). Weir length ($WL$) and weir height ($WH$) are the two main weir dimensions linked to the river shape, as a first attempt weir length corresponds to the river width, while weir height corresponds to the water depth, but it could be obviously increased to raise the gross head.

The river flow ($HY_{(t)}$) is always greater than the nominal power group discharge ($GD_{nom}$), at least to ensure the fauna life with a 'Residual flow' ($RF_{(t)}$) and the 'Excess flow' ($EF_{(t)}$) overflows the weir, adding an extra head ($EH_{(t)}$) that weighs on the structure. In the most critical period the maximum flow ($HY_{max}$) generates the maximum extra head ($EH_{max}$), amplifying the maximum flow by a flood coefficient ($fl$) of 20, the 'Flood extra head' ($FH$) is computed:

$$FH = (\frac{fl * HY_{max}}{1,6 * WL})^{2/3}$$

Where 1,6 is the coefficient used for broad crested weirs (Ref. [Sinniger & Hager]).

### 13.1.2. Weir turning sizing

Usually the weir is sized to resist sliding and turning, but in the analyzed cases the turning test is always the most critical, so it will be the only one considered. The trapezoid section weir is sized on turning around the base downstream edge that is the most critical situation a small simple weir can be submitted.

Different weir materials can be used, but in this model the choice has been limited to armed concrete and rocks, mainly depending on the transport accessibility of the weir location. Each material has its own density $\rho_M$, specific cost in $USD/m^3$, and a different size coefficient ($sc$) to oversize the computed bases of the trapezoid weir, the more unrielable the building material, the bigger the size coefficient ($sc_{concrete} = 1,5$ ; $sc_{rocks} = 2,1$).

Figure 13.2 helps to understand the algorithm 13.1 in which the sizing formulas are presented. Red numbers indicate the hydro-static loads, small black letters indicate the weir dimensions, related to the weir height $z$. For example $bz$ is the secondary base width, were $b$ is the secondary base factor; $hz$ is the flood extra head due to overflow in the flood critical condition, that is the $FH$ defined previously; $1 \rightarrow$ is the main hydro-static load while $4 \downarrow$ is the static load due to the weir own weigth.

The algorithm refers to the moments generated by the hydro-static forces around the edge $O$ with the capital letter $M_i$. The moment summation [1] results in a second degree equation in $b$ [2], from which the positive value of $b$ is computed [3].

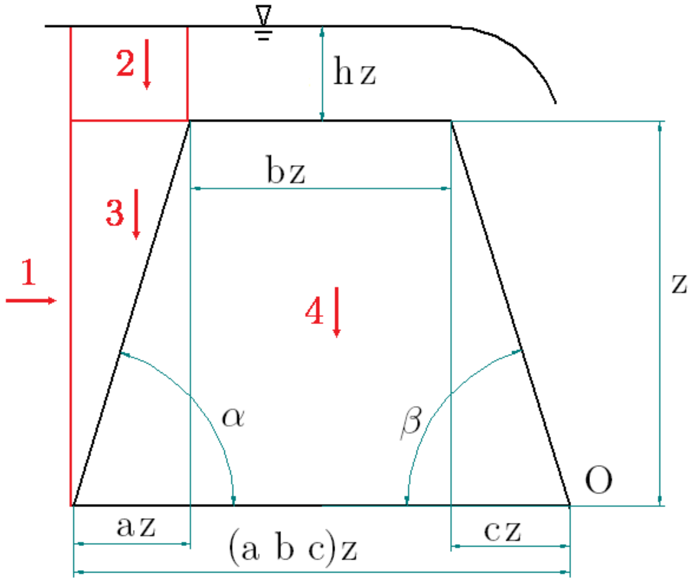


Figure 13.2.: Weir turning sizing sketch

**Algorithm 13.1** Weir turning sizing

$$M_1 = (\rho_{H_2O} * g * \frac{((1+h)*z)^2}{2}) * (\frac{1}{3} * (1+h) * z)$$

$$M_2 = (\rho_{H_2O} * g * hz * az) * (c + b + \frac{a}{2}) * z$$

$$M_3 = (\rho_{H_2O}*g*sin(\alpha)*bz*az)+(\rho_{H_2O}*g*sin(\alpha)*cz*az)+(\rho_{H_2O}*g*sin(\alpha)*\frac{(az)^2}{2})$$

$$M_4 = \rho_M * g * ((a+b+c)*z + bz) * \frac{z}{2} * (c + \frac{b}{2}) * z$$

$$M_1 = M_2 + M_3 + M_4 \, [1]$$

[...]

$$A * b^2 + B * b + C = 0 \, [2]$$

$$With:$$

$$A = \frac{1}{2} * \rho_M * z^3$$

$$B = \rho_{H_2O} * z^2 * (h * a * z + sin(\alpha)) + \rho_M * z^3 * (\frac{5}{4} * c + \frac{1}{4} * a)$$

$$C = \rho_{H_2O}*z^2*(-\frac{1}{6}*(1+h)^3*z+h*a*c*z+\frac{1}{2}*h*a^2*z+sin(\alpha)*c*a+\frac{1}{2}*a*sin(\alpha))+\frac{1}{2}*\rho_M*c*z^3*(a+c)$$

$$Then:$$

$$b = \frac{-B + (B^2 - 4*A*C)^{0,5}}{2*A} \, [3]$$

The computed $b$ value is oversized using the material size coefficient $c_S$, then all the other weir dimensions can be found, knowing the upstream angle $\alpha$ and the downstream angle $\beta$, for which a value of 80° has been considered.

The lateral protection walls that diretcs the water flow to the weir are similarly sized to avoid overflow during floods.

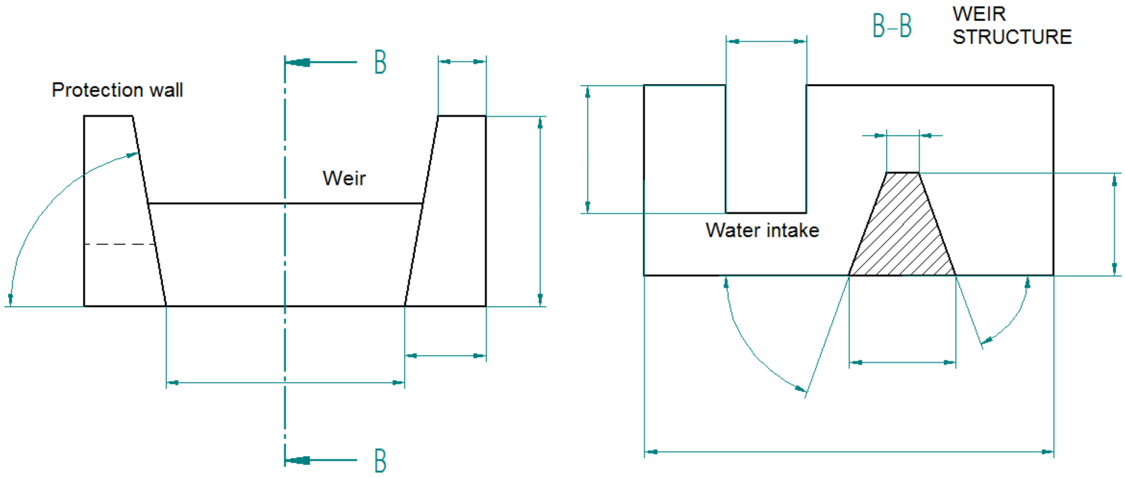


Figure 13.3.: Weir drawing

## 13.2. Conveyance intake structure

This small structure holds a protective trashrack, a gate between two concrete pillars and a short channel to divert water to the sediment trap.

### 13.2.1. Intake channel sizing

The short intake rectangular channel is assumed to have the same hydraulic gradient of the long channel and its lining is build with the same material. Then assuming that the channel section shape is an half square and the flow is in the rough turbolent zone, the Manning's equation can be used. According to Manning the water flow ($GD_{nom}$) is function of the hydraulic gradient ($S$) and the Manning's roughness coefficient $n$, so the following fomula to compute the water depth ($D_W$) has been obtained from the Manning's equation:

$$D_W = (k_S * GD_{nom} * n * S^{-0,5})^{\frac{3}{8}}$$

Where $k_S$ is a shape coefficient, that for rectangular section channels assumes a value of 1,26. The channel top width ($W_C$) and the 'Channel cross section' ($A_C$) are immediatly computed as:

$$W_C = 2 * D_W$$

$$A_C = 2 * D_W^2$$

The freeboard depth ensures that water waves aren't able to overflow the channel border. It's usually sized as one third of the channel depth. The sum of channel and freeboard depth results in the channel total depth ($D_T$).

### 13.2.2. Trashrack sizing

The trashrack is a grate of bars whose main aim is to stop the bigger debris and protect the turbine(s). Its sizing depends on the bar spacing necessary to protect the turbine, in fact each turbine type has its own admittable bars spacing ($b$): 9 $cm$ for Kaplan, 4,5 $cm$ for Francis and 2,5 $cm$ for Pelton. Different shapes of bar section are available, but this model considers the most common one, the circular shape, and the most efficient one, the drop shape. Each bars type has its own specific cost in $USD/m$, main thickness ($t$) and its own shape factor ($k$), used to compute the head loss introduced by the trashrack.

First of all it is necessary to compute the 'Trashrack approach velocity' ($V_T$), knowing the trashrack angle of slope ($\gamma$) [1], then the head loss introduced by the trashrack ($HL_{trashrack}$) can be computed by the Kirschmer formula [2] (Ref. [Mosonyi]):

**Algorithm 13.2** Trashrack head loss

$$V_T = \frac{GD_{nom}}{W_C * D_W} * sin(\gamma) \, [1]$$

$$HL_{trashrack} = k * (\frac{t}{b})^{4/3} * (\frac{V_T^2}{2 * g}) * sin(\gamma) \, [2]$$

### 13.2.3. Gate sizing

The gate is a simple metal sheet that holds water pressure to prevent the water entering the channel, its dimensions are heigth ($H_G$) and width ($W_G$), equal to the intake channel width. The gate must fulfill its function even in flood critical condition. In order to ensure its function, a simple pressure test has been used to compute the gate thickness ($t_G$) [$m$].

The most critical point of the gate is its bottom, where water pressure is greater; during floods the water level reaches the top of the gate, so the bottom has a water depth equal to the gate height ($H_G$). The hydrostatic pressure ($P$) [$Pa$] is immediatly computed as:

$$P_{hydro} = g * \rho_{H_2O} * H_G$$

The gate has a tensile strength ($\sigma$) of 200 $Mpa$, so under cut condition the stress limit ($\tau$) is computed as follow:

$$\tau = 0,8 * \sigma$$

Then the resulting gate thickness is computed as the thickness necessary to hold water pressure, using a great size coefficient ($sc$) of 30 to prevent the fail due to corrosion, aging or shocks:

$$t_G = sc * \frac{0,5 * (P_{hydro} * W_G)}{\tau} + 0,001$$

Finally the pillars have been sized using a turning test, similar to the one used for weir and protection walls, that considers the hydrostatic force operating on the closed gate in critical flood conditions.

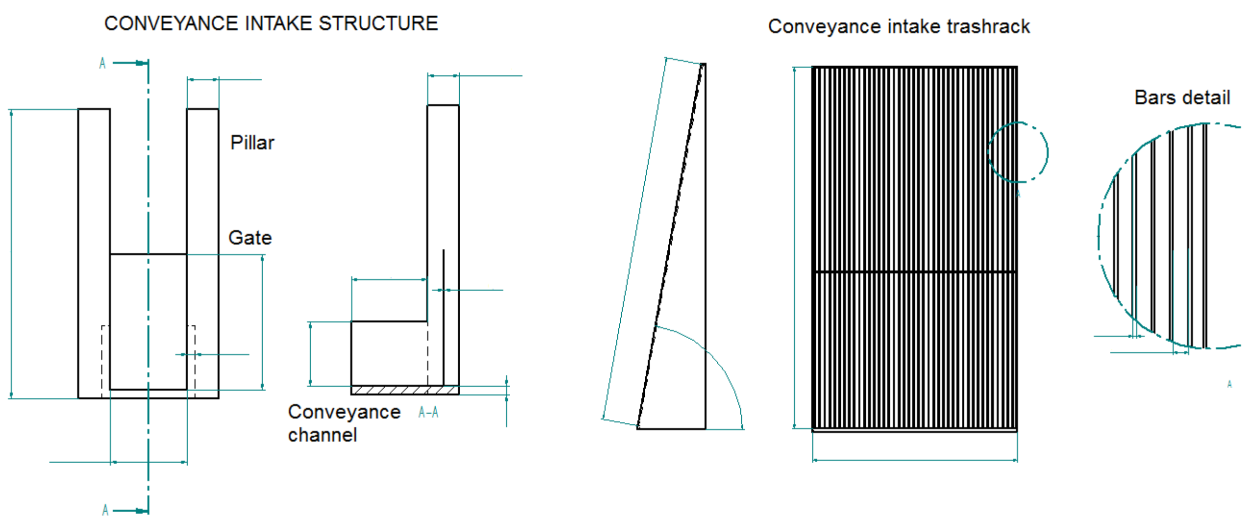


Figure 13.4.: Conveyance intake drawing

## 13.3. Sediment trap

The sediment trap aim is to stop the sand carried by the water to extend the turbine life. The sand is collected on the bottom of the trap and is periodically flushed away via a dedicated gate. In this model the sediment trap has been sized to capture the sand carried by the river until 0,3 $mm$ of grain diameter, that is a standard value. The algorithm 13.3 sizes the length of the sediment trap $L_T$ $[m]$ as a function of the trap width $W_T$ $[m]$ and the water discharge ($GD_{nom}$) [2]. The deposition velocity $V_D[m/s]$ is computed as function of the minimum stopped grain diameter $d_G$ $[mm]$ with the empirical Zanke's formula [1]. Remember that the main aim of this model is not to correctly size the hydropower plant, but to roughly size it to finally compute a total cost of the power plant. Then, this formula could be simply used to have an approximation, but not a correct value (Ref. [Bouvard]).

**Algorithm 13.3** Sediment trap sizing

$$V_D = \frac{0,1}{(9 * d_G)} * ((1 + 157 * (d_G)^3)^{0,5} - 1)\ [1]$$

$$L_T = \frac{GD_{nom}}{V_D * W_T}\ [2]$$

Furthermore is recommended to satisfy the relation $L_T > (8 * W_T)$, so a corrective coefficient of 2 is applied to the trap length.

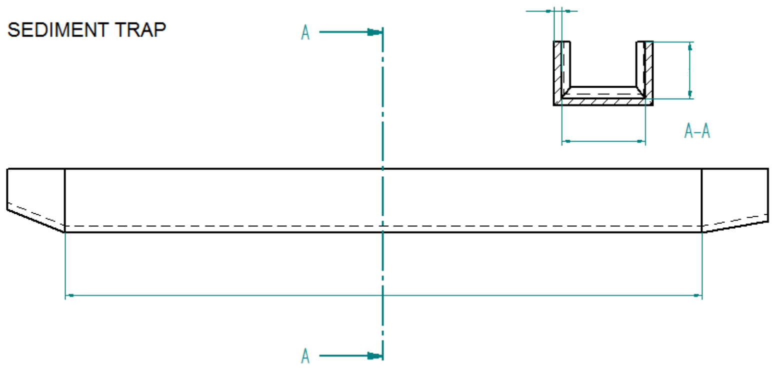


Figure 13.5.: Sediment trap drawing

The sediment trap is excavated and then covered with a lining of the same material and thickness used for the channel.

# 14. Channel and penstock sizing

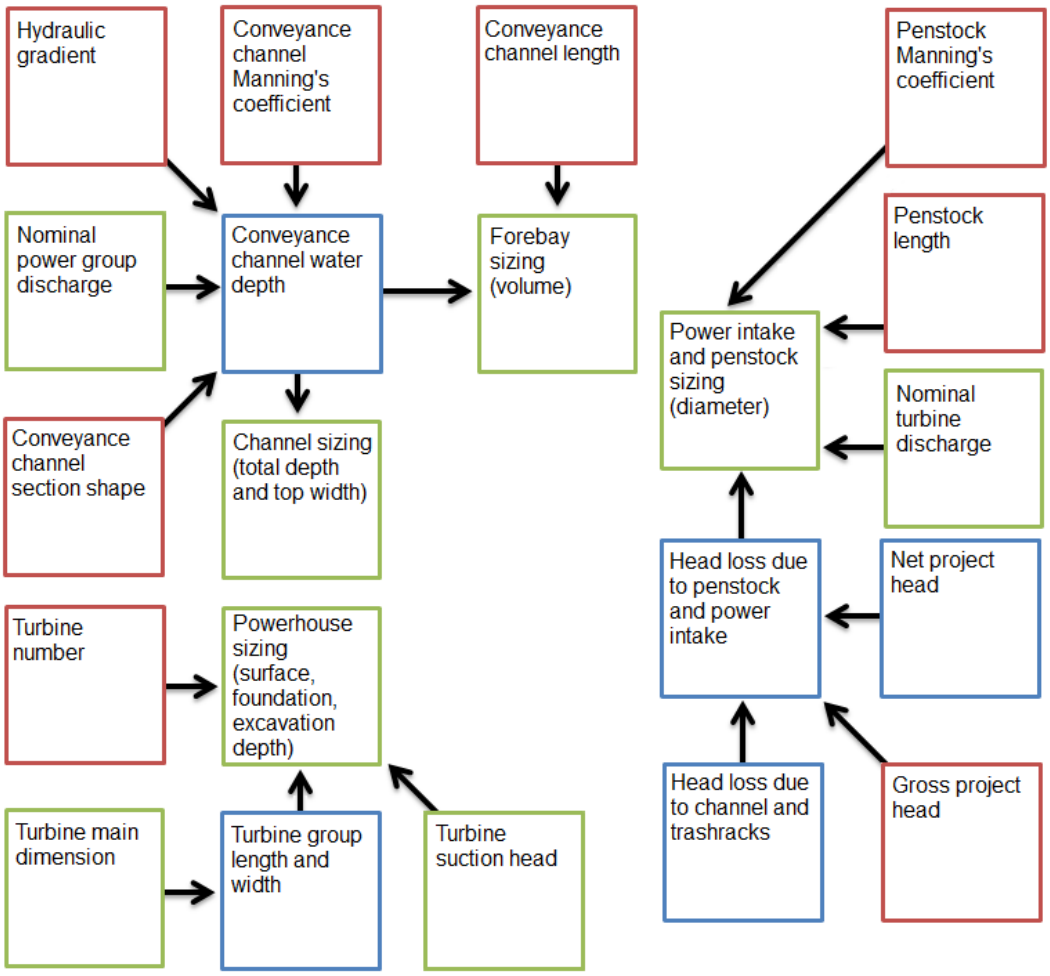


Figure 14.1.: 'Channel and penstock sizing' flow chart

## 14.1. Channel

The channel leads water from the sediment trap to the forebay. Its length ($L_C$) and its hydraulic gradient ($S$) depend on the hydropower plant layout, in fact the gradient is computed as the ratio between the channel length and the heigth gap between weir top and forebay water level.

As for the weir, two different materials are available in the model: concrete and rocks. The choice of the materials affects quantitative parameters like Manning's coefficient ($n$), lining thickness ($t_L$) and specific lining cost expressed in $USD/m^3$, but also qualitative parameters like building time, structure reliability, maintenance frequency, that have to be considered during the project stage. The used lining thickness are 35 $cm$ for rocks and 25 $cm$ for concrete (Source[POLIMI2]).

For the channel two different section shapes could be considered: rectangular (half square) and trapezoid (half hexagon). Again this choice affects quantitative parameters like channel depth, top width, wetted perimeter, excavation cost coefficient, but also qualitative parameters like building complexity, cleaning operations difficulty, structure resistance.

The following formula sizes the channel water depth ($D_W$) for a trapezoid channel, with a shape coefficient value ($k$) of 0,92:

$$D_W = (k_S * GD_{nom} * n * S^{-0,5})^{\frac{3}{8}}$$

The channel top width ($W_C$) is computed as: $W_C = 2,31 * D_W$, while the freeboard is sized as one third of the water depth, giving the total channel depth ($D_T$).

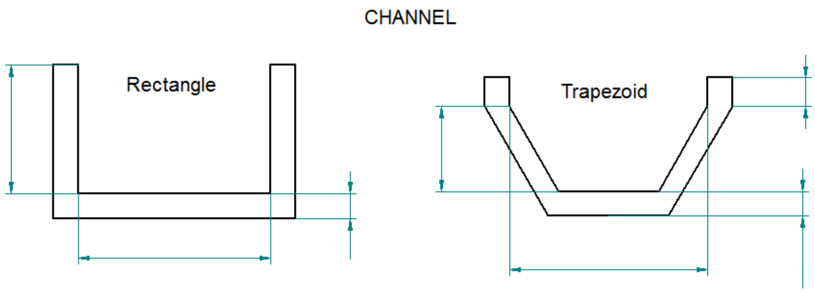


Figure 14.2.: Channel drawing

## 14.2. Forebay

A simple rectangular tank is the forebay model sized to ensure supply continuity for small supply stops.

Forebay depth ($D_F$) and width ($W_F$) are connected to channel dimensions through geometrical relations:

$$D_F = 3 * D_T$$

$$W_F = 3 * W_C * TN^{0,5}$$

The turbine number $TN$ is considered in the sizing to admit the necessary spacing to accomodate all the penstock(s).

Forebay volume $V_F$, then forebay length $L_F$, are sized to ensure supply continuity for short flow stops or fluctuations, using channel length $L_C$ and channel depth $D_W$ as input. The formula [1] computes the forebay filling time $T_f$ as the time the channel takes to empty its water, the [2] computes the forebay volume needed to ensure power continuity during this time.

**Algorithm 14.1** Forebay sizing

$$T_f = \frac{2 * L_C}{(D_W * g)^{0,5}} \text{ [1]}$$

$$V_F = GD_{nom} * T_F \text{ [2]}$$

Again is the channel that imposes the lining material and its thickness to the forebay lining.

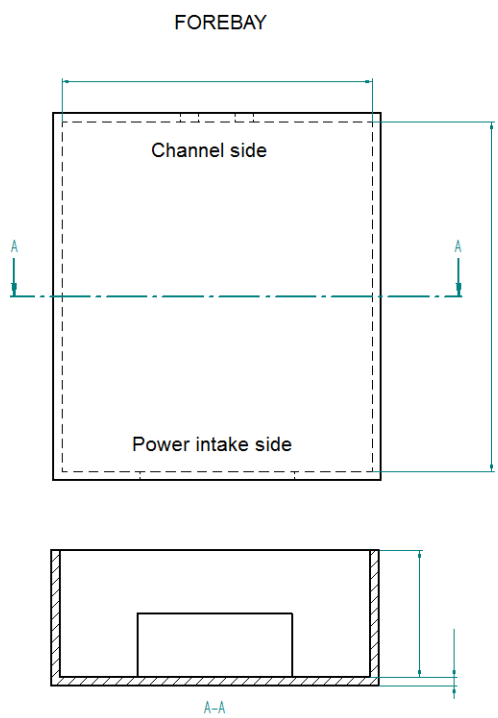


Figure 14.3.: Forebay drawing

## 14.3. Power intake structure

The power intake structure is composed by a second trashrack, placed at the bottom of the forebay, that protects a pyramidal shape structure conveying the water from the forebay to the penstock(s). The pyramidal shape has been chosen because it's the one that minimizes the head loss. Power intake inlet dimensions are connected to forebay dimensions through simple geometrical relations.

The head loss introduced by the second trashrack adds up to the first trashrack head loss, giving the total headloss due to trashracks, named $HL_{trashracks}$.

Even for the pyramidal structure of the power intake, the channel imposes the lining material and its thickness.

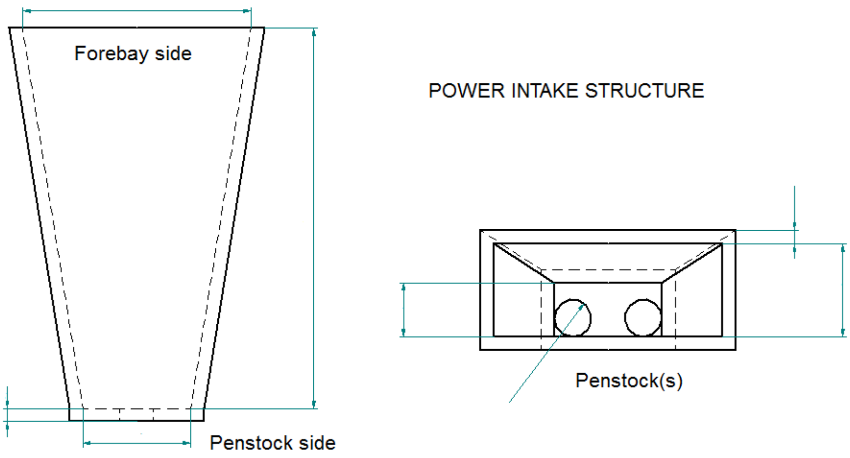


Figure 14.4.: Power intake drawing

## 14.4. Penstock group

It includes the different pipe(s), one pipe for each turbine of the power group, and their dedicated 'Power valve'. The pipe diameter is sized on the desired head loss, rounded to the closest commercial available diameter.

Two different materials have been considered in the model: polyethylene and welded steel. Each pipe has its own specific cost in $USD/m$ and its own Manning's coefficient. The choice depends mainly on the net head, high head needs a steel pipe, while for low head a polyethilene pipe can be the simpler and cheaper one. Besides the terrain type could affect the pipe material selection.

The power intake expected head loss, computed from an empirical formula (Ref. [ASCE]), depends on the penstock inlet velocity, as well as the penstock head loss itself. Then penstock and power intake are sized together to ensure the respect of the project head loss. The formula [1] computes head loss of the pyramidal intake as function of the mean penstock velocity $V_P$. The Manning's formula [2], adapted to the penstock, computes the penstock head loss as function of the single turbine discharge $TD_{nom}[m^3/s]$, the Manning's roughness coefficient $n$ and the penstock length $L_P$. The formulas [1] and [2] have been merged in the formula [3]. Then the head loss due to penstock and pyramidal intake ($HL_{intake+penstock}$) as the difference between gross head ($GH$) and net head ($NH$) minus the head losses due to trashracks ($HL_{trashracks}$) and channel ($HL_{channel}$) is computed [4]. Finally, processing the formula [3], the penstock diameter ($D_P$) is obtained [5].

**Algorithm 14.2** Penstock sizing

$$HL_{intake} = 0,19 * \frac{V_P^2}{2 * g} \text{ [1]}$$

$$HL_{penstock} = L_P * 10,3 * \frac{(n * TD_{nom})^2}{D_P^{5,333}} \text{ [2]}$$

[...]

$$HL_{intake+penstock} = 0,0157 * \frac{TD_{nom}^2}{D_P^4} + 10,3 * L_P * \frac{n^2 * TD_{nom}^2}{D_P^{5,333}} \text{ [3]}$$

$$HL_{intake+penstock} = GH - NH - HL_{channel} - HL_{trashracks} \text{ [4]}$$

[...]

$$D_P = (\frac{TD_{nom}^2}{HL_{intake+penstock}} * (0,0157 + L_P * 10,3 * n^2))^{0,19827} \text{ [5]}$$

## 14.5. Powerhouse building

The powerhouse is a rectangular concrete building protecting the machineries. It is divided into a 'Power room' that holds the penstock(s) outlet and the turbine group(s), and a 'Control room' that holds the electrical control systems and other electrical equipment.

The powerhouse is sized on the 'Turbine group', whose dimensions are related to the turbine rotor main dimension ($D_{max}$). As a first approach the turbine group has been considered as a parallelepiped of width: $W_{TG} = 3 * D_{max}$ and length: $L_{TG} = 6 * D_{max}$. It's surely a rough estimation, but the real cases are so various that it is impossible to obtain an universal estimation. Some pictures of turbine groups have been reported in figure 14.5 to give an idea of the existing relations between turbine rotor and turbine group dimensions (Source [Andritz]).

Figure 14.5.: Turbine groups: Kaplan, Francis, Pelton

To compute the power house dimensions a standard distance of 3 $m$ between walls and machines has been used, in order to ensure accessability to the turbines for maintenance (Source [POLIMI2]). The concrete foundation thickness ($T_P$) computation uses again a simple relation: $T_P = 0,5 * W_{TG}$. Obviously the real powerhouse project depends on many parameters that change from case to case, so the resulting powerhouse dimensions (and cost) could change widely from the predicted. Remember that the powerhouse must be partially buried, if the suction head ($SH$) results in a negative value (Alg. 11.2).

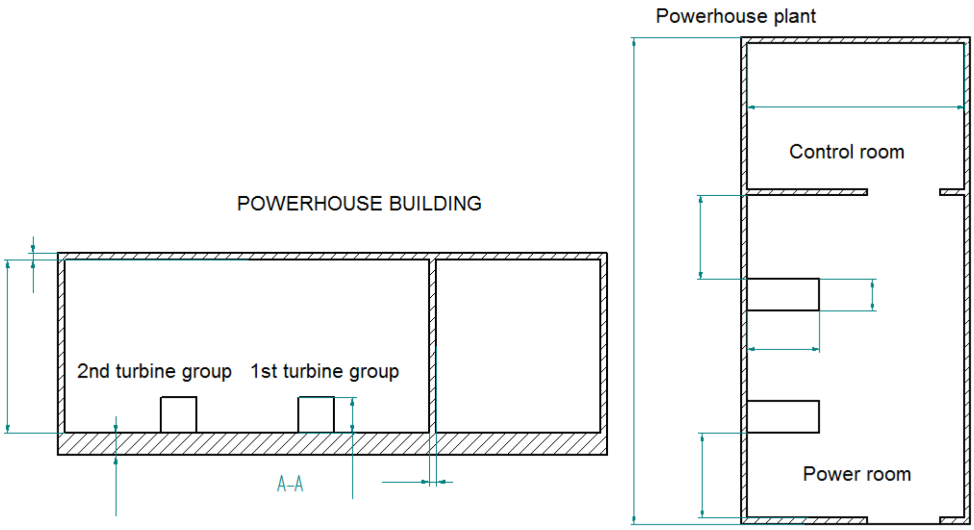


Figure 14.6.: Powerhouse drawing

# 15. Hydropower plant productivity

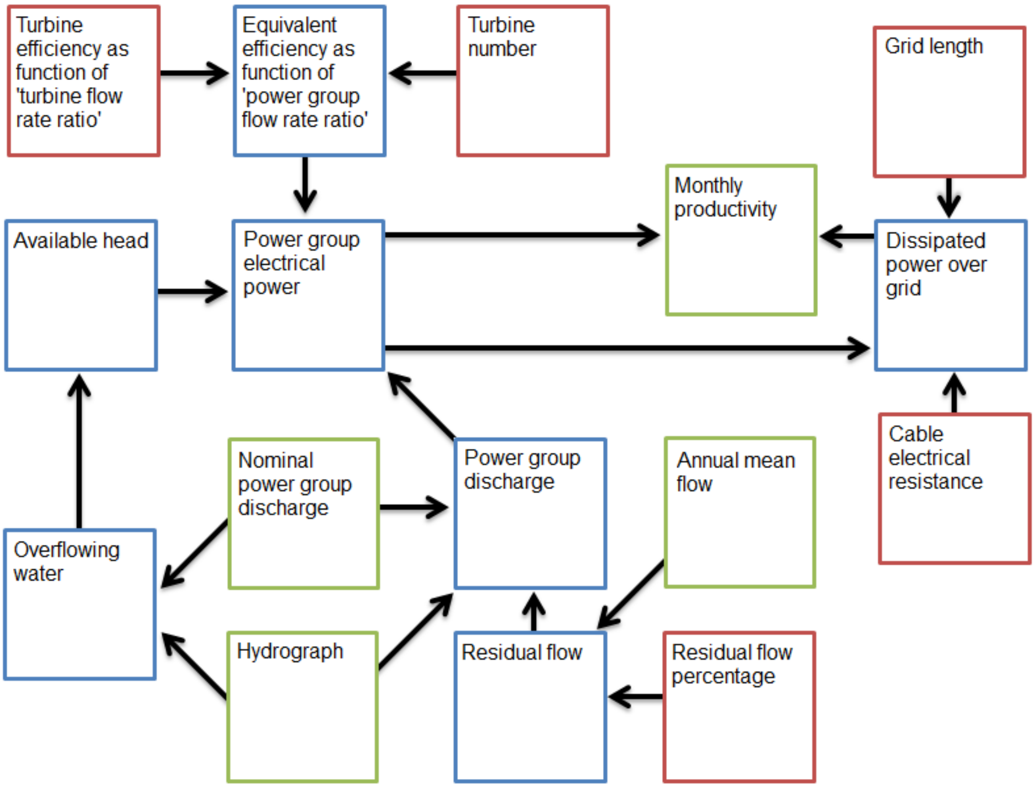


Figure 15.1.: 'Hydropower plant productivity' flow chart

## 15.1. Power group equivalent efficiency

The model is able to manage the simulation of a turbine set consisting of six or less parallel turbines (larger number is unusual for minihydro applications) of the same size and type. In order to evaluate the overall efficiency, the main idea is to handle the 'Power group', composed by the different turbine groups, as a single turbine with a particular efficiency curve 15.1, computed as an equivalent efficiency.

To do that an algorithm has been developed (Alg. 15.1):

- $fr_G$ is the 'Power group flow rate ratio', defined as the ratio between 'Power group discharge' $GD_{(t)}$ and 'Nominal power group discharge' $GD_{nom}$.

- $TN$ is the number of installed parallel turbines.
- $OT$ is the number of operative turbines.
- $\eta_{(fr_T)}$ is the global efficiency of one turbine group as function of the 'Turbine flow rate ratio' $fr_T$ (Section 11.2).
- $\varepsilon_{(fr_G)}$is the global equivalent efficiency as function of the 'Power group flow rate ratio'.

The principle is to run all the $TN$ turbines until water flow decreases behind the $(TN-1)$ flow limit, then run $(TN-1)$ turbines until flow rate decreases behind the $(TN-2)$ flow limit, and then operate $(TN-2)$ turbines, and so on, until only one machine works. The maximum efficiency of the single turbine ($\eta_{max}$) has the same value of the maximum equivalent efficiency ($\varepsilon_{max}$) of the power group, because the power group flow rate is equally distributed so, if each machine works in the maximum efficiency condition, the mean efficiency value is the same.

**Algorithm 15.1** Equivalent efficiency ratio

$$OT \geq (fr_G * TN)\,[1]$$

$$With\,OT\,positive\,integer$$

$$fr_T = fr_G * \frac{TN}{OT}\,[2]$$

$$\varepsilon_{(fr_G)} = \eta_{(fr_T)}\,[3]$$

$$\frac{\varepsilon_{(fr_G)}}{\varepsilon_{max}} = \frac{\eta_{(fr_T)}}{\eta_{max}}\,[4]$$

An example, explained step by step, can help to understand the process:

1. Assuming a power group of three installed Francis turbines. In two different periods characterized by a different river flow rate, the operative turbine number is computed as follows [1]:
   a) In the first period the power group flow rate $fr_G$ assumes a value of 0,80 so all the three machines are operative ($OT = 3$), because the $TN-1$ operative limit matches the condition: $fr_G = \frac{TN-1}{TN} = \frac{2}{3} = 0,67$.

b) In the second period the power group flow rate $fr_G$ assumes a value of 0,50 so two machines are operative ($OT = 2$), because the $TN - 2$ operative limit matches the condition: $fr_G = \frac{TN-2}{TN} = \frac{1}{3} = 0,33$.

2. Then the water flow in each operative turbine is computed as: $TD = \frac{GD}{OT}$, remember that: $TD_{nom} = \frac{GD_{nom}}{TN}$, so: $fr_T = fr_G * \frac{TN}{OT}$ [2].

   a) In the first period the turbine flow rate assumes the same value of the power group flow rate, in fact: $fr_T = fr_G * \frac{3}{3} = fr_G = 0,80$.

   b) In the second period the turbine flow rate assumes the value of: $fr_T = fr_G * \frac{3}{2} = 0,75$.

3. Now is possible to compute the equivalent efficiency as the mean efficiency of parallel turbines: $\varepsilon_{(fr_G)} = \eta_{(fr_T)}$ [3].

   a) The first period returns an equivalent efficiency of: $\varepsilon_{(0,80)} = \eta_{(0,80)}$, that is the same result of using one turbine.

   b) The second period returns an equivalent efficiency of: $\varepsilon_{(0,50)} = \eta_{(0,75)}$, increasing the efficiency compared to a single turbine.

Then the equivalent efficiency ratio is immediatly computed [4]. The main effect is to obtain a more stable efficiency curve.

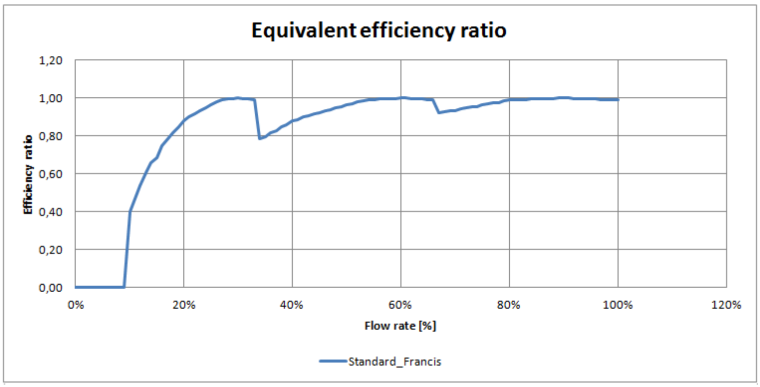


Figure 15.2.: Equivalent efficiency ratio (example)

## 15.2. Power group productivity

A lot of parameters change their value leaving the nominal operation conditions, for example the river flow ($HY_{(t)}$) could be higher than the nominal power group discharge ($GD_{nom}$), generating an extra head, or smaller, resulting a turbine efficiency and electrical power loss.

To ensure the fauna life, a percentage of the river flow, named 'Residual flow' ($RF$), must always overflow the weir, following the river natural course. Usually the $RF$ is given as a percentage of the river annual average flow and it's normally regulated by law. The model computes the residual flow as follows: $RF = (rf * MF)$, where $rf$ is the requested percentage, for which a standard value of 10% could be used, and $MF$ is the yearly mean flow of the stream. Obviously if the river flow during a dry period is'nt sufficient to cover at least the residual flow, the power gate is closed and all the water diverted to the natural course. Then the 'Available river flow' is defined as the river flow except residual flow: $AF_{(t)} = (HY_{(t)} - RF)$.

The 'Power group discharge' ($GD_{(t)}$) indicates the water flow passing through the turbine group and is computed as the minimum value between the available river flow ($AF_{(t)}$) and the 'Nominal power group discharge' ($GD_{nom}$), as a monthly mean value.

Also the 'Available head' ($AH_{(t)}$) is appreciably affected by the river flow, when the 'Overflowing water' ($OF_{(t)}$) assumes a great value: $OF_{(t)} = (HY_{(t)} - GD_{(t)})$.

The algorithm 15.2 computes a 'Power group electrical power' ($GP_{(t)}$) for each month. The formula [1] computes the available head $AH_{(t)}$, where $WL$ is the weir length, and the coefficient 1,6 is used for broad crested weirs. Then the power group flow rate ratio of the considered period ($fr_G$) is computed. At the end the formula [3] end the algorithm computing the monthly average power ($GP_{(t)}$).

**Algorithm 15.2** Power group electrical power

$$AH_{(t)} = NH + (\frac{OF_{(t)}}{(1,6 * WL)})^{2/3} \; [1]$$

$$fr_G = \frac{GD_{(t)}}{GD_{nom}} \; [2]$$

$$GP_{(t)} = GD_{(t)} * g * AH_{(t)} * \varepsilon_{(fr_G)} \; [3]$$

A small percentage of the produced power is dissipated on the transmission grid (Chapter 12). Remember that the grid voltage ($GV$) is 11 $kV$ , the single cable resistance ($R_{cable}$) is 2,733 $\Omega/km$, for the power factor ($pf$), as the ratio between real and apparent power [$kW/KVA$], a standard value of 0,9 has be taken (Ref. [POLIMI3]):

$$DP_{(t)} = L_{grid} * R_{cable} * (\frac{GP_{(t)}}{pf * GV})^2 * 10^{-3}$$

Resulting in the 'Net power': $NP_{(t)} = (GP_{(t)} - DP_{(t)})$. At the end the 'Monthly productivity' ($MP_{(t)}$) is computed in $MWh$, by the following formula where working hours $WH_{(t)}$ are the monthly hours except maintenance stop:

$$MP_{(t)} = NP_{(t)} * WH_{(t)} * 10^{-3}$$

The maintenance stop is the amount of hours necessary to hold the ordinary yearly maintenance, usually a value around 400 $h$. From the chart 15.3 is possible to see that the productivity mainly depends on the river flow rate during that period, but also by the period during which maintenance takes place. That's why it should be wise to conduct maintenance operations during the dry season, besides it's possible that the machines have already been stopped due to water shortage.

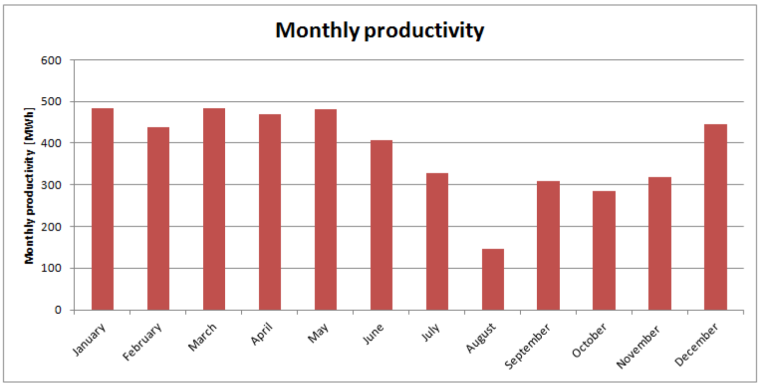


Figure 15.3.: Monthly productivity (example)

# 16. Hydropower plant costs

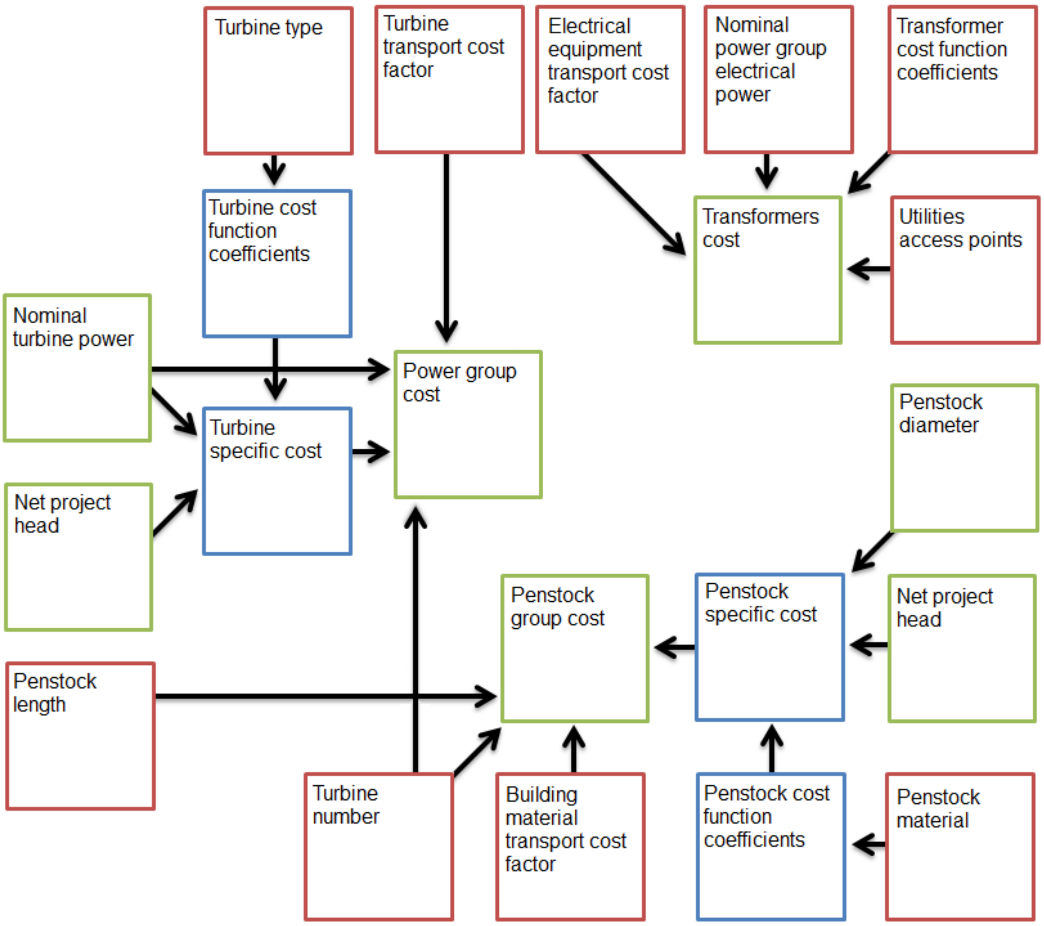


Figure 16.1.: 'Hydropower plant costs' flow chart I

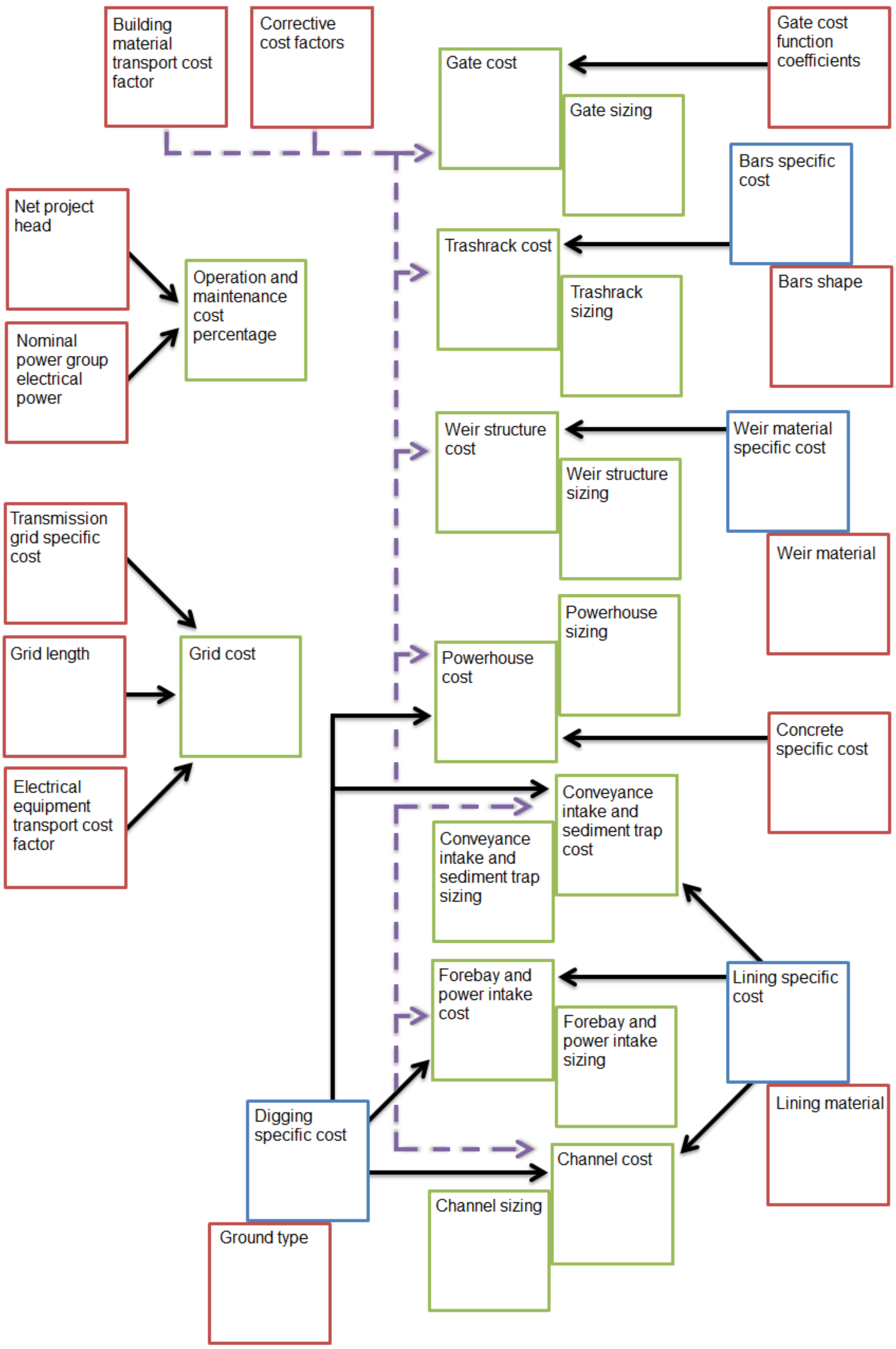


Figure 16.2.: 'Hydropower plant costs' flow chart II

## 16.1. Costs introduction

The cost determination has been the most diffucult issue during the developing of the software, due to the difficulty of obtain reliable data. The main idea was to relate the components cost to some design parameters through empirical functions, named 'Cost functions'. Besides the cost functions, that maybe have been obtained from databases from all over the world, must be adapted to Tanzania. As a future improvement, the cost databases of the software, on which the cost functions have been obtained, to improve the program reliability can be extended.

The main currency used in the model is the United State Dollars ($USD$), because the local currency, the Tanzanian Shilling ($TZS$), suffers severe temporal fluctuations and can't be used in expensive projects. So all the costs obtained in different currency like € or $TZS$, have been converted in $USD$.

At the end the resulting component costs have been tested on the Madunda hydropower plant in the Njombe district, Iringa region. The information has been obtained by the italian NGO 'ACRA', working on the project. However the Madunda power plant has a different configuration from the developed one, so only some components have been corrected comparing the different costs and adding a corrective cost factor ($cf$), for the other components the availability of reliable informations have prevailed (Source [ACRA]).

Moreover a transport cost factor ($tf$) could be multiplied, depending on the distance between the power plant and the purchasing zone of building materials. Some materials are assumed to be available in short distance, like stones and gravelly, so the transport cost is ignored. In addition if the components are imported from a different country, doganal taxes could be included in the model rising the transport coefficient.

## 16.2. Turbine cost function

Following the 'Cost functions' idea, a study from the Jaen University has been used to valuate the turbine group (Source [Jaen University]).

For the determination of the cost of the electro-mechanical equipment, there are graphs which can approximately calculate them. But these graphs refer to a distant time period, since they are at least 10 years old. Besides, manufacturers of turbines and alternators do not supply any information about cost, since every installation is different and complex.

From an analytical point of view and analyzing the state of art for the calculation of the cost of electro-mechanical equipment, it has been checked that a great part of authors use an expression depending on the 'Nominal turbine power' ($TP_{nom}$) and net head ($NH$) of the small plant. This expression or 'Cost function' is:

$$SC_{turbine} = c_1 * NH^{c_2} * TP_{nom}^{c_3}$$

Where $SC_{turbine}$ is the 'Turbine specific cost' in € / $kW$. The cost function coefficients $c_1$, $c_2$ and $c_3$ have been computed on a database of several spanish power plants, and have been also tested on a large database of european power plant (Ref. [Jaen University]). For the Francis turbine type, a table showing the results of the cost function application to the spanish powerplants (Fig. 16.3) and a drawing of the surface described by the function (Fig. 16.4) are reported.

| Name of the Plant | *P* (kW) | *H* (m) | Real cost (€/kW) | Simulated cost (€/kW) | Error (%) |
|---|---|---|---|---|---|
| Cristo de la Fe | 200 | 29 | 788.83 | 860.89 | −9.13 |
| Sp-F1 | 235 | 25 | 744.68 | 801.52 | −7.63 |
| Potril | 250 | 32 | 880.00 | 750.28 | 14.74 |
| Sp-F3 | 263 | 84 | 760.46 | 645.00 | 15.18 |
| Cubillas | 300 | 12 | 720.00 | 767.49 | −6.60 |
| Sp-F2 | 313 | 50 | 511.18 | 625.01 | −22.27 |
| Pinos Puente | 350 | 14 | 840.00 | 690.33 | 17.82 |
| Lojeña | 350 | 35.8 | 805.71 | 612.59 | 23.97 |
| Moclín | 400 | 70 | 473.30 | 521.95 | −10.28 |
| San Clemente | 450 | 36 | 471.19 | 531.77 | −12.86 |
| Nuevo Alcázar | 500 | 85 | 424.07 | 449.39 | −5.97 |
| Moclín | 550 | 70 | 377.00 | 436.68 | −15.83 |
| El Portillo 2 | 750 | 55.5 | 353.40 | 378.04 | −6.97 |
| Rumblar | 1000 | 47 | 315.53 | 328.66 | −4.16 |
| El Portillo 1 | 1000 | 55.5 | 302.91 | 321.78 | −6.23 |
| Río Frío | 1000 | 155 | 317.00 | 282.36 | 10.93 |
| Valdepeñas | 1500 | 116 | 260.00 | 233.45 | 10.21 |

Figure 16.3.: Turbine cost function test

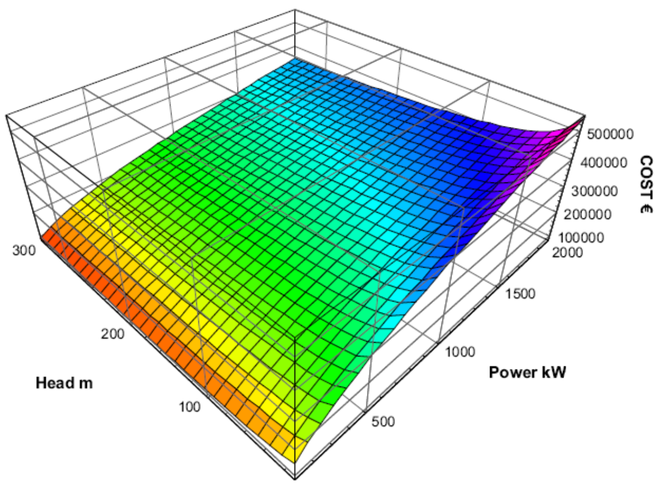


Figure 16.4.: Turbine cost function drawing

The power-function form for the cost function presents some advantages compared to different function forms:

- It's not strong dependent by the database on which it has been developed.

In fact this function type permits to simulate in a range higher or lower than the database range, obtaining reliable results.

- Once the coefficients $c_2$ and $c_3$have been fixed through the first database, the first coefficient $c_1$ could be changed to adapt the function to a new database in a different country or in a different time, with very reliable results. As example the spanish cost function has been adapted changing $c_1$ to fit a database collected in Canada in the 1986, obtaining a mean error of 8,24% and a maximum error of 24,95% (Fig. 16.5).

- Is possible to see in an intuitive way the connection between the design parameter(s), and the component cost.

That's why the power-function form has been taken as a model for all the plant components whose cost is computed through a cost function.

The first coefficient $c_1$ doesn't change adapting the cost for Tanzania, because missing local producers, it's assumed to import the turbine group from Europe.

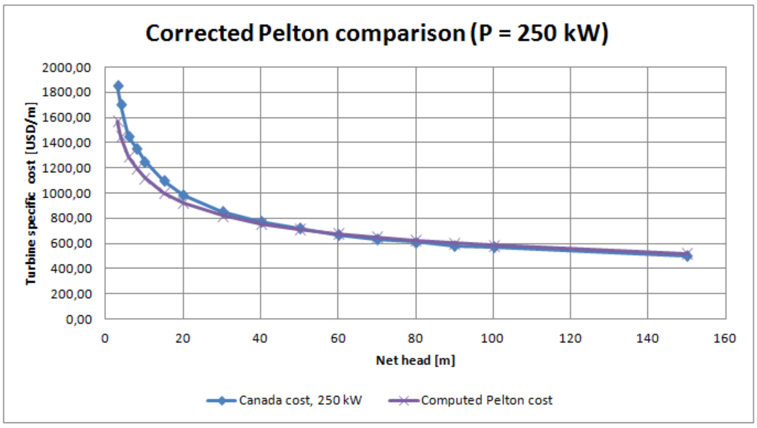


Figure 16.5.: Turbine cost function comparison

The following table summarizes the cost coefficients for the different turbine types:

| Cost coefficients | Kaplan [€/$kW$] | Francis [€/$kW$] | Pelton [€/$kW$] |
|---|---|---|---|
| $c_1$ | 33236 | 25698 | 17693 |
| $c_2$ | -0,113901 | -0,127243 | -0,281735 |
| $c_3$ | -0,58338 | -0,560135 | -0,3644725 |

Table 16.1.: Turbine cost coefficients

## 16.3. Transformer cost function

Taking the turbine cost function as a model, even to estimate the transformer cost a power-function has been used. The project parameters that normally affects the transformer cost are: apparent power $[KVA]$ and voltage ratio between high and low voltage $[kV/kV]$, but the choice of a standard for the grid and loads voltage (11 $kV$ and 0,4 $kW$) unbinds the cost function from the voltage ratio.

The apparent power is computed from the 'Nominal power group electrical power' ($GP_{nom}$ $[kW]$) and the grid power factor ($pf$ $[kW/KVA]$). The transformer 'Cost function' for the step up transformer is:

$$CC_{transformer} = c_1 * (\frac{GP_{nom}}{pf})^{c_2}$$

While for the step down transformer(s), that share the total power, the function is slightly modify:

$$CC_{transformer} = c_1 * (\frac{GP_{nom}}{UA * pf})^{c_2}$$

Where $CC_{transformer}$ is the transformer component cost $[USD]$ and $UA$ the utilities acces points.

The cost function has been sized on a database of resin-isolated transformers from an italian producer (Source [POLIMI3]). The voltage ratio of all the transformers is set equal to 24 while the assumed ratio is 27,5, but this is the best matching between italian an tanzanian standards. The cost coefficients assumes the values of 370 for $c_1$ and 0,48 for $c_2$.

The cost fitting on the database returns a mean error of 10,64% and a maximum error of 24,86% (Fig. 16.6).

To adapt the cost function for Tanzania, the first coefficient $c_1$, according to price informations from local producers, has been changed to the value of 2034 (Source [DIT2]). The cost increasing is probably due to the local manufacturing of the transformer and the poor availability of the raw materials.

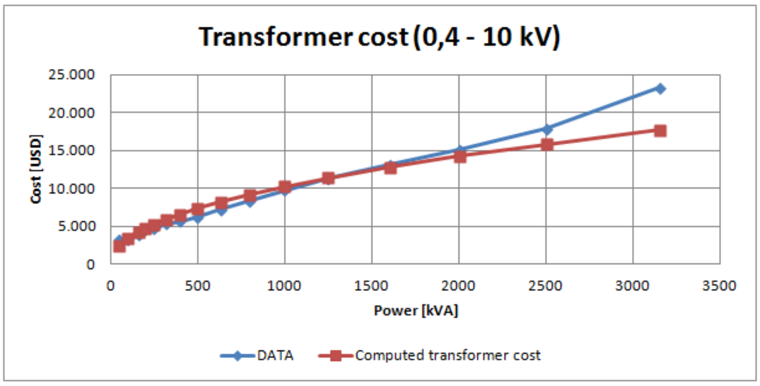


Figure 16.6.: Transformer cost function comparison

## 16.4. Penstock cost function

Two different penstock types are available for this model: polyethilene and welded steel. Analyzing a database of penstock costs it was noticed that each type has its own cost function, in fact the 'Steel pipe specific cost' ($SC_{s.p.}$) is affected only by the penstock inlet diameter ($D_P$), as for the 'Power valve' cost ($CC_{valve}$), while the 'Polyethilene pipe specific cost' ($SC_{p.p.}$) is function of the penstock inlet diameter and the power plant net head ($NH$). The database is from a dated canadian document (Ref. [Sigma eng.]), so the functions have been resized on italian mini hydropower plants, information obtained from the Lombardia region (Source [Lombardia]).

The 'Cost function' for the steel pipe, where $SC_{s.p.}$is the specific cost in $USD/m$, is:

$$SC_{s.p.} = c_1 * D_P^{c_2}$$

Similarly for the power valve, where $CC_{valve}$ is the component cost in $USD$:

$$CC_{valve} = c_1 * D_P^{c_2}$$

While the cost function for the polyethilene pipe, where $SC_{p.p.}$is the penstock specific cost in $USD/m$, has the form:

$$SC_{p.p.} = c_1 * D_P^{c_2} * NH^{c_3}$$

The figure 16.7 shows the canadian database used to size the cost functions coefficients:

- In the first table the specific costs are collected as $USD/m$ for penstocks and $USD$ for valve. Black fonts refers to the polyethilene data, red fonts to the steel pipe data, while the last row in green fonts collects the power valve data.
- The second table contains the specific costs, obtained through the proper cost function for each component.
- The third and last table is filled by the relative error between the first and second tables data: $E_{ij} = \frac{SC_{data,ij} - SC_{computed,ij}}{SC_{data,ij}}$

| Cost [USD/m] | diameter [m] | | | | | |
|---|---|---|---|---|---|---|
| gross head [m] | 0,2 | 0,315 | 0,5 | 0,8 | 1 | 1,2 |
| 31,6 | 25 | 64 | 155 | 405 | 625 | 910 |
| 42,2 | 35 | 80 | 205 | 530 | 1.030 | 1.235 |
| 56,2 | 43 | 106 | 265 | 683 | 1.030 | 1.235 |
| 70,3 | 52 | 128 | 324 | 830 | 1.030 | 1.235 |
| 87,8 | 62 | 154 | 518 | 830 | 1.030 | 1.235 |
| 112,5 | 78 | 190 | 518 | 830 | 1.030 | 1.235 |
| 140,6 | 92 | 220 | 518 | 830 | 1.030 | 1.235 |
| 150 | 170 | 330 | 518 | 830 | 1.030 | 1.235 |
| Cost [USD] | 240 | 410 | 2.630 | 7.740 | 10.400 | 17.700 |

| Cost [USD/m] | diameter [m] | | | | | |
|---|---|---|---|---|---|---|
| gross head [m] | 0,2 | 0,315 | 0,5 | 0,8 | 1 | 1,2 |
| 31,6 | 24 | 61 | 155 | 403 | 635 | 920 |
| 42,2 | 31 | 79 | 203 | 528 | 1.050 | 1.283 |
| 56,2 | 41 | 103 | 265 | 689 | 1.050 | 1.283 |
| 70,3 | 51 | 127 | 326 | 821 | 1.050 | 1.283 |
| 87,8 | 62 | 157 | 490 | 821 | 1.050 | 1.283 |
| 112,5 | 78 | 197 | 490 | 821 | 1.050 | 1.283 |
| 140,6 | 96 | 243 | 490 | 821 | 1.050 | 1.283 |
| 150 | 179 | 295 | 490 | 821 | 1.050 | 1.283 |
| Cost [USD] | 168 | 546 | 1.814 | 6.158 | 11.000 | 17.671 |

| Error % | diameter [m] | | | | | |
|---|---|---|---|---|---|---|
| gross head [m] | 0,2 | 0,315 | 0,5 | 0,8 | 1 | 1,2 |
| 31,6 | 3,97% | 5,46% | 0,04% | 0,44% | 1,59% | 1,12% |
| 42,2 | 10,21% | 0,99% | 1,06% | 0,41% | 1,94% | 3,90% |
| 56,2 | 4,57% | 2,43% | 0,07% | 0,90% | 1,94% | 3,90% |
| 70,3 | 2,80% | 0,48% | 0,67% | 1,03% | 1,94% | 3,90% |
| 87,8 | 0,26% | 1,74% | 5,44% | 1,03% | 1,94% | 3,90% |
| 112,5 | 0,38% | 3,87% | 5,44% | 1,03% | 1,94% | 3,90% |
| 140,6 | 4,74% | 10,40% | 5,44% | 1,03% | 1,94% | 3,90% |
| 150 | 5,17% | 10,71% | 5,44% | 1,03% | 1,94% | 3,90% |
| Error % | 30,20% | 33,11% | 31,01% | 20,44% | 5,77% | 0,16% |

Figure 16.7.: Penstocks canadian database

The cost fitting on the steel pipe database returns a mean error of 3,35% and a maximum error of 10,71%, while the cost fitting on the power valve returns worse results, with a mean error of 20,12% and a maximum error of 33,11%, but its cost have a low effect on the total cost (Fig. 16.9).

The cost fitting on the polyethilene pipe database returns a mean error of 2,55% and a maximum error of 10,40%. Depending by two parameters, the mathematical expression of the polyethilene cost function is a surface (Fig. 16.8). Anyhow the figure 16.8 shows the comparison between real and computed costs for the first row ($NH = 31,6$) and the first column ($D_P = 0,2$) of the database tables 16.7, because the database miss the complete informations.

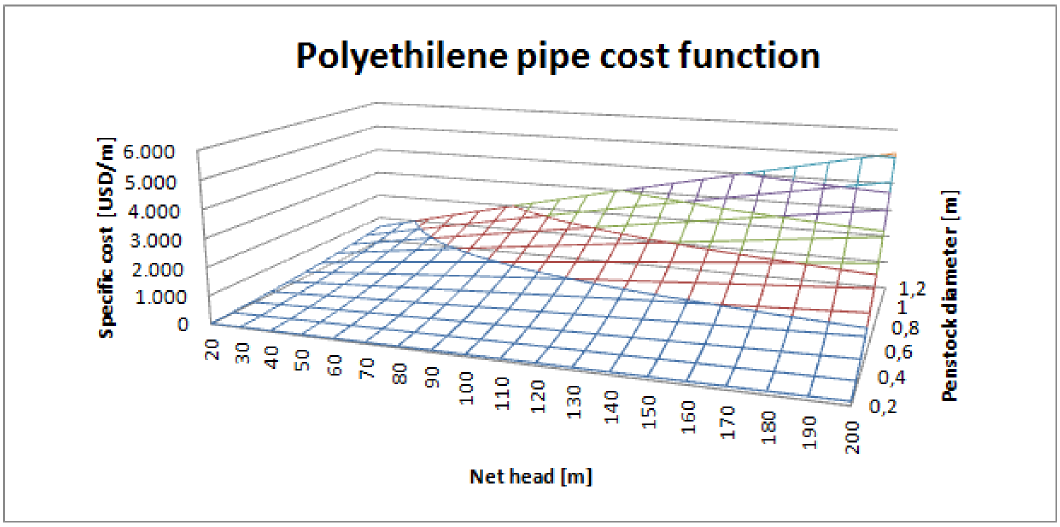


Figure 16.8.: Polyethilene pipe cost function

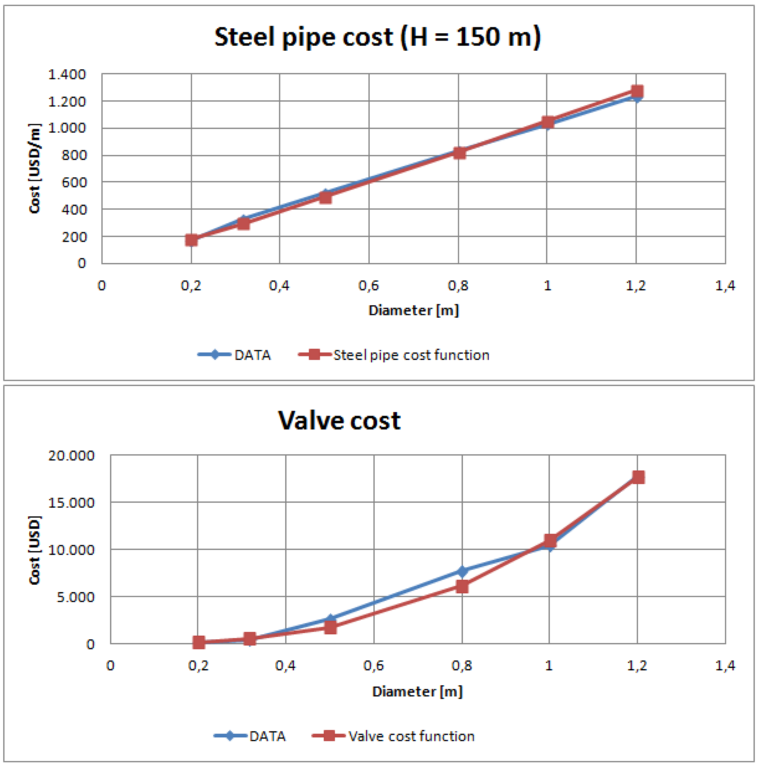


Figure 16.9.: Steel pipe and power valve cost function comparison

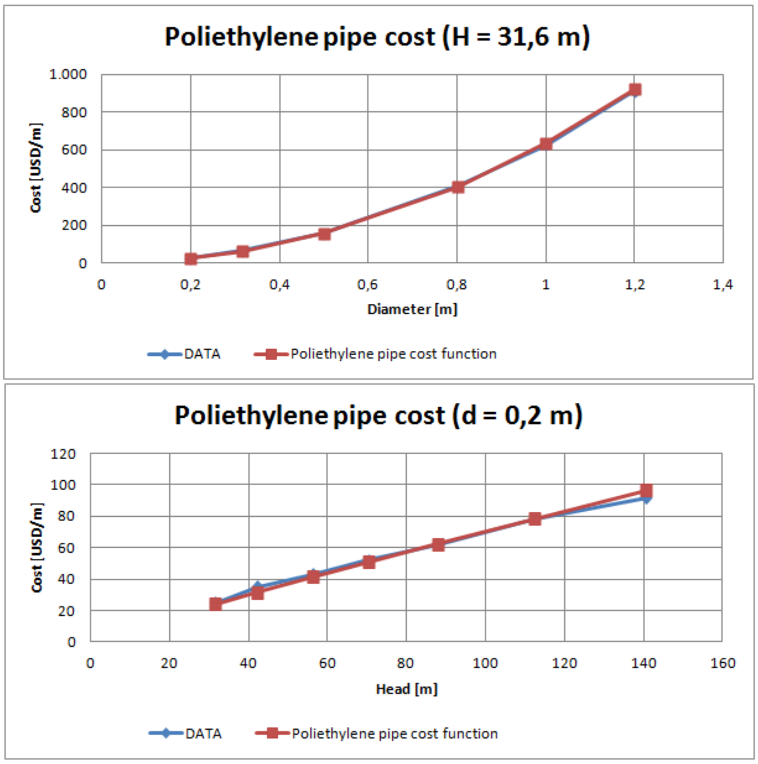


Figure 16.10.: Polyethilene pipe cost function comparison

The following table summarizes the cost coefficients obtained for the different component, after the adapting on the italian power plants:

| Cost coefficients | Steel pipe $[USD/m]$ | Polyethilene pipe $[USD/m]$ | Power valve $[USD]$ |
|---|---|---|---|
| $c_1$ | 550 | 55 | 22000 |
| $c_2$ | 1,1 | 2,035 | 2,6 |
| $c_3$ | - | 0,931 | - |

Table 16.2.: Turbine cost coefficients

## 16.5. Maintenance cost function

Maintenance cost function comes from a valuation of the 'Politecnico di Milano' university, carried on italian mini hydropower plants (Source [POLIMI1]). The POLIMI collected a database of power plants divided into 'Low head', for which a value of 10 $m$ has been assumed, and 'High head', corresponding to a value of 100 $m$.

The main idea was to cumpute the 'Operation and maintenance yearly cost' $(MC)$ as a percentage of the 'Investment cost' $(IC)$, assumed to be constant for each year of the power plant service life. According to the database, the operation and maintenance cost percentage ($mc$) is a function of power plant electrical power ($GP_{nom}$) and net head ($NH$), according to the function:

$$mc = c_1 * NH^{c_2} * GP_{nom}^{c_3}$$

Then, fitting the function on the database, the coefficients have been found and the function turns into:

$$mc = 0,4 * NH^{0,01401} * GP_{nom}^{-0,342}$$

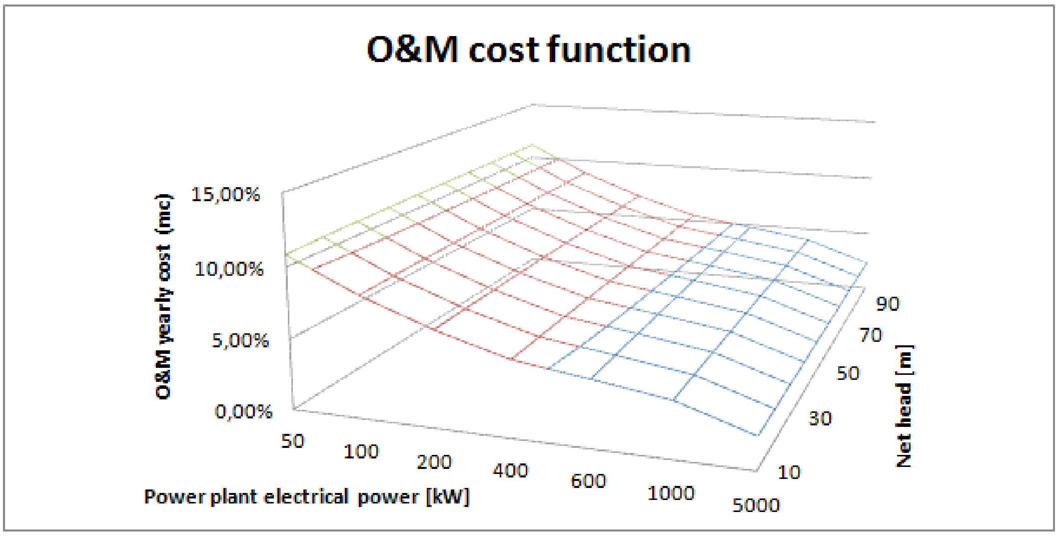


Figure 16.11.: Maintenance cost function

The comparison gives a mean error of 11,31% and a maximum error of 19,25%, as shown in the figure below:

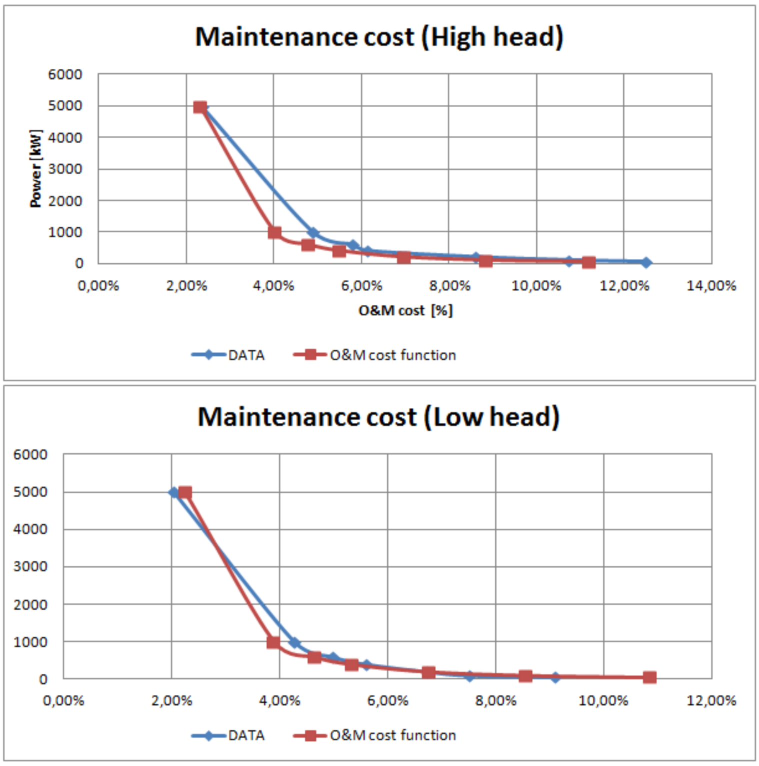


Figure 16.12.: Maintenance comparison

At the end operation and maintenance yearly cost ($MC$) is computed as follow:

$$MC = IC * mc$$

## 16.6. Gate cost function

The power gate, that is a sub-component of the 'Conveyance intake structure' uses a simple cost function to define its cost. The specific cost of the metal sheet ($SC_{gate}$) in $USD/m^2$ is computed as a function of the gate thickness ($t_G$) through the following equation:

$$SC_{gate} = c_1 * t_G^{c_2}$$

The cost coefficient values are: 14400 for $c_1$ and 1,06 for $c_2$, making it very similar to a linear function. Database informations have been taken in Tanzania.

## 16.7. Grid cost

Remember that for the transmission grid a wood-pole line with three-fase 100 $mm^2$ ACSR cables have been considered. The specific cost of the grid $SC_{grid}$ $[USD/km]$

is then obtained by tanzanian suppliers, including materials and manpower. The obtained value is 16594 $USD/km$. The grid length ($L_{grid}$) is the summation of all the transmission grid branches, assumed to be realized with the same standard (Source [DIT2]).

## 16.8. Hydraulic works cost

The remaining hydraulic works components share the feature to be designed using simple building materials or operations. Then the main idea was to size the components computing the necessary concrete, rocks, excavation volumes and finally obtain the component price as the product between the materials quantity and the relative specific cost. The table 16.3 summarizes the building materials and operations that have been used in the model developing. The 'Specific cost' ($SC$) includes the manufacture and installation of the material, all informations have been supplied by local experts in Tanzania (Ref. [DIT1]).

| Buiding material | Specific cost | Unit of measure | Add transport coefficient |
|---|---|---|---|
| Hard ground digging | 11,8 | $USD/m^3$ | NO |
| Medium ground digging | 9,5 | $USD/m^3$ | NO |
| Soft ground digging | 7,1 | $USD/m^3$ | NO |
| Armed concrete for weir | 235,3 | $USD/m^3$ | YES |
| Rocks for weir | 58,9 | $USD/m^3$ | NO |
| Armed concrete for pillars | 235,3 | $USD/m^3$ | YES |
| Circular bars for trashrack | 1,5 | $USD/m$ | YES |
| Drop shape bars for trashrack | 2,5 | $USD/m$ | YES |
| Rocks for channel lining | 20,62 | $USD/m^2$ | NO |
| Concrete for channel lining | 44,13 | $USD/m^2$ | YES |
| Armed concrete for powerhouse | 235,3 | $USD/m^3$ | YES |

Table 16.3.: Building materials specific costs

Quite roughly results using this method were obtained, so a corrective cost factor ($cf$) has been added to each component cost to make it match with the real cost from the Madunda power plant.

# 17. Utilities

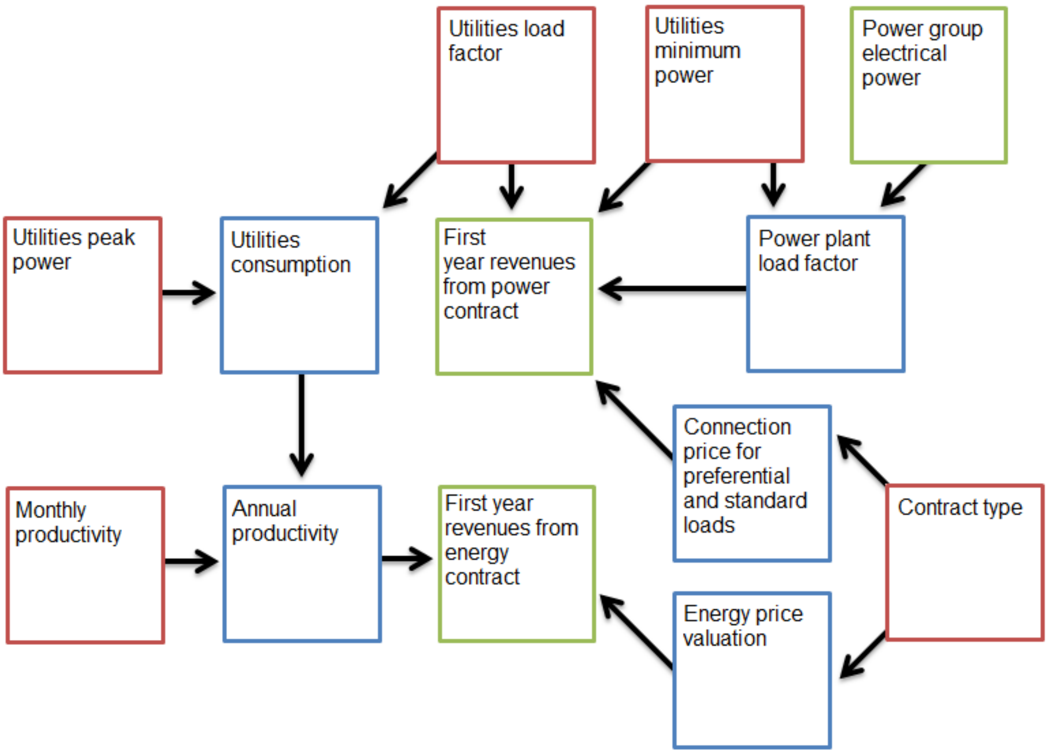


Figure 17.1.: 'Utilities' flow chart

The minihydro power plant is designed to meet the rural utilities needs and improve rural electrification. So the utilities play a main rule in the power plant project and is necessary to quantify them inside the model.

The first step is to estimate the connected utilities, finding the near villages on the map, measuring their distance from the powerhouse and estimating their energy purchasing capacity. However determining the connected loads is the most difficult issue of the whole simulation, because widely different scenarios could be considered.

For example the first scenario includes in the local grid connection (3 $km$) only the nearest village with its mill and water pump, the second includes another bigger village at 10 $km$ away, the third would expect a connection to the national power grid with the nearest connection point at 20 $km$ away. Each scenario has obviously different loads, but also different grid length, acces points and maybe different contract types. Then, once technical parameters like: river flow, turbine type, channel length, penstock length, etc. have been set, each scenario could be simulated changing only the loads-connected parameters and, comparing the solutions, the better will be chose.

The utilities features have been summarized in three quantitative parameters:

- 'Utilities load factor' ($LF_{utilities}$) is simply the ratio between equivalent hours and total year hours, as an index of utilities power usage; intending the utilities equivalent hours as the ratio between annual energy consumption $[kWh]$ and installed electrical loads $[kW]$.
- 'Utilities minimum power' ($UMP$) is the power amount of all the preferential loads; for example a factory, a water pump, or an hospital are preferential loads. It means that all over the year, except for scheduled maintenance or unpredictable events, the mini hydro plant is able to grant them the requested power.
- 'Utilities peak power' ($UPP$) is the power amount of preferential and standard loads; for example households, schools, offices are standard loads. The standard loads are connected to the power grid and receive the power supply in nominal operation condition, but during the dry season they might be disconnected.

## 17.1. Off grid

An isolated power grid presents different constraints.

### 17.1.1. Annual productivity

First: the utilities set a limit on the energy sales. In fact the loads use a maximum amount of energy and the excess energy is dissipated, because the run-of-river configuration has no storing capacity. Translating that idea in a formula:

$$UC_{(t)} = WH_{(t)} * LF_{utilities} * UPP * 10^{-3}$$

Where $UC_{(t)}$ is the 'Monthly utilities consumption' $[MWh]$ and $WH_{(t)}$ are the 'Working hours' (Section 15.2). Then the 'Monthly sold energy' ($SE_{(t)}$) is computed as the minimum value between utilities consumption ($UC_{(t)}$) and 'Monthly productivity' ($MP_{(t)}$) for each month.

'Annual productivity' ($AP$) as amount of the monthly sold energy is finally obtained:

$$AP = \sum_{t=1}^{12} SE_{(t)}$$

'Equivalent hours' ($Eh$) are the resulting of the ratio between annual productivity ($AP$) and installed electrical power ($GP_{nom}$), as an index of plant good sizing and machine(s) utilization. In the following figures the 'Monthly sold energy' as function of time (Fig. 17.2) and the 'Annual productivity' as function of 'Power group electrical power' (Fig. 17.3) are plotted. In the first chart is possible to see as the utilities purchasing limit cuts the productivity bar on the same value (small fluctuations due to the different days number in the different months), while during the maintenance month the energy value falls down. In the first chart is possible to notice as the $AP$ value grows until it reaches the maximum river potential, then it starts to decrease due to the power group efficiency loss ($\varepsilon_{(fr_G)}$), operating with a low flow rate ratio ($fr_G$). It could happen that, while the $AP$ value is growing with the electrical power, it suddenly stops on a costant value when utilities purchasing limit is reached.

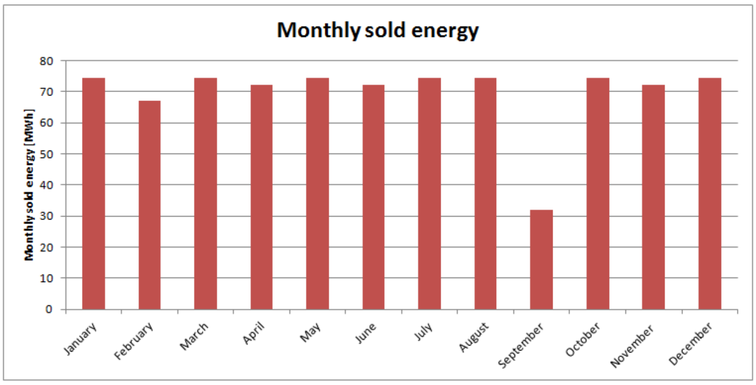


Figure 17.2.: Monthly sold energy (example)

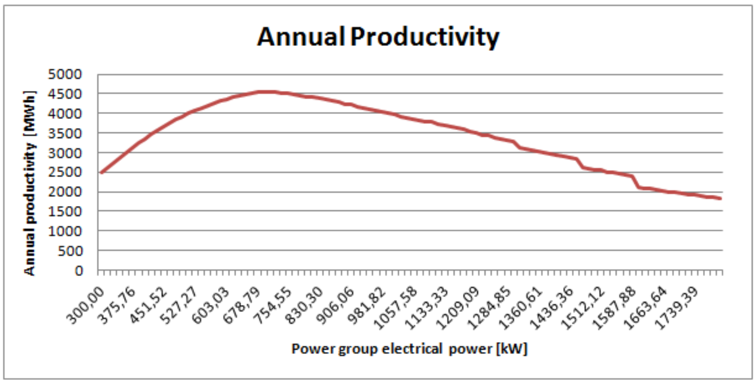


Figure 17.3.: Annual productivity trend (example)

### 17.1.2. Power plant load factor

Second: if the hydropower plant fails in providing the energy supply to the preferential loads, there are no other energy sources that could overcome the problem. To quantify this limitation a 'Power plant load factor' ($LF_{plant}$) has been introduced as an index of plant good sizing and service continuity. 'Operative hours' ($Oh$) are the sum of the hours during which the river flow is able to cover the utilities minimum power ($UMP$), or preferential loads, during the year; maintenance stop is'nt considered in the operative hours computation. Then $LF_{plant}$ is simply the ratio between operative hours and total year hours:

$$LF_{plant} = \frac{Oh}{8760}$$

The power plant load factor is plotted below as function of the 'Nominal power group electrical power' ($GP_{nom}$). It can be noticed that the $LF_{plant}$value is set on the optimum value of 1 in a large power range, but it starts to decrease together with the power group efficiency ($\varepsilon_{(fr_G)}$), when the turbine(s) starts to be oversized compared to the stream water flow.

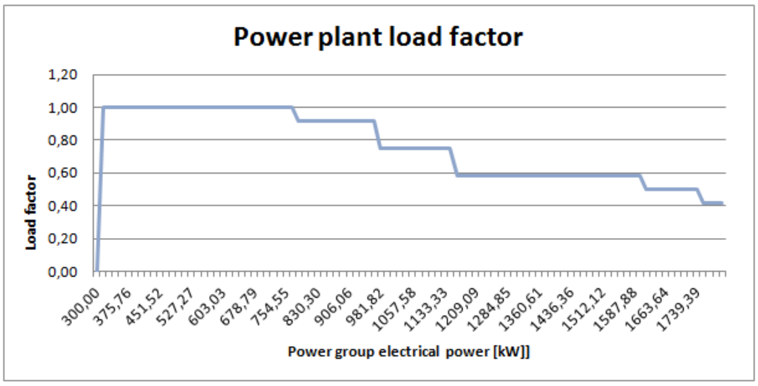


Figure 17.4.: Power plant load factor trend (example)

## 17.2. On grid

The power grid connection solves the previous problems, so the minihydro plant takes advantage of the whole river potential and sells all the generated electricity to the national grid, without the loads bond. This situation has been simulated in the model removing the utilities purchasing limit and fixing the $LF_{plant}$ value to 1.

## 17.3. Revenues

### 17.3.1. Energy contract

An energy contract is the most common way to compute the 'First year revenues' ($RE$) [$USD$], starting from an energy price that can be a local or a national price.

The 'Energy price valuation' ($EP$) is a valuation of the utilities willingness to pay, expressed as a specific energy cost in $USD/kWh$, if the power plant is disconnected from the national grid. Otherwise the current national energy price [$USD/kWh$] can be applied to the loads; notice that the off-grid and the on-grid prices could probably be different.

Then the first year revenues are computed through the formula:

$$RE = AP * EP * 10^3$$

The problem of the energy contract type is that it needs an energy counter for each user, with an informatic or human tariff control system. The energy counters cost is not considered in this model, and it will fall on the utilities. Furthermore sometimes is very hard to maintain an efficient control system, especially in rural areas.

### 17.3.2. Power contract

To overcome the previous problems, sometimes a different contract is proposed to the utilities (Source [ACRA]). The power contract idea is to impose a yearly tariff that allow the connection to the power grid with a power limiter. So the electrical power needs to be gauged only at the powerhouse to compute the power plant load factor ($LF_{plant}$).

Therefore two different tariffs are applied:

- 'Connection price for preferential loads' ($PCP$) in $USD/kW$ is the yearly tariff demanded to the premium utilities for one $kW$ service connection. The summation of premium utilities power results in the utilities minimum power ($UMP$).
- 'Connection price for standard loads' ($SCP$) in $USD/kW$ is the yearly tariff demanded to the standard utilities for one $kW$ service connection. The difference between premium and standard loads is that: premium are used to compute the power plant load factor ($LF_{plant}$), so their power continuity is guaranteed during the year, while standard loads can suffer power interruptions.

Applying the power contract, first year revenues are computed as follow:

$$RE = (PCP * UMP + SCP * \frac{(GP_{nom} - UMP)}{LF_{utilities}}) * LF_{plant}$$

All the preferential loads are connected to the power grid, while the standard connections fill the power gap between the 'Power group electrical power' ($GP_{nom}$) and the 'Preferential loads total power' or 'Utilities minimum power' ($UMP$), that is the same. It's evident that the 'Power plant load factor' should be equal to one, to maximize the revenues.

# 18. Economic analysis

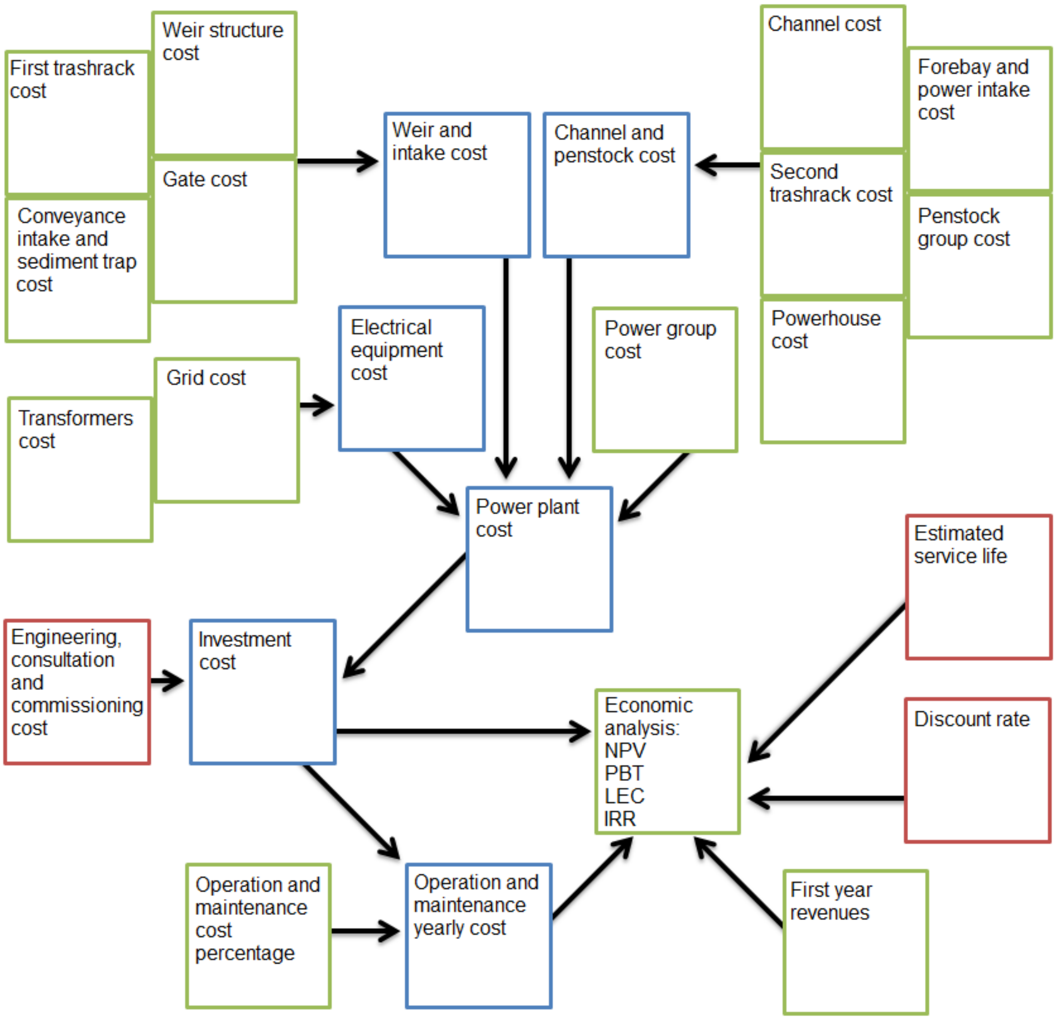


Figure 18.1.: 'Economic analysis' flow chart

## 18.1. Investment cost

The 'Power plant cost' ($PC$) is the summation of the components cost. The table 18.1 summarizes parts, components and sub-components of the hydropower plant, with the related cost computation method.

| Components and sub-components | Cost computation method | Final cost |
|---|---|---|
| *Power group* | Turbine cost function | $TP_{nom} * SC_{turbine(TP_{nom},NH)} * TN$ |
| *Electrical equipment* | | |
| Step up transformer | Transformer cost function | $CC_{transformer(GP_{nom})}$ |
| Step down transformer(s) | Transformer cost function | $CC_{transformer(GP_{nom}/UA)} * UA$ |
| Transmission grid | Specific cost data | $SC_{grid} * L_{grid}$ |
| *Weir and intake* | | |
| Weir | Material cubic meters | $V_{weir} * SC_{material}$ |
| Protection walls | Material cubic meters | $2 * V_{wall} * SC_{material}$ |
| Intake channel | Digging cubic meters | $V_{intake\,channel} * SC_{digging}$ |
| Intake channel lining | Lining material surface | $S_{intake\,channel} * SC_{lining}$ |
| Power gate | Gate cost function | $S_{gate} * SC_{gate(t_G)}$ |
| First trashrack | Total length of bars | $L_{bars} * SC_{bars}$ |
| Intake pillars | Concrete cubic meters | $V_{pillars} * SC_{concrete}$ |
| Trap volume | Digging cubic meters | $V_{trap} * SC_{digging}$ |
| Trap lining | Lining material surface | $S_{trap} * SC_{lining}$ |
| *Channel and penstock* | | |
| Channel volume | Digging cubic meters | $V_{channel} * SC_{digging}$ |
| Channel lining | Lining material surface | $S_{channel} * SC_{lining}$ |
| Forebay volume | Digging cubic meters | $V_{forebay} * SC_{digging}$ |
| Forebay lining | Lining material surface | $S_{forebay} * SC_{lining}$ |
| Pyramidal intake volume | Digging cubic meters | $V_{power\,intake} * SC_{digging}$ |
| Pyramidal intake lining | Lining material surface | $S_{power\,intake} * SC_{lining}$ |
| Second trashrack | Total length of bars | $L_{bars} * SC_{bars}$ |
| Pipe(s) | Pipe cost function | $TN * L_{penstock} * SC_{pipe(D_P,NH)}$ |
| Power valve(s) | Valve cost function | $TN * SC_{valve(D_P)}$ |
| Powerhouse foundation volume | Digging cubic meters | $V_{foundation} * SC_{digging}$ |
| Powerhouse total volume | Concrete cubic meters | $V_{building} * SC_{concrete}$ |

Table 18.1.: Components cost

To provide an idea of the components costs distribution, two pie charts are plotted below (Fig. 18.2). The first 'Electro-mechanical cost distribution' includes the parts 'Power group' and 'Electrical equipment', the second chart 'Hydraulic works cost distribution' includes the parts 'Weir and intake' and 'Channel and penstock'.

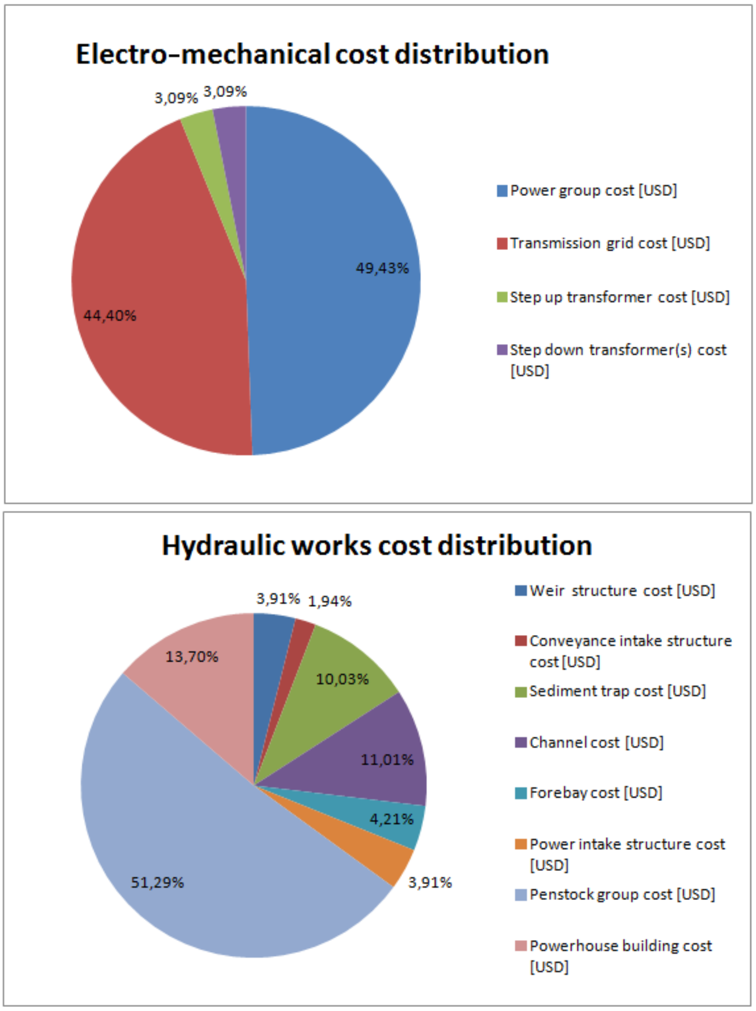


Figure 18.2.: Hydropower plant cost distribution (examples)

The 'Engineering, consultation and commissioning cost' ($ecc$) has been computed as a percentage of the 'Power plant cost' ($PC$), with a value around 10%. Finally adding this cost to the $PC$, the 'Investment cost' ($IC$) is obtained:

$$IC = (1 + ecc) * PC$$

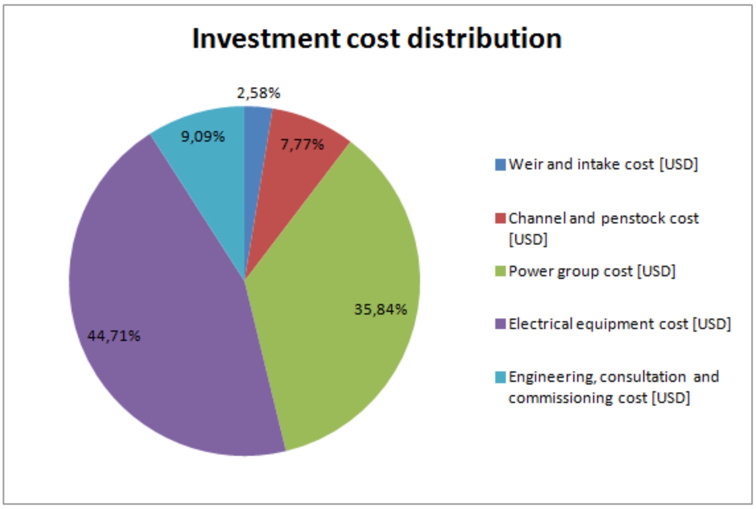


Figure 18.3.: Investment cost distribution (example)

## 18.2. Economic parameters

There are two main economic parameters that must be chosen before undertake an economic analysis:

- 'Estimated service life' ($SL$) indicates the period during which the power plant is able to run and generate electricity without extraordinary intervents on machinery or hydraulic works. For mini hydro projects a value from 25 to 35 years should be considered.

- 'Discount rate' ($r$) reflects the time value of money, according to the theory of time preference, and a risk premium representing the extra return investors demand to be compensated for the risk that the cash flow might not materialize. The economical results are quite sensitive to the discount rate, and failure to select the appropriate rate may alter or even reverse the efficiency ranking of projects. Since changing the discount rate can change the outcome of the evaluation, it should be considered carefully. For a private developer, the discount rate will be such that will allow him to choose between investing on a small hydro project or keep his saving in the bank. This discount rate, depending on the inflation rate, usually varies between 5% and 12%.

## 18.3. Specific plant cost

'Specific plant cost' ($SC_{power\,plant}$) is the price of the single installed kiloWatt [$USD/kW$]. Specific cost is affected by the whole hydropower plant design, the lower the specific cost, the better the power plant; but it doesn't consider utilities and performance during the service life. Besides it could be used as a comparison parameter between different hydropower plants, if the investment cost ($IC$) is the main concern. $SC_{power\,plant}$ is computed according to the formula:

$$SC_{power\,plant} = \frac{IC}{GP_{nom}}$$

## 18.4. Net Present Value

The 'Investment cost' ($IC$) is divided by the model into two years:

- Year 0 carries the hydraulic works cost ('Weir and intake', 'Channel and penstock').
- Year 1 carries electromechanical and administrative costs ('Power group', 'Electrical equipment', 'Engineering, consultation and commissioning').

'Net present value' ($NPV$) is a method of ranking investment proposals. The net present value is equal to the present value of future returns, discounted at the marginal cost of capital, minus the present value of the cost of the investment. The present formula has been used to compute the $NPV$:

$$NPV = \sum_{i=0}^{SL} \left(\frac{RE_i - I_i - MC_i}{(1+r)^i}\right)$$

Where 0 and 1 are building years, carrying the 'Yearly investment cost' ($I_i$), while years 2 and following are operative years, carriyng operation and maintenance costs ($MC_i$) and collecting revenues ($RE_i$), assumed to be constant all over the power plant service life ($SL$).

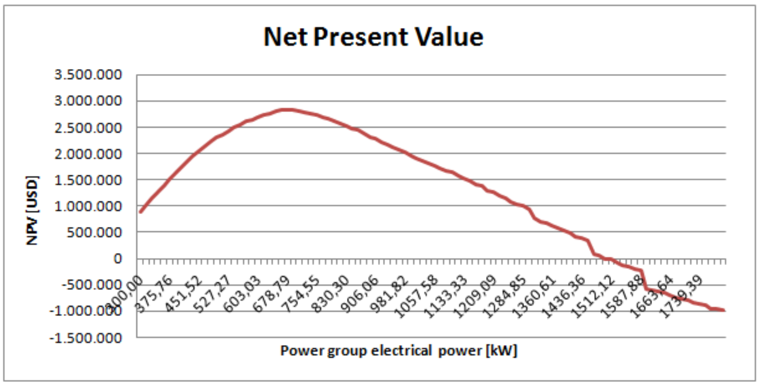


Figure 18.4.: Net present value trend (example)

## 18.5. Pay Back Time

The payback method determines the number of years required for the invested capital to be offset by resulting benefits ($PBT$). The required number of years is termed the payback, recovery, or break-even period. The calculation is as follows:

$$PBT = \frac{IC}{RE}$$

## 18.6. Levelized Energy Cost

'Levelised energy cost' ($LEC$) is the price at which electricity must be generated and sold to reach the break-even. It is an economic assessment of the cost of the energy generating system including all the costs over its lifetime and is very useful in comparing the costs of generation from different sources.

$$LEC = \frac{\sum_{i=0}^{SL}(\frac{I_i+MC_i}{(1+r)^i})}{\sum_{i=0}^{SL}(\frac{AP_i}{(1+r)^i})}$$

Where annual productivity ($AP$) is assumed to be constant all over the power plant service life.

## 18.7. Internal Rate of Return

The 'Internal rate of return' ($IRR$) method of analysing a major project allows consideration of the time value of money. Essentially, it determines the interest rate that is equivalent to the monetary returns expected from the project. Once the rate is known, it can be compared to the rates that could be earned by investing the money in other projects or investments. $IRR$ is computed through an iterative method, to reach the relation:

$$0 = \sum_{i=0}^{SL}(\frac{RE_i - I_i - MC_i}{(1+IRR)^i})$$

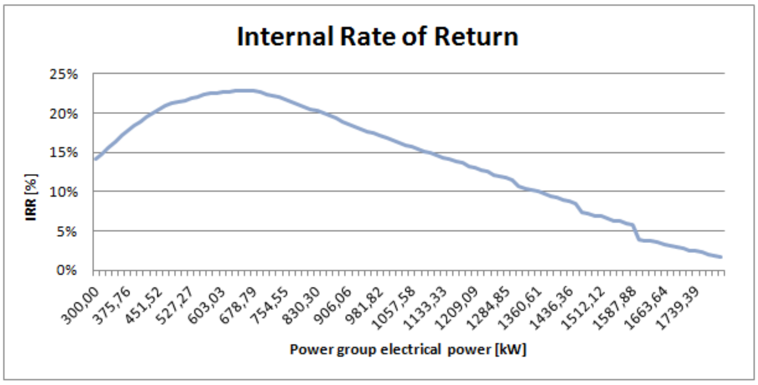


Figure 18.5.: Internal rate of return trend (example)

# 19. Software development

## 19.1. File logical structure

The *'Mini hydro plants simulator'* is a model, implemented in *Microsoft excel 2007* ®, that, starting from a simple pre-feseability study on a potential site, optimizes the size of the power plant and computes the profitability of the investment.

The software *'Mini hydro plants simulator'* has been developed to simplify the insertion of data, to enable future improvement, to make it user-friendly as much as possible. The following sections present the logical structure that has been used in the software pursuing this objective.

### 19.1.1. Writing conventions

Some writing conventions have been also used to simplify the file reading and filling:

- Macros are activated clicking on rectangular shape buttons.
- Thick border cells have to be filled by the user with the proper number or by chosing an option from a drop-down menu.
- Red font cells refer to one ore more macros and their cell number must remain the same, to make the program working.

### 19.1.2. Sheets partition

The file is divided into five different sheets, each sheet contains a different topic, as shown in the following list:

1. 'Site informations' is about the river features like head, flow and flow distribution during the year. It computes the hydrograph distribution ($HY_{(t)}$).
2. 'Turbine informations' is about the turbine group and the electrical equipment, contains informations like type, efficiency and cost. It computes: power group equivalent efficiency ($\varepsilon_{(fr_G)}$), annual productivity ($AP$), costs of the parts 'Power group' and 'Electrical equipment', and other parameters linked to the turbine like specific speed ($n_{QE}$) and suction head ($SH$).
3. 'Plant informations' is about hydraulic works, contains a first attempt sizing with related cost and drawing for each component. It computes 'Weir and intake' and 'Channel and penstock' costs.

4. 'Economic analysis' contains different economical parameters and the proposed utilities contract type. It computes all the economical parameters like investment cost ($IC$), specific plant cost ($SC_{power\,plant}$), $NPV$, $PBT$, $LEC$ and the internal rate of return ($IRR$)

5. 'Simulation' contains the utilities demand and shows the main simulation results.

### 19.1.3. Sheet logical structure

Each sheet has been thought with the same structure to simplify the comprehension and allow future development. Some sheet miss some parts of the general structure, but in this section all the parts are presented. The different parts are signed on the sheet with light red lines, the following list presents them:

1. INPUT DATA: this part is filled by the user and is specific for each site and each configuration, it contains all the thick border cells and most of the buttons that activate macros. Some cells have to be filled directly by the user, while other provide different options from a drop down list.

2. DATA FROM OTHER SHEETS: contains links between the different sheets, these cells refer to their counterparts from the section 'SHEET OUTPUT' in the other sheets. It's better not to modify this links.

3. DATA FROM THEORY: contains information from theory like cost functions, cost database, efficiency database, material features. This part could be modify by advanced users in order to maintain the file updated, particularly cost database and cost functions.

4. COMPUTATIONS: the computations take as input only cells from the previous section 'DATA FROM OTHER SHEETS' and 'DATA FROM THEORY' of the same sheet, in order not to create complex function plots between different sheets. This part should not be modified unless strong changes for the software are planned, in fact it will be hide by the macro 'Hide' to avoid accidental changes.

5. SHEET OUTPUT: all the outputs are displayed in this part, using cells that refer to their counterparts in the section 'COMPUTATIONS', in the form of numerical data, pie chart, bar graph or line chart and dimensional drawings.

## 19.2. Logical steps

The 'Nominal power group electrical power' ($GP_{nom}$) has been chosen as a free parameter of optimization. It means that the whole power plant sizing depends on its value, and the main macros work on this cell, contained in the section

'INPUT DATA' of the 'Turbine informations' sheet. So it's possible to refer to this parameter as the software 'key parameter' or 'key cell'.

To use the program is quite simple, the following list shows the steps the user need to follow:

1. Fill all the thick cells in the section 'INPUT DATA' of each sheet. At the end, in the sheet 'Simulation' define the simulation power range between 'Utilities minimum power' ($UMP$) and 'Utilities peak power' ($UPP$). The utilities demand is linked to the simulation range because there is no need to simulate a solution who isn't able to satisfy the utilities demand and isn't wise to generate power over the maximum request.

2. Once all the thick cells are filled, push the button 'Run Simulation', this action actives the macro 'Simulation' that generates a database of solution as function of the 'Power group electrical power' and the main economical and technical parameters contained in the database are plotted.

3. To select the best solutions from the database, different buttons are available: 'Maximize $AP$', 'Maximize $NPV$', 'Minimize $LEC$', 'Maximize $IRR$'. To compare these solutions, push all the button and read the mean output in the small table over the button itself.

4. Notice that pushing one of the optimization button copies the corresponding 'Nominal power group electrical power' ($GP_{nom}$) value in the key cell, so the whole file is updated pushing one of this buttons. Once the choice has made, push again the desired button and read more detailed output about each topic in the different sheets.

5. Now is time to change some input if the previous solution is not satisfying. Notice that changing the input will immediatly modify the output in the first four sheets, while the output in the final sheet 'Simulation' is changed only by the button 'Run Simulation' and the other optimization buttons.

A simplified example can help to understand the process:

1. Fill the thick cells in 'Site informations' with the requested values, linked to the river features, in this example a gross head of 30 $m$ and an annual average flow of 2,33 $m^3/s$ are considered. In 'Turbine informations' the turbine type choice is mainly linked to the river head, the turbine number choice is usually made to ensure the service continuity, while the grid lenght is hard to choose, it depends on how many people will be linked to the power plant, different scenarios could be investigated changing these parameters; in this example one Francis turbine has been chosen, with a 5 $km$ grid. The sheet 'Plant informations' contains informations like channel, penstock and weir length who are strictly linked to the terrain morphology, and other information linked to the availability of different materials. Fill 'Economic analysis' with

the proper economic parameters. Finally for this example a close village with an utilities minimum power of 100 $kW$ and an utilities peak power of 1000$kW$ have been chosen (1st configuration).

2. Analyzing the charts (Fig. 19.1) is possible to see that the best option for the economical optimization ($NPV$) is limited by the utilities peak power, in fact the $NPV$ value grows until it reaches the utilities purchase limit, then decrease rapidly.

3. As expected the button 'Maximize $NPV$' returns a 'Power group electrical power' value of 500 $kW$, an $IRR$ of 21% and a load factor of 1. The 'Maximize $AP$' button returns the same values, because the utilities limit has been reached.

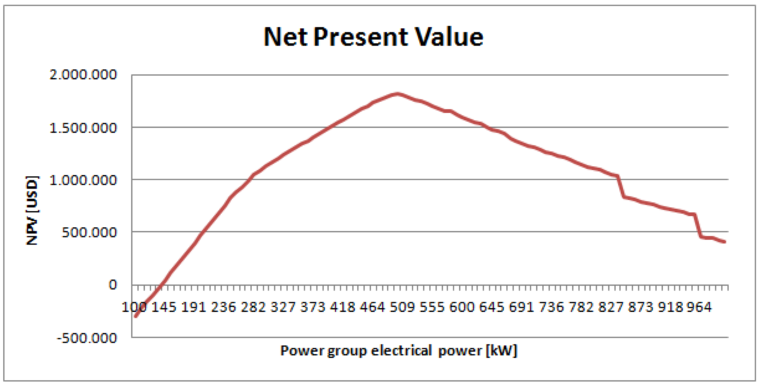


Figure 19.1.: NPV (example, 1st configuration)

1. At this point different options can be examined:
   - The first option (corresponding to the 2nd configuration) is to increase the linked utilities reaching a second village, and run again the simulation. The new values are 300 $kW$ for utilities minimum power and 1'800 $kW$ for utilities peak power, with a grid length of 10 $km$. In the new configuration, the button 'Maximize $NPV$' returns a 'Power group electrical power' value of 650 $kW$, an $IRR$ of 14% and a load factor of 0,6. The economic benefits decrease compared to the previous solution, but the new configuration adds social benefits due to the villages electrification. However this solution should probably be discarded.
   - The second option (corresponding to the 3rd configuration) is to simulate the power plant linked to the national grid. To do that is sufficient to click the button 'On Grid' and use a new grid length of 15 $km$ to reach the nearest connection point. The $UMP$ is set to 200 $kW$ , while the $UPP$ decrease to 880 $kW$ , but with an utilities load factor equal to 1. The 'Maximize $NPV$' button returns a value of 645 $kW$ that is the

maximum electrical power obtainable from the river (Fig. 19.2). The *IRR* value decrease to 10%. Again the economic benefits decrease compared to the previous solutions, but the new configuration adds great social benefits due not only to the villages electrification, but also to the national grid connection. At this point the choice between the first or second option is linked to the preference between economic or social benefits.

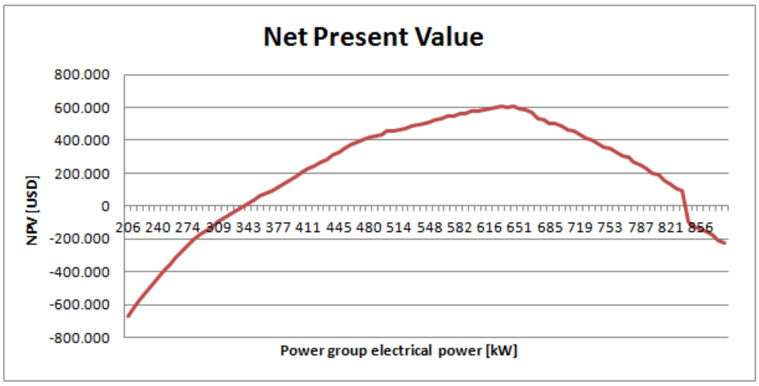


Figure 19.2.: NPV (example, 3rd configuration)

### 19.2.1. Software flow chart

The flow chart 19.3 helps to understand the logical steps of the software computations, starting from 'INPUT DATA'.

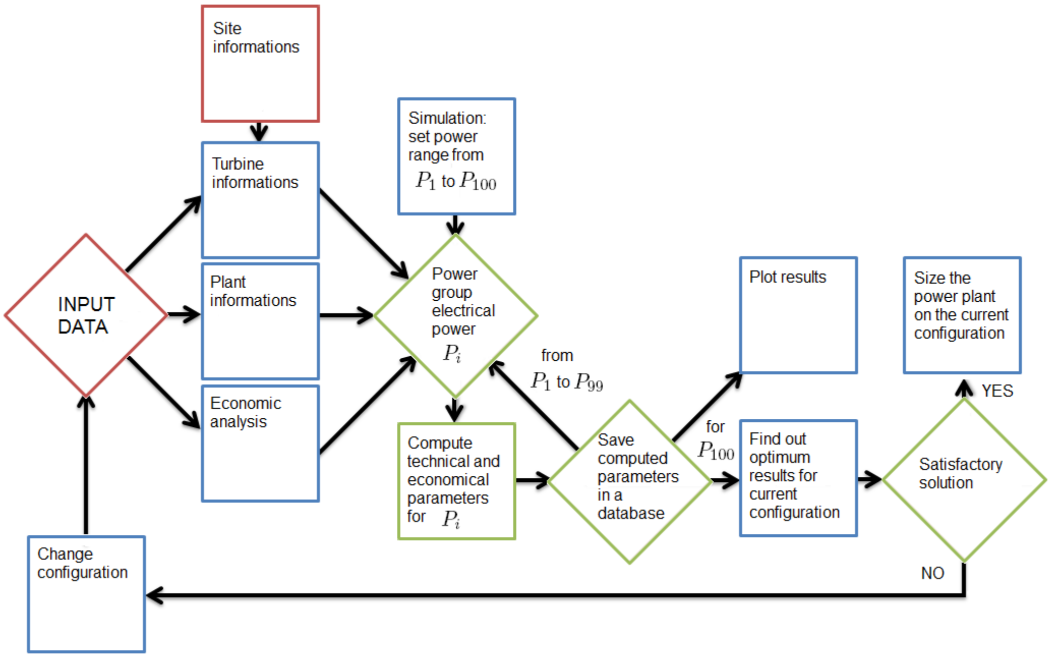


Figure 19.3.: Mini hydro plant simulator flow chart

## 19.3. Software computations

### 19.3.1. Simulation

The 'Simulation' macro subdivides the $UMP$ to $UPP$ power range in 100 power steps ($SPS$) and equals each of them to the 'Nominal power group electrical power' ($GP_{nom}$) sequentially. In the following algorithm $GP$ is simply used to indicate $GP_{nom}$:

**Algorithm 19.1** Simulation algorithm

$$SPS = \frac{UPP - UMP}{99}$$

$$UMP = GP_1$$

$$GP_1 + SPS = GP_2$$

[...]

$$GP_{99} + SPS = GP_{100} = UPP$$

Then the table 19.1 is generated, for the first iteration the macro copies the $GP_1$ value in the key cell and takes the output values from the different sheets to copy them in the corresponding row 1; the same for the second iteration that use $GP_2$ as input in the key cell, to copy the output in the row 2.

| $GP_{nom}$ | $Eh$ | $Oh$ | $LF_{plant}$ | $AP$ | $IC$ | $NPV$ | $PBT$ | $LEC$ | $IRR$ |
|---|---|---|---|---|---|---|---|---|---|
| $GP_1$ | | | | | | | | | |
| $GP_2$ | | | | | | | | | |
| [...] | | | | | | | | | |
| $GP_i$ | | | | | | | | | |
| [...] | | | | | | | | | |
| $GP_{100}$ | | | | | | | | | |

Table 19.1.: Simulation empty table

Repeating this procedure for all the $GP_i$ values, the table is filled as shown (Tab. 19.2):

| $GP_{nom}$ | $Eh$ | $Oh$ | $LF_{plant}$ | $AP$ | $IC$ | $NPV$ | $PBT$ | $LEC$ | $IRR$ |
|---|---|---|---|---|---|---|---|---|---|
| $GP_1$ | $Eh_1$ | $Oh_1$ | $LF_1$ | $AP_1$ | $IC_1$ | $NPV_1$ | $PBT_1$ | $LEC_1$ | $IRR_1$ |
| $GP_2$ | $Eh_2$ | $Oh_2$ | $LF_2$ | $AP_2$ | $IC_2$ | $NPV_2$ | $PBT_2$ | $LEC_2$ | $IRR_2$ |
| [...] | | | | | | | | | |
| $GP_i$ | $Eh_i$ | $Oh_i$ | $LF_i$ | $AP_i$ | $IC_i$ | $NPV_i$ | $PBT_i$ | $LEC_i$ | $IRR_i$ |
| [...] | | | | | | | | | |
| $GP_{100}$ | $Eh_{100}$ | $Oh_{100}$ | $LF_{100}$ | $AP_{100}$ | $IC_{100}$ | $NPV_{100}$ | $PBT_{100}$ | $LEC_{100}$ | $IRR_{100}$ |

Table 19.2.: Simulation filled table

### 19.3.2. Maximize and minimize

The macros 'Maximize $AP$', 'Maximize $NPV$', 'Minimize $LEC$', 'Maximize $IRR$' are responsible to search interesting values in the table 19.2 created by the macro 'Simulation'. Once one of these values has been discovered [1], the corresponding power value is copied in the key cell and the whole file is updated to this solution [2]. Immediatly the small table over the button is filled by the sensitive values [3].

The algorithm 19.2 helps to understand the process; in this example pushing the button 'Maximize $NPV$' the macro finds in the 26th row of the table the maximum $NPV$ value.

**Algorithm 19.2** Maximize $NPV$

$$NPV_{max} = NPV_{26}\,[1]$$

$$GP_{nom} = GP_{max\,NPV} = GP_{26}\,[2]$$

| Max annual productivity power $[kW]$ $(GP_{max\,NPV})$ | $GP_{26}$ | |
|---|---|---|
| Equivalent hours $[h]$ | $Eh_{26}$ | [3] |
| Operative hours $[h]$ | $Oh_{26}$ | |
| Power plant load factor | $LF_{26}$ | |
| Annual productivity $[MWh]$ | $AP_{26}$ | |
| Investment cost $[USD]$ | $IC_{26}$ | |
| Net Present Value $[USD]$ | $NPV_{26}$ | |
| Pay Back Time $[y]$ | $PBT_{26}$ | |
| Levelized Energy Cost $[USD/kWh]$ | $LEC_{26}$ | |
| Internal Rate of Return % | $IRR_{26}$ | |

Then each column of the table 19.2 is plotted in a line chart, except the operative hours. These charts could help showing the trend of the different parameters. Besides, as shown in the algorithm 19.2 over each maximize or minimize button is reported a small table containing the sensitive data about the respective solution.

## 19.4. Software comparison

Other software operating on minihydro are freely available on the web, two of them have been used to compare the *'Mini hydro plants simulator'* software (Source [SMART, RET]):

- '*SMART mini-idro ®*' created by 'CESI RICERCA', Italy.
- '*RETScreen ®*' created by 'Natural Resources Canada', Canada.

*SMART mini-idro* ® is an Excel-based, user-friendly program, developed to be applied to mini hydropower plants in northern Italy, to get a productivity and cost estimation.

*RETScreen* ® is an Excel-based clean energy project analysis software tool that helps decision makers determine the technical and financial viability of potential renewable energy, energy efficiency and cogeneration projects. Since it was developed in Canada, it needs an economical comparison between Canada and the foreign conutry in which the hydropower project should be realized, to returns reliable results. Both the softwares compute the technical and economic parameters once that the electrical power has been introduced as input.

The *Mini hydro plants simulator* offers several advantages compared to the similar softwares, the following list summarizes them:

1. Includes computation of some technical turbine parameters.
2. Includes sizing of hydraulic structures and provides their dimensional drawings.
3. Provide productivity trends over time.
4. Makes use of exponential functions instead of polynomial to valuate the cost of components.
5. Making use of local prices, is inside tanzanian situation.
6. Includes the loads bond in computations, necessary to perform an off-grid simulation.
7. Performs the optimization, finding the optimum value of power which combines the potential of the river with the request of the utilities.
8. It's user friendly and allows future improvement in a simple way.

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# Part IV.

# Tanzanian sites simulation

# 20. Model validation on Madunda power plant

The Madunda power plant has been used in the software developing to fix some missing informations about sizing and cost of hydraulic structures and to compare the results of the software with data regarding the existing plant in order to validate the model. These data (Ref. [ACRA2]) were kindly given by the NGO ACRA, the main developer of the project in Madunda which is still working on it, aiming to increase the electricity connection to nearby villages.

This chapter shows and explains the main points of the software comparison with the existing plant.

## 20.1. Site description

The hydropower plant is located near the Madunda mission, Njombe district, Iringa region. The run-of-river power plant has been supported by the italian NGO ACRA, but is owned by the tanzanian NGO LUMAMA that operates it and decides the local tariffs.

The power plant conveys the water from the Kisongo stream, whose catchment area has a surface around 42 $km^2$, at the average altitude of 1200 $m$ above mean sea level. The river flows with a light slope for 10 $km$, then runs down with an high slope before conveying in the Kiliwaka river. The hydropower plant is located on the last stream stretch using a gross head around 80 $m$.

Via a local grid (15 $km$) the hydropower plant provides the electric energy to the Mawengi, Madunda and Lupande nearby villages. Due to the particular tariffs system, is quite impossible to have a valuation of the plant profitability (that is not the main concern of the NGO), that's why this chapter only simulates the power plant building and the relative components costs to obtain a software validation.

The Madunda power plant scheme is quite different by the modelized one, but some tricks can easily adapt it to the software:

- The power plant presents a drop intake that conveys the water to a sediment trap then to the forebay, while the software uses a lateral conveyance intake. To adapt it a fake measure of 1 $m$ and an estimated hydraulic gradient have been used in the channel project. The real intake is structurally more complicated than the lateral intake so it will be probably more expensive.

- The Madunda plant uses a long steel penstock divided into two sections: for the first section, called 'Conduct of derivation' a single pipe has been used, the second section splits up into two 'Pressure pipes', one for each turbine group. The software has been developed to use the penstock only for the pressure section, besides one pipe for each turbine group from the forebay to the powerhouse. A conduct of derivation is surely cheaper than two pressure pipes, so the modelized structure will be more expensive than the real one, but more efficient in the limitation of head losses.

## 20.2. Sensitive data

The 'Sensitive data' are the inputs that the software *'Mini hydro plants simulator'* needs to perform its simulation (Ref. [ACRA]). They are collected in the table 20.1 following the logical flow presented in the 'Part III'.

| **Location** | | **River features** | |
|---|---|---|---|
| Latitude | -9,850000 | Hydrograph input type | Computed |
| Longitude | 34,450000 | Min g. flow ($HY_{min}$) [$m^3/s$] | 0,50 |
| Weir altitude A.M.S.L. [$m$] | 1596 | Minimum gauge period | October |
| Gross project Head ($GH$) [$m$] | 79,80 | Max g. flow ($HY_{max}$) [$m^3/s$] | 2,10 |
| Project head loss % ($hl_{nom}$) | 2% | Maximum gauge period | February |
| | | Residual flow ($rf$) % | 10% |
| **Power group** | | **Electrical equipment** | |
| Turbine type | Francis | Grid length ($L_{grid}$) [$km$] | 15,00 |
| Turbine number ($TN$) | 2 | Utilities acces points ($UA$) | 7 |
| Nominal power group electrical power ($GP_{nom}$) [$kW$] | 300 | Electrical equipment transport cost coefficient ($tf$) | 1,10 |
| Turbine tr. cost coefficient ($tf$) | 1,30 | Annual maintenance hours [$h$] | 400 |
| **Weir and intake** | | **Channel and Penstock** | |
| Ground type | Medium | Channel lining material | Concrete |
| Weir lenght ($WL$) [m] | 13,90 | Channel section shape | Rectangle |
| Weir height ($WH$) [m] | 5,00 | Channel length [$m$] | 1,00 |
| Weir material | Armed concrete | Channel hyd. grad. ($S$) [$m/m$] | 0,0500 |
| Trashrack bars shape | Circular | Penstock material | Steel |
| Building material transport cost coefficient ($tf$) | 1,20 | Penstock length [$m$] | 254,40 |
| | | Penstock deposition type | External |

Table 20.1.: Madunda sensitive data

The software is filled with the proper input and then the output are immediatly available. There is no need of perform the optimization process, because the

'Nominal power group electrical power' ($GP_{nom}$) is set on the same value of the real power plant to make the comparison (two Francis turbines of 150 $kW$ each).

## 20.3. Comparison

Firstly the components costs, contained in the Madunda report (Ref. [ACRA2]), have been reorganized into the following categories to match the software:

- Weir and intake: from weir to sediment trap.
- Channel and penstock: from forebay to the penstocks outlet.
- Powerhouse building
- Power group: turbines, alternators, control systems.
- Grid: MV transmission line and related safety equipment.
- Transformers: step up and step down transformers.

Then the cost of each category has been compared to the computed one. The more evident difference is in the transformers cost (43%). The data from ACRA provides a total cost of 95436 $USD$ for the 7 transformers, while the computed cost is 136410 $USD$, consistent with the specific cost provided by local producers. The cost gap between the simulated and the real transformers is explained in the ACRA report , where is told that the Madunda plant employs disused transformers retrieved in Italy by the NGO, and only some of them have been locally bought.

The other categories returns comparable results, summarized in the table 20.2, while the comparison is shown in the chart 20.1.

| Costs table [$USD$] | Weir and intake | Channel and penstock | Powerhouse building | Power group | Transmission grid |
|---|---|---|---|---|---|
| Madunda power plant data | 126228 | 63107 | 63883 | 605352 | 321138 |
| *'Mini hydro plants simulator'* results | 77608 | 78223 | 32285 | 469346 | 273801 |

Table 20.2.: Cost comparison

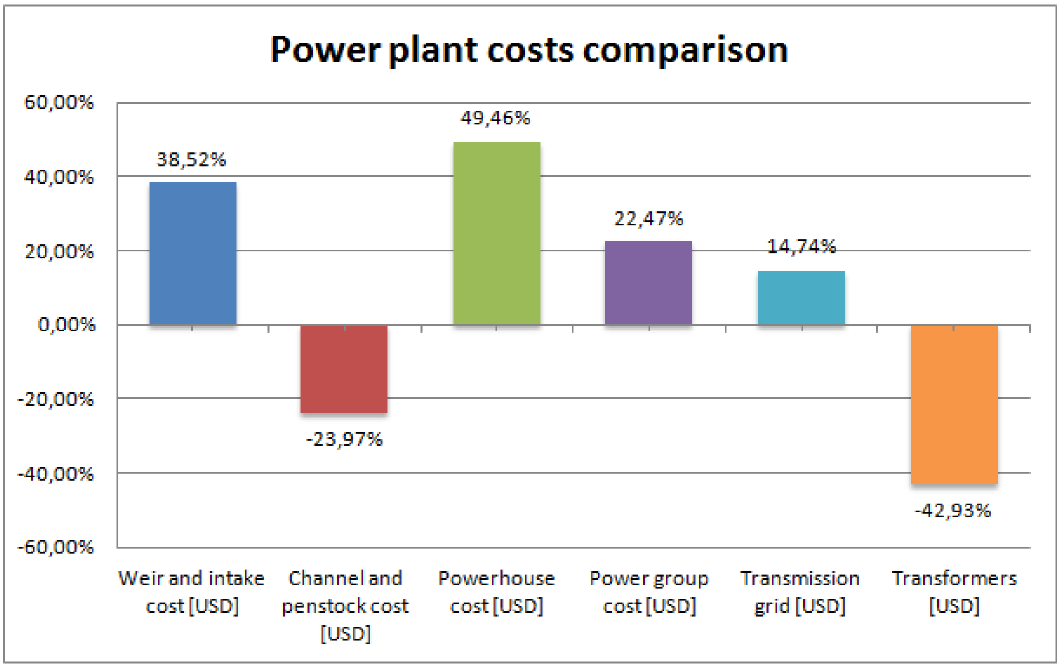



Figure 20.1.: Cost comparison chart

As expected the real weir results more expensive than the simulated one (39%), while the builded steel penstock is cheaper than the simulated pipe (24%). The powerhouse of the Madunda plant is clearly oversized for the two machines (49%), maybe to have the future possibility of hold a third turbine, improving the plant productivity. The fluctuation on the costs of power group and transmission grid is in line with the price variation between different suppliers (22%, 15%).

The Power plant cost ($PC$) results about 1,28 million $USD$ for the ACRA report, 1,07 $USD$ for the simulator, with an error value of 16,27%, mainly due to the powerhouse oversizing. The power plant specific cost ($SC_{power\,plant}$) assumes the value of 3844 $USD/kW$. Two pie charts report the cost distribution of the real power plant and the simulated one:

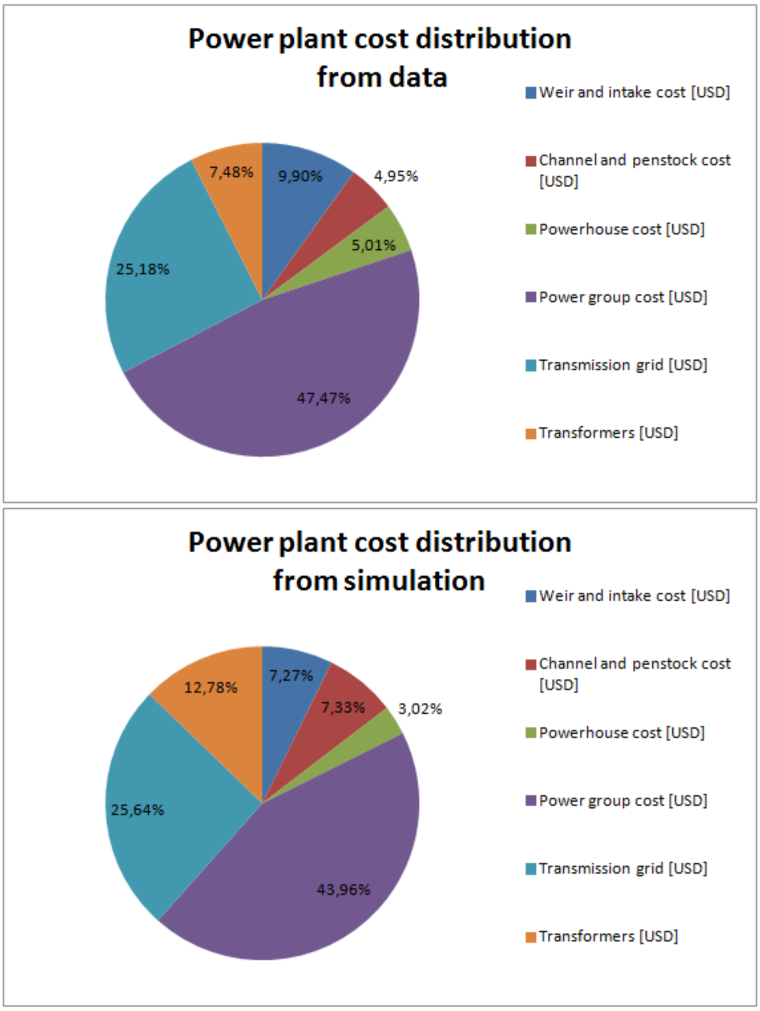



Figure 20.2.: Cost distribution

## 20.4. General conclusion

The comparison gives quite different results for each component, but the overall investment results surely in a good approximation. Besides the *'Mini hydro plants simulator'* simulates the plant following the hypothesis of:

- Technological efficiency, mainly for turbines and electrical equipment.
- Economic efficiency, mainly in the sizing of hydraulic works.
- Mini hydropower plant built from scratch.

Obviously leaving this hypothesis exist endless possibilities, that should be considered case by case, adjusting the simulated results.

At the end the simulation on the Madunda site, assuming that the power plant is well sized on the utilities request and using the TANESCO energy price for general usage of 157 $TZS/kWh$, equal to 0,092 $USD/kWh$, has been performed. Then the Madunda power plant results in a profitable investment with an $IRR$ value of 12,08%, enough for a self-sustaining project.

# 21. Makete in Ijangala district

This site and the followings are merely simulations: contrary to previous chapter (20), here no comparison is performed, because these are potential sites and the result of the simulations can be used by developers to decide if the given project is feasible or not.

Makete in particular is the most important site, because is the one that DIT and REA want to develop first. The first configuration (21.3) was suggested by DIT while the second one was modified a bit and, since it is considered the most interesting solution, its related section (21.4) describes more in detail the simulation steps and the results. Finally, in the third configuration, the on-grid option has been tested.

## 21.1. Site description

The Tandala Diaconical Centre of the South Central Diocese of the Evangelical Lutheran Church of Tanzania has commissioned an hydropower feasibility study to the Dar Es Salaam Institute of Technology. The project intends to take advantage of the hydropower potential of Ijangala river in Makete District for the diaconical centre own consumption and to electrify neighbouring villages. The centre deals with people with various disabilities, orphans and other disadvantaged persons and has been in contact with various church authorities in Germany that have shown interest in sponsoring the project.

The locations of the main plant components such weir, forebay and powerhouse have been decided during a local survey on the proposed plant site. Besides through two different surveys in October, during the dry season, and in March during the rain season, the stream flow has been gauged using the velocity-area method. Other informations about flow stability and floods frequency have been obtained interviewing local people.

Figure 21.1.: Makete district

The gauged stream flow varies between 2,80 to 4,00 $m^3/s$, resulting in a very stable hydrograph curve, computed through the 'Rainfall to Hydrograph' algorithm, because a gauging station doesn't exist and better data weren't available.

The Makete hydropower plant is a low-head type with a gross head of 18 $m$, suitable for a Francis turbine. To ensure the power supply continuity, a two parallel turbines configuration has been chosen. The light slope stream requires a long channel (141 $m$) to gain the desired head, ending with a short penstock (36 $m$) which envolves small head losses (5%). The main problem of the power plant are the connected utilities: the stream has a good hydropower potential, greater than the loads request, that's why the project economic feasibility is uncertain. To perform an economical optimization and reach the economic sustainability of the project, three different scenarios have been analized in the following sections.

Figure 21.2.: Ijangala river

## 21.2. Sensitive data

The table below summarizes the input used in the hydropower plant simulations, the data linked to the plant layout are the same for the different configurations , while the utilities data change from case to case (Ref. [DIT1]).

| **Location** | | **River features** | |
|---|---|---|---|
| Latitude | -9,444678 | Hydrograph input type | Computed |
| Longitude | 34,273215 | Min g. flow ($HY_{min}$) [$m^3/s$] | 2,80 |
| Weir altitude A.M.S.L. [$m$] | 1850 | Minimum gauge period | October |
| Gross project Head ($GH$) [$m$] | 18 | Max g. flow ($HY_{max}$) [$m^3/s$] | 4,00 |
| Project head loss % ($hl_{nom}$) | 5% | Maximum gauge period | March |
| | | Residual flow ($rf$) % | 10% |
| **Power group** | | **Electrical equipment** | |
| Turbine type | Francis | Grid length ($L_{grid}$) [$km$] | 10,50 |
| Turbine number ($TN$) | 2 | Utilities acces points ($UA$) | 7 |
| Nominal power group electrical power ($GP_{nom}$) [$kW$] | 160 | Electrical equipment transport cost coefficient ($tf$) | 1,10 |
| Turbine tr. cost coefficient ($tf$) | 1,20 | Annual maintenance hours [$h$] | 400 |
| **Weir and intake** | | **Channel and Penstock** | |
| Ground type | Hard | Channel lining material | Concrete |
| Weir lenght ($WL$) [m] | 10,00 | Channel section shape | Trapezoid |
| Weir height ($WH$) [m] | 5,00 | Channel length [$m$] | 141,00 |
| Weir material | Armed concrete | Channel hyd. grad. ($S$) [$m/m$] | 0,0020 |
| Trashrack bars shape | Circular | Penstock material | Steel |
| Building material transport cost coefficient ($tf$) | 1,10 | Penstock length [$m$] | 36,00 |
| | | Penstock deposition type | External |
| **Economic parameters** | | **Utilities** | |
| Estimated service life ($SL$) [$y$] | 30 | Utilities min power ($UMP$) [$kW$] | 150 |
| Discount rate % ($r$) | 8% | Utilities peak power ($UPP$) [$kW$] | 275 |
| Engineering, consultation and commissioning cost % ($ecc$) | 10% | Utilities load factor ($LF_{utilities}$) | 0,60 |
| Energy price valuation ($EP$) [$USD/kWh$] | 0,092 | Connection price for preferential loads ($PCP$) [$USD/kW$] | - |
| | | Connection price for standard loads ($SCP$) [$USD/kW$] | - |

Table 21.1.: Makete sensitive data

The table 21.2 shows in the first row the rainfall data collected by the Makete gauging station, in the second the 'Rainfall to Hydrograph' results, monthly discretized.

| Month | January | February | March | April | May | June |
|---|---|---|---|---|---|---|
| Rainfall ($RA_{(t)}$) $[l/m^2]$ | 220 | 219 | 227 | 208 | 40 | 8 |
| Hydrograph ($HY_{(t)}$) $[m^3/s]$ | 4,05 | 4,00 | 4,00 | 4,01 | 3,99 | 3,57 |
| Month | July | August | September | October | November | December |
| Rainfall ($RA_{(t)}$) $[l/m^2]$ | 1 | 1 | 1 | 34 | 116 | 263 |
| Hydrograph ($HY_{(t)}$) $[m^3/s]$ | 3,21 | 2,80 | 2,80 | 2,80 | 3,54 | 3,84 |

Table 21.2.: Makete Hydrograph

## 21.3. First configuration

### 21.3.1. Layout

The first configuration provides to include in the connected utilities the Tandala diaconical centre, that sponsorizes the project, and the nearby religious and social works. This seven load centres are listed with their estimated power demand in bracket:

- Tandala lutheran deaconical centre (50 $kW$).
- Church area (50 $kW$).
- Flour milling machine (50 $kW$).
- Teachers training college and nearby primary school (50 $kW$).
- Hostel, parish office and pastor's residence (25 $kW$).
- College staff houses (25 $kW$).
- Tandala market (25 $kW$).

The power demand estimation has been performed by a DIT team during the local survey, according to the deaconical centre requests. As preferential loads (150 $kW$) the deaconical centre, college, and church area have been considered, while the total power demand reaches the 275 $kW$ value. The loads have been mapped (Fig. 21.6 ) and the length of the transmission grid branches computed, resulting in the total value of 10,5 $km$.

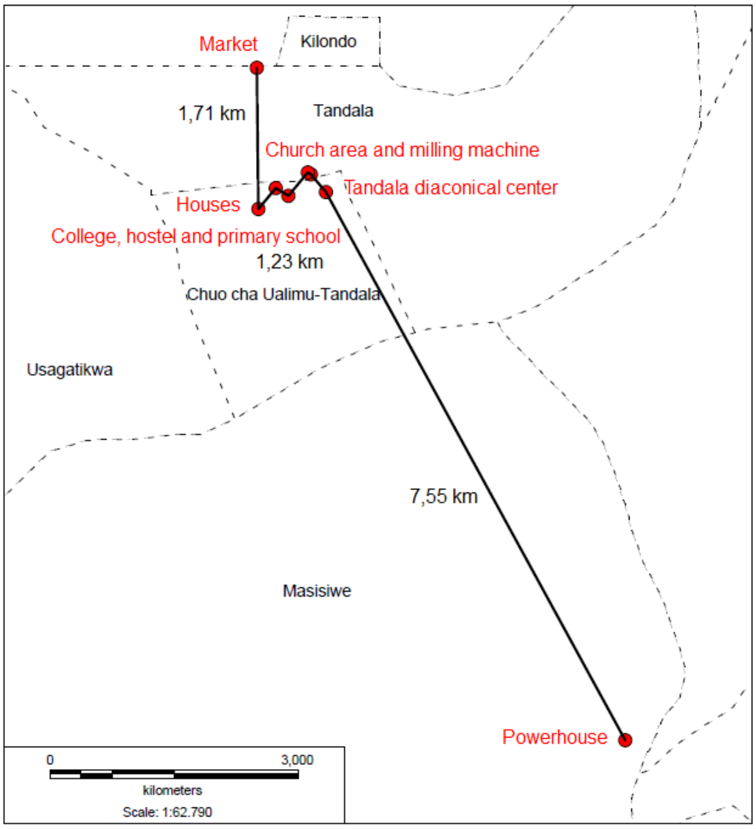



Figure 21.3.: Makete, first configuration grid map

### 21.3.2. Results

Connecting these utilities to the local grid, the optimum 'Power group electrical power' ($GP_{nom}$) results in 160 $kW$, with two parallel Francis of 80 $kW$ each. The power plant specific cost ($SC_{power\,plant}$) assumes a very high value of 6103 $USD/kW$, because small size turbines have an high specific cost and the great distance between loads and power house is unbalanced compared to the installed power. The estimated investment cost ($IC$) assumes the value of 976557 $USD$, the investment cost distribution through the different parts is shown below in the first pie chart, the second chart shows the detailed hydraulic works while the third shows the detailed electro-mechanical cost distribution.

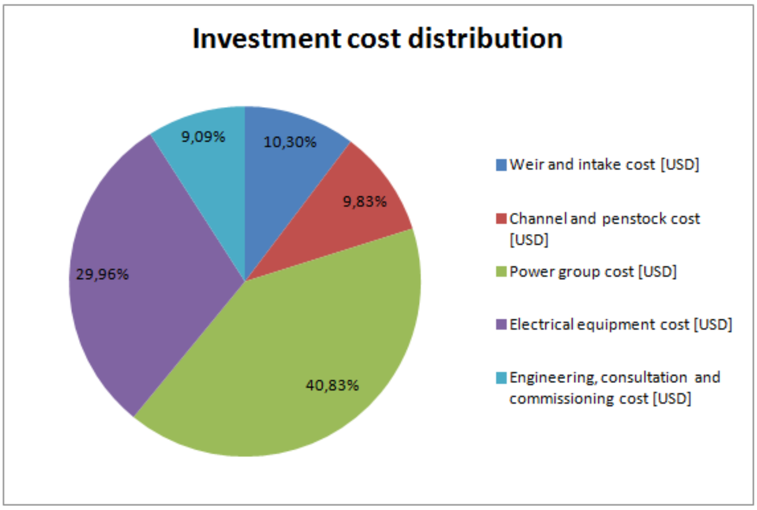
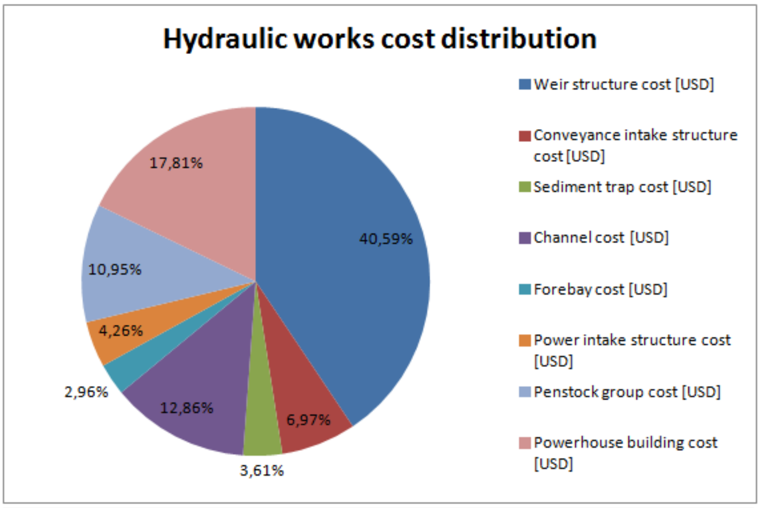



Figure 21.4.: Makete, first configuration cost distribution



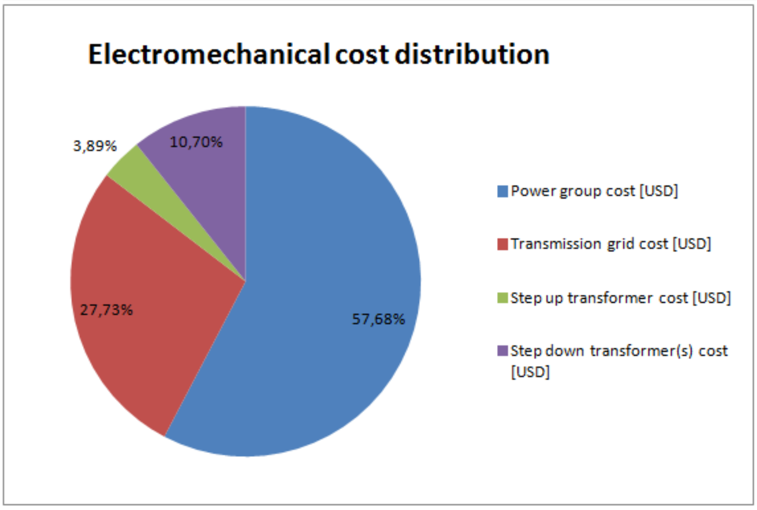




Figure 21.5.: Makete, first configuration detailed cost distribution

Using again the TANESCO energy price for general usage of 157 $TZS/kWh$ or 0,092 $USD/kWh$ to perform the economic analysis and compute the revenues, an $IRR$ value of 3,08% and a levelized cost of energy ($LEC$) value of 0,100 $USD/kWh$ have been obtained. Then the project in the first configuration is definitely unsuitable if the main pursued aim is the economical self-sustain.

Analyzing the plant productivity is evident that the turbine size cuts the productivity to a low value (Fig. 21.6), in fact the maximum river potential ($HP_{max} = 715\,kW$) is much higher than the installed power ($GP_{nom} = 160\,kW$), then the idea is to increase the connected loads, taking advantage of the river potential and collecting more revenues from the selling of electricity.

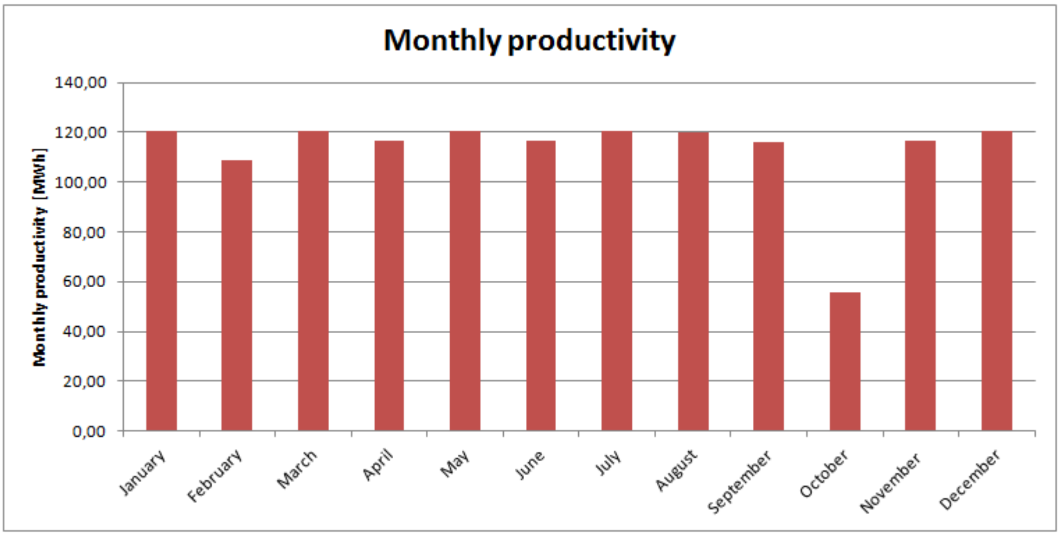



Figure 21.6.: Makete, first configuration productivity

## 21.4. Second configuration

### 21.4.1. Layout

The second configuration provides to add nearby utilities to maximize the river exploitation. Many utilities in the area demand electric connection, but the trade-off between revenues and connection cost have excluded most of them, at the end only four big load centres have been added. They are listed below with estimated power demand in bracket:

- Tandala village (population: 1897 ; 142 $kW$).
- Ikonda village (population: 1455 ; 109 $kW$).
- Ikonda hospital (30 $kW$).
- Msisiwi primary school (10 $kW$).

The power demand estimation is set on high values, assuming that during the power plant service life the villages will increase the electric consumption developing small industries and laboratories (milling machines, wood workshops, water pumps, offices, etc.). As preferential loads (275 $kW$) the utilities of the first configuration have been considered, while the total power demand reaches the 566 $kW$ value. Again the local utilities have been mapped (Fig. 21.18) and the length of the transmission grid branches computed, resulting in the total value of 13,5 $km$.

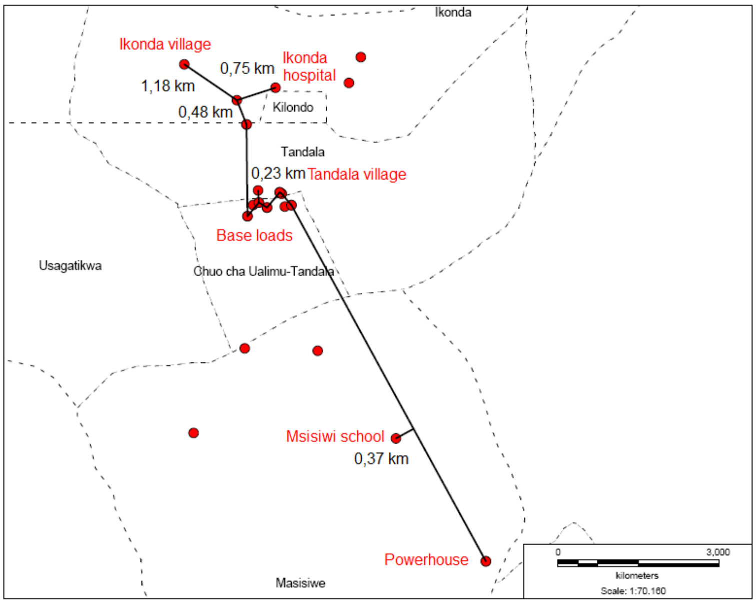



Figure 21.7.: Makete, second configuration grid map

## 21.4.2. Simulation steps

The flow chart below (already introduced in Part III) will be followed to explain the simulation steps. Next sections are named as the software sheets, and contain some screenshots from the software itself.

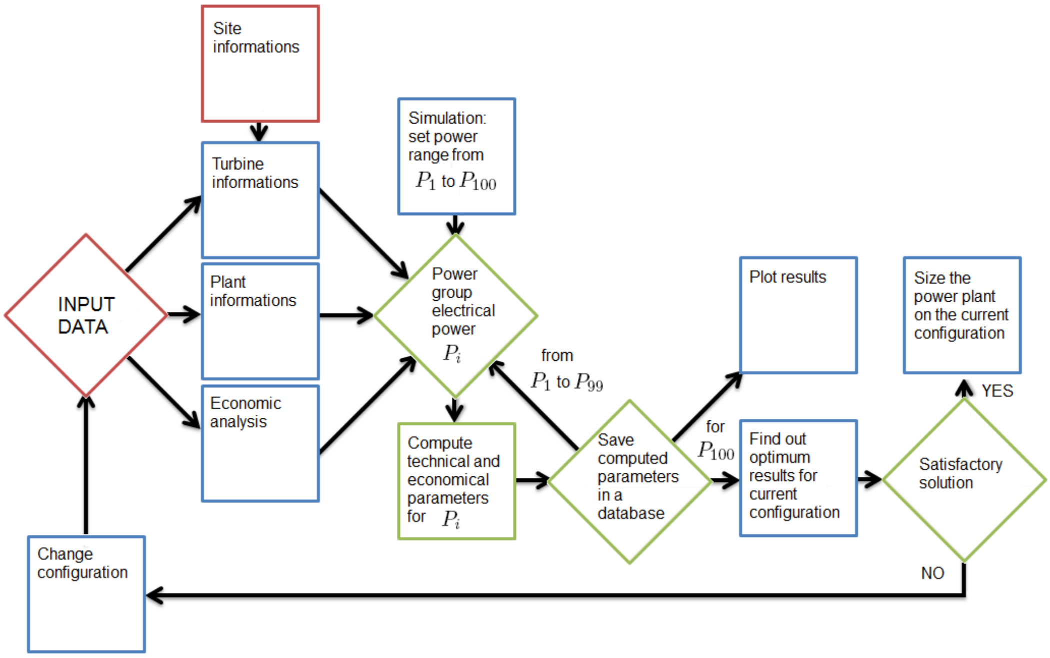



Figure 21.8.: Software flow chart

### Site informations

| | |
|---|---|
| Site location | |
| Site name | makete |
| Latitude | -9,444678 |
| Longitude | 34,273215 |
| Weir altitude above mean sea level [m] | 1850 |
| | |
| Hydraulic measures | |
| Gross project head [m] | 18,00 |
| Project head loss % | 5% |
| Minimum flow [m^3/s] | 2,80 |
| Minimum gauge period | October |
| Maximum flow [m^3/s] | 4,00 |
| Maximum gauge period | March |
| Residual flow % | 10% |

Rainfall to Hydrograph

Generate FDC

Figure 21.9.: Site information input

As said in section 21.1, only the maximum flow (measured in October) and minimum (measured in March) are gauged.

Since only these two values are available, is necessary to compute the hydrograph through the rainfall, in order to estimate the monthly river flow trend during the year.

Latitude, longitude and altitude are used as input in the *New_LocClim*® software by FAO which gives as output an estimation of the monthly rainfall in the area. Using these rainfall data and the two known flows, hydrograph and flow duration curve, are calculated by pushing the button 'Rainfall to Hydrograph' and 'Generate FDC' (Fig. 21.9).

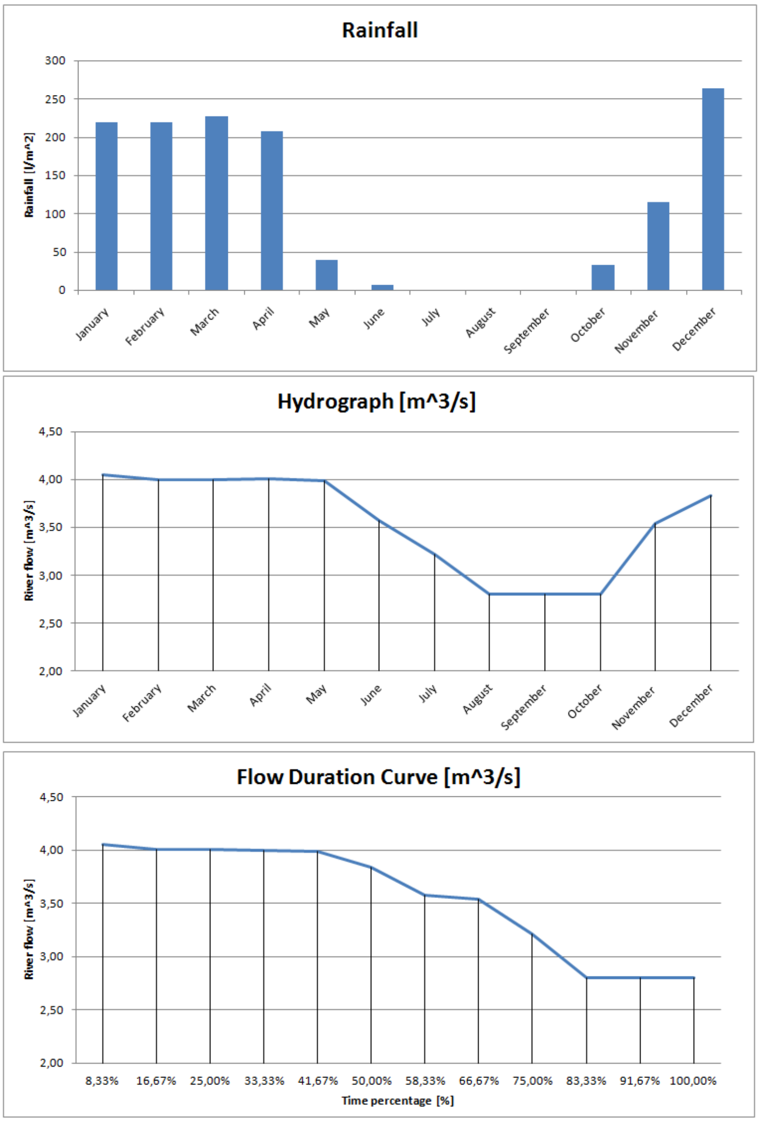



Figure 21.10.: Rainfall, hydrograph and FDC for Ijangala river

Desired project head loss and residual flow values were given by DIT professors.

### Turbine informations

| Power group and electrical equipment | |
|---|---|
| Turbine type | Standard_Francis |
| Turbine transport cost coefficient | 1,20 |
| Electrical equipment transport cost coefficient | 1,10 |
| Number of parallel turbines | 2 |
| Utilities grid acces points | 11 |
| Grid total length [km] | 13,50 |
| Annual maintenance hours (up to 650) [h] | 400 |
| Maintenance period | October |
| Nominal power group electrical power [kW] | |

Figure 21.11.: Turbine informations input

The gross head equal to 18 $m$ is suitable for a Francis turbine. As said in section 21.1, two parallel turbines configuration has been chosen to ensure the power supply continuity and to make the transport easier. Turbine and trasport coefficient, as well as annual maintenance hours values, were suggested by DIT professors. Manteinance period was set in October because it is the month with the minimum flow.

Inserting the GPS coordinates of all the utilities into the GIS software *Map Info Pro*® it was possible to draw them on the map, decide the utilities grid access points and compute the transmission grid total lenght (Fig. 21.7).

The cell 'Power group electrical power' has not to be compiled because, as can be seen in figure 21.8, it's the key cell, whose value will be changed automatically by the software during the simulation.

### Plant informations

| Weir and intake | |
|---|---|
| Building materials transport cost coefficient | 1,10 |
| Ground type | hard_ground |
| Weir length [m] | 10,00 |
| Weir height [m] | 5,00 |
| Weir material | Armed_concrete |
| Trashrack bars shape | stainless_circular_[12mm] |
| | |
| Channel and penstock | |
| Channel lining | artificially_concreteC15 |
| Channel shape | trapezoid_(half_hexagon) |
| Channel length [m] | 141,00 |
| Channel hydraulic gradient [m/m] | 0,0020 |
| Penstock material | welded_steel |
| Penstock length [m] | 36,00 |
| Penstock deposition type | External |

Figure 21.12.: Plant informations input

Ground type was set on 'hard_ground' after performing tests at DIT soil laboratory on samples taken during the survey.

Weir possible dimensions have been estabilished after measurements of river width and depth during the survey. Armed concrete was chosen as building material because of the availability from nearby suppliers.

Thanks to the GPS coordinates for weir, forebay and powerhouse taken during the survey, channel length, channel hydraulic gradient and penstock diameter were computed. For penstock material, steel was preferred to PVC because it could be obtained easier from local producers. Due to the ground conformation, the choice of an external penstock was obliged.

### Economic analysis

| | |
|---|---|
| Economic parameters | |
| Discount rate % | 8% |
| Estimated service life [y] | 30 |
| Engineering, consultation and commissioning cost % | 10% |
| | |
| Contract type | Energy_contract |
| Energy contract | |
| Energy price valuation [USD/kWh] | 0,0920 |

Figure 21.13.: Economic input

Discount rate, estimated service life and engineering, consultation and commissioning costs were gived by the DIT.

As a first attempt for computing the revenues in the economic analysis, DIT staff decided to use an energy contract type, with the TANESCO energy price for general usage of 157 $TZS/kWh$ equal to 0,092 $USD/kWh$.

### Simulation

| | | | |
|---|---|---|---|
| Utilities data | | | |
| Utilities load factor | 0,60 | On Grid | Run Simulation |
| Utilities minimum power (preferential loads) [kW] | 275,00 | | |
| Utilities peak power (total loads) [kW] | 566,00 | | |

Figure 21.14.: Simulation input

The utilities load factor was assumed equal to 0,60.

This configuration, considered as off-grid, needs in input the utilities minimum power, computed as sum of preferential loads (this is the power that should always be guaranteed by the power plant), and the utilities maximum power, that is the sum of all the loads. The previous section 21.4.1 gives details about these loads.

Pushing now the button 'Run simulation', a macro will (Fig. 21.8):

- divides the power range 275-566 $kW$ into 100 steps
- starts the iteration from 275 $kW$, writing this value into the fundamental cell called 'nominal power group electrical power' (Fig. 21.11)
- computes and save all the technical and economical parameters resulting for this value of power
- repeats the precedure with the value of power of the second iteration, until 566 $kW$ is reached

Thus a chart, which describe the variation of each parameter as function of nominal power group electrical power, will be plotted (some of them are shown in figure 21.15 and 21.16).

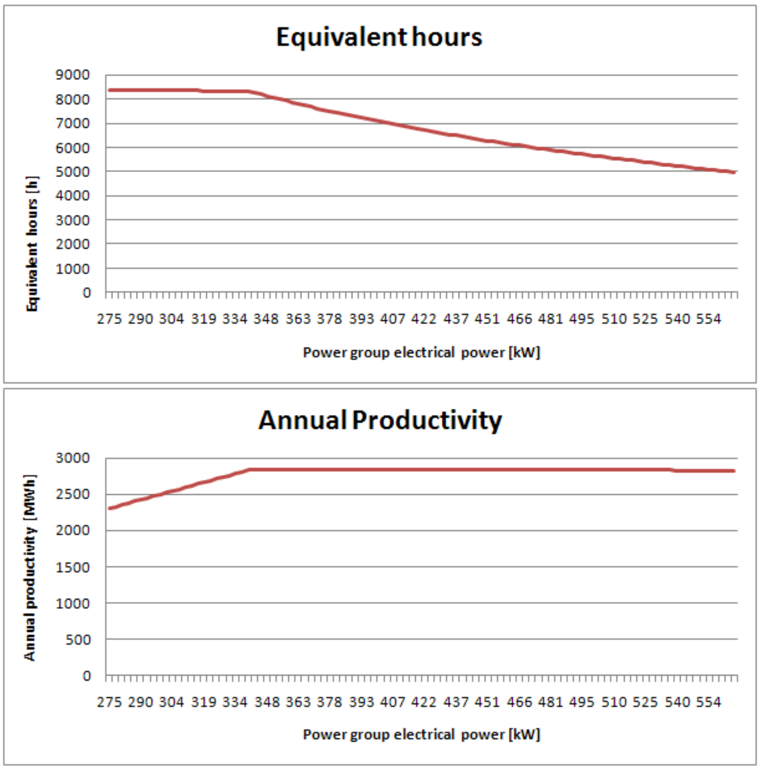



Figure 21.15.: Technical parameters variation charts

Equivalent hours and power are inversely proportional, because a small power turbine can work at nominal load also when the river flow is low, therefore it will have a high equivalent hours value. The bigger is the turbine, the higher is the discharge it needs for working at nominal load, but a bigger discharge will be available for less time during the year, causing a drop in equivalent hours.

Multiplying the utilities load factor for the utilities total power, is possible to obtain a value describing the power which can be “sold” to the utilities (about 340 *kW*). Indeed over this value the productivity remains steady, because the utilities purchase power is reached.

This value is approximately the one which maximize and minimize the economical parameters charts in figure below: before this value, IRR increases with the power, because more energy is produced and more profits are made; after this value, IRR becomes inversely proportional to the power, because the turbine and the other plant components keep on increasing their size and cost, but the utilities purchase power is reached and thus the revenues remain steady. For the same reason, PBT and energy cost have a similar (but reversed) trend.

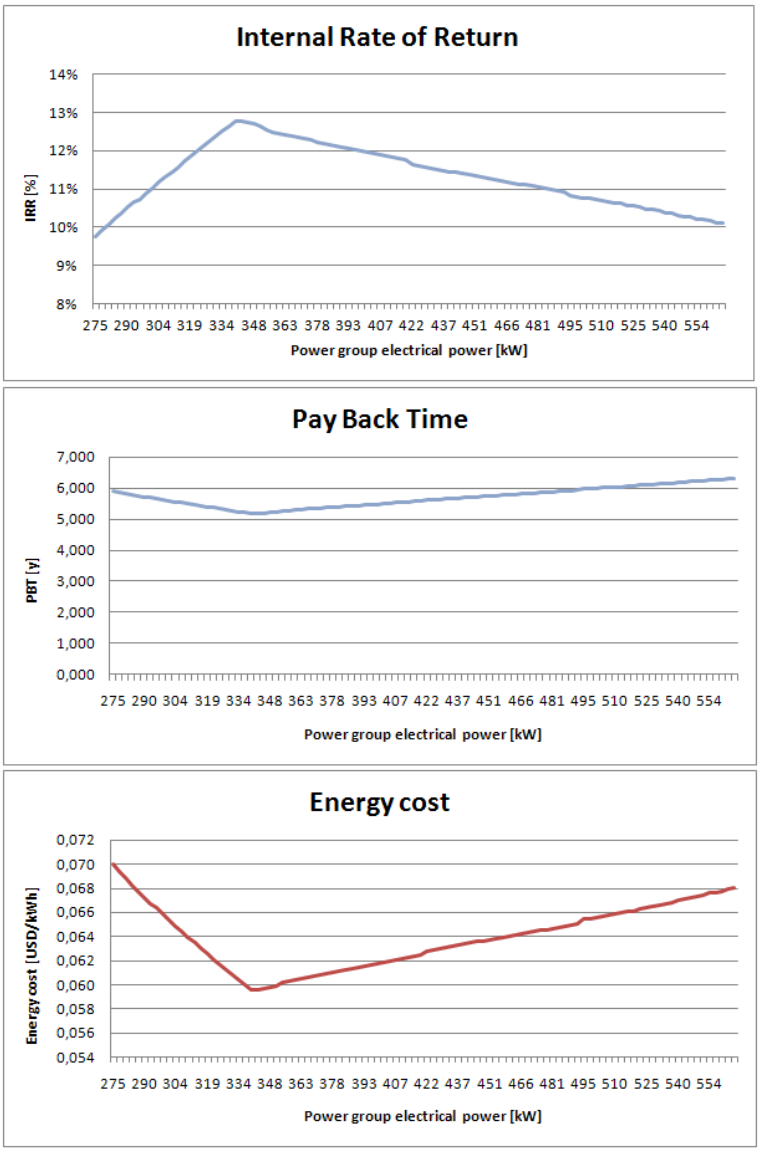



Figure 21.16.: Technical parameters variation charts

When the simulation is finished, it is possible to choose the parameter to optimize. Pushing the related button (Fig. 21.17), another macro will compute the power for which the given parameter reaches its maximum/minimum. Then it will print out the values of all the other technical and economical parameters related to that power.

| Maximize annual productivity | | Maximize Net Present Value | |
|---|---|---|---|
| Max annual productivity power [kW] | 342,61 | Max Net Present Value power [kW] | 342,61 |
| Equivalent hours [h] | 8287 | Equivalent hours [h] | 8287 |
| Operative hours [h] | 8760 | Operative hours [h] | 8760 |
| Power plant load factor | 1,00 | Power plant load factor | 1,00 |
| Annual productivity [MWh] | 2839,06 | Annual productivity [MWh] | 2839,06 |
| Investment cost [USD] | 1.359.693 | Investment cost [USD] | 1.359.693 |
| NPV [USD] | 626.046 | NPV [USD] | 626.046 |
| PBT [y] | 5,21 | PBT [y] | 5,21 |
| Levelized Energy Cost [USD/kWh] | 0,0596 | Levelized Energy Cost [USD/kWh] | 0,0596 |
| IRR % | 12,78% | IRR % | 12,78% |

Maximize AP | Maximize NPV

| Minimize Levelized Energy Cost | | Maximize Internal Rate of Return | |
|---|---|---|---|
| Min Levelized Energy Cost power [kW | 342,61 | Max Internal Rate of Return power [kV | 342,61 |
| Equivalent hours [h] | 8287 | Equivalent hours [h] | 8287 |
| Operative hours [h] | 8760 | Operative hours [h] | 8760 |
| Power plant load factor | 1,00 | Power plant load factor | 1,00 |
| Annual productivity [MWh] | 2839,06 | Annual productivity [MWh] | 2839,06 |
| Investment cost [USD] | 1.359.693 | Investment cost [USD] | 1.359.693 |
| NPV [USD] | 626.046 | NPV [USD] | 626.046 |
| PBT [y] | 5,21 | PBT [y] | 5,21 |
| Levelized Energy Cost [USD/kWh] | 0,0596 | Levelized Energy Cost [USD/kWh] | 0,0596 |
| IRR % | 12,78% | IRR % | 12,78% |

Minimize LEC | Maximize IRR

Figure 21.17.: Maximize/minimize and output

In this case the power which maximizes the annual productivity, Net Present Value, Internal Rate of Return and minimizes the Levelized Energy Cost is the same, and precisely 342,61 $kW$. Sometimes this might not happen and, changing the parameter of optimization, the optimum power can vary slightly.

### 21.4.3. Results

Here the results for a 'Power group electrical power' ($GP_{nom}$) equal to 342,61 $kW$ are shown, this value of power can be rounded off to 340 $kW$, with two parallel Francis of 170 $kW$ each (Fig. 21.18). The power plant specific cost decrease from the first configuration to 3990 $USD/kW$, because the turbine size is now balanced with the grid total length.

Results a positive $IRR$ value of 12,78%, the levelized cost of energy ($LEC$) value is 0,060 $USD/kWh$ and the PBT is 5,21 years.

The second configuration is surely better than the first solution, the investment seems to be profitable and the energy request by preferential loads is satisfied all over the year, with a load factor ($LF_{plant}$) value equal to 1.

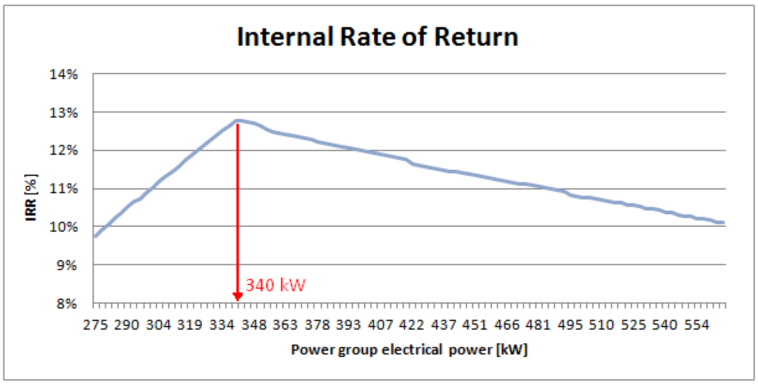



Figure 21.18.: Makete, second configuration $IRR$ trend

The estimated investment cost ($IC$) assumes the increased value of 1,36 million $USD$. The investment cost distribution through the different parts is shown below in the first pie chart, the second chart shows the detailed hydraulic works while the third shows the detailed electro-mechanical cost distribution.

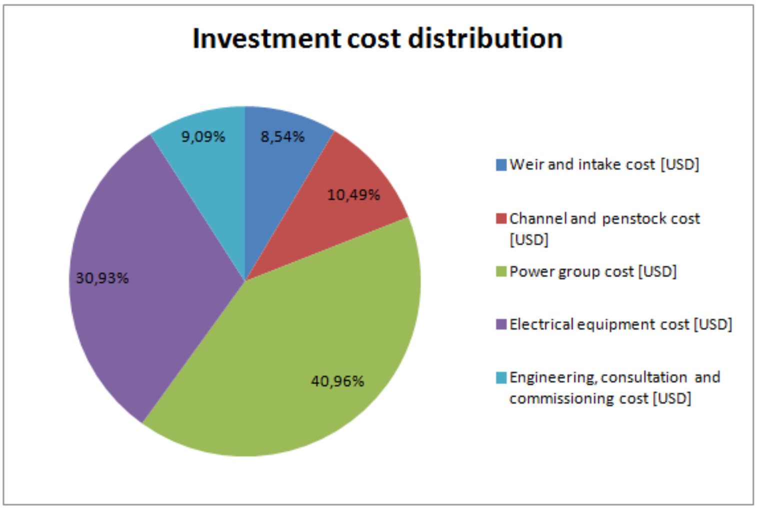
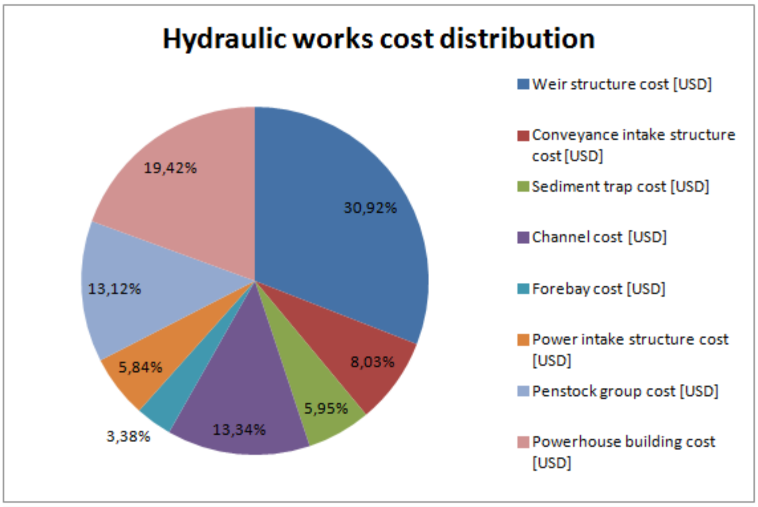



Figure 21.19.: Makete, second configuration cost distribution

Moving from 160 kW ($1^{st}$ configuration) to 340 kW, power group and transformers increase their costs, as well as the transmission grid (which is 3 km longer than the $1^{st}$ configuration). This makes the power group and the electrical equipment (grid and transformers) increase their share in the investment cost distribution, from 40,83% to 40,96% and from 29,96% to 30,93% respectively.



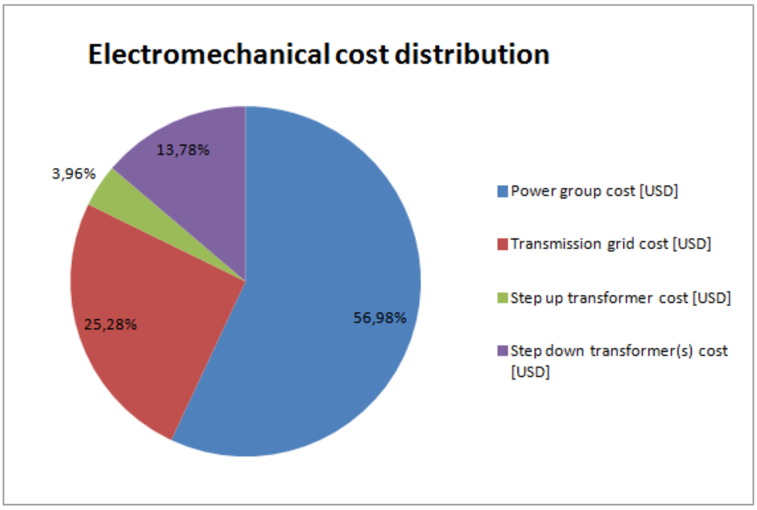




Figure 21.20.: Makete, second configuration detailed cost distribution

Regarding the hydraulic works, all the components increase their costs due to the bigger power, the only component which keeps its dimensions and cost is the weir, which clearly reduces its share from 40,59% to 30,92%.

Analyzing the plant productivity is possible to notice that the power group is not yet able to take advantage of the whole river potential, in fact the productivity trend doesn't follow the hydrograph distribution, but is limited by the turbines maximum power.

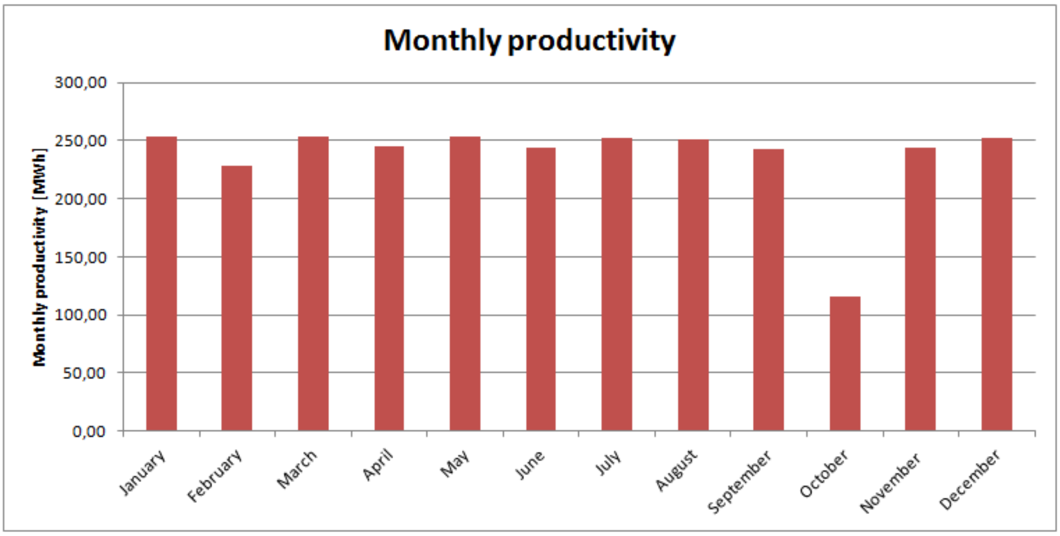



Figure 21.21.: Makete, second configuration productivity

The software provides also dimensional drawings of the hydraulic components of the hydropower plant.

The trapezoid weir rises up the gross head of the stream and diverts the water to the intake, the protective walls support the banks of the river and bring water to the weir.

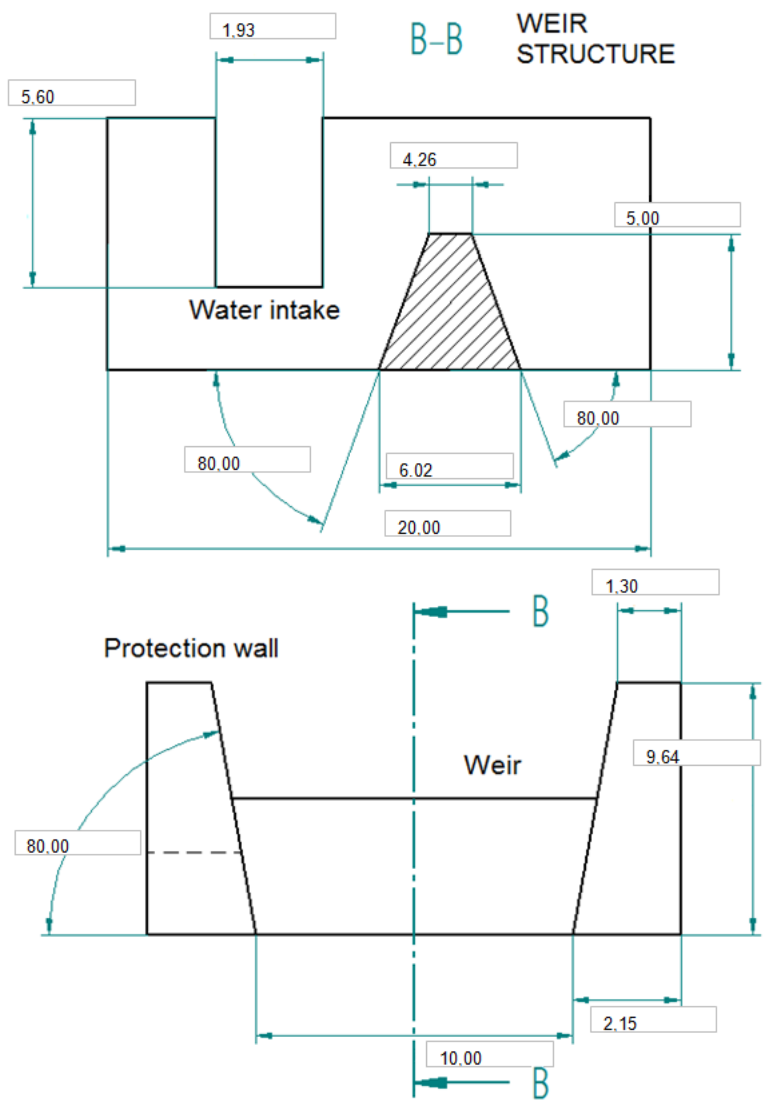



Figure 21.22.: Weir dimensional drawing

The conveyance intake structure holds a trashrack in front of the main power gate to stop the floating debris to entering the channel while the gate is open. The sliding gate is located between two pillars, that allow to move it regulating the water flow.

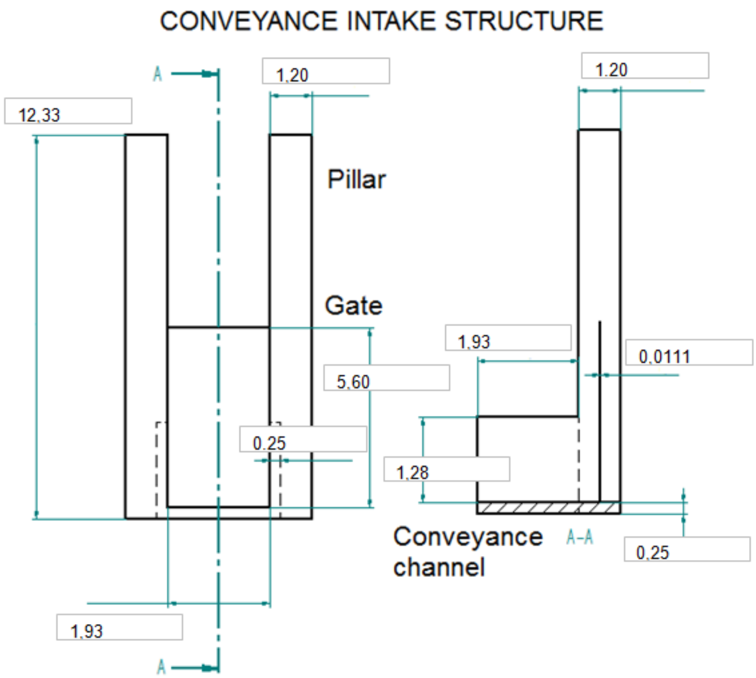



Figure 21.23.: Conveyance intake dimensional drawing

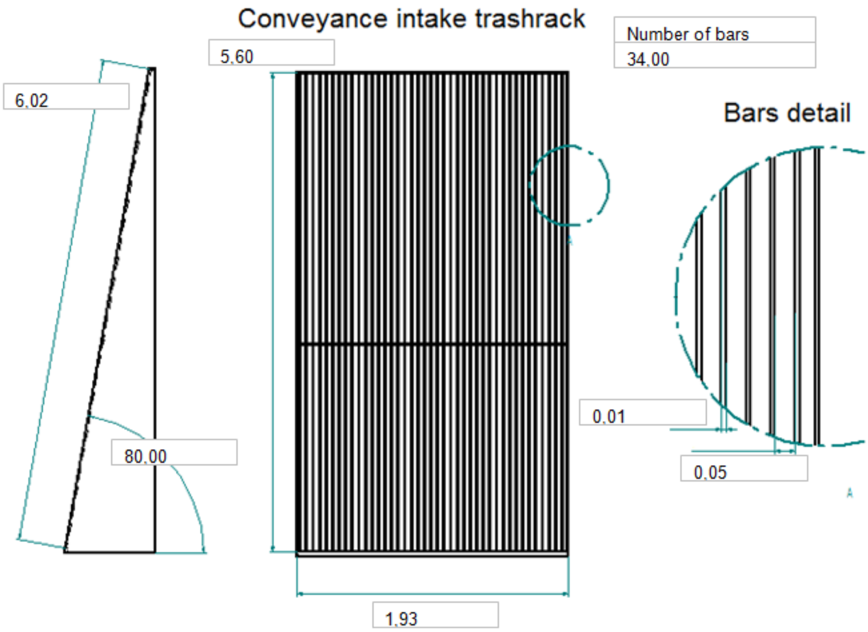



Figure 21.24.: Conveyance intake dimensional drawing (trashrack)

The trap prevents sand particles to enter the channel. The sand settles on the bottom of the trap and is periodically flushed away via a flushing gate.

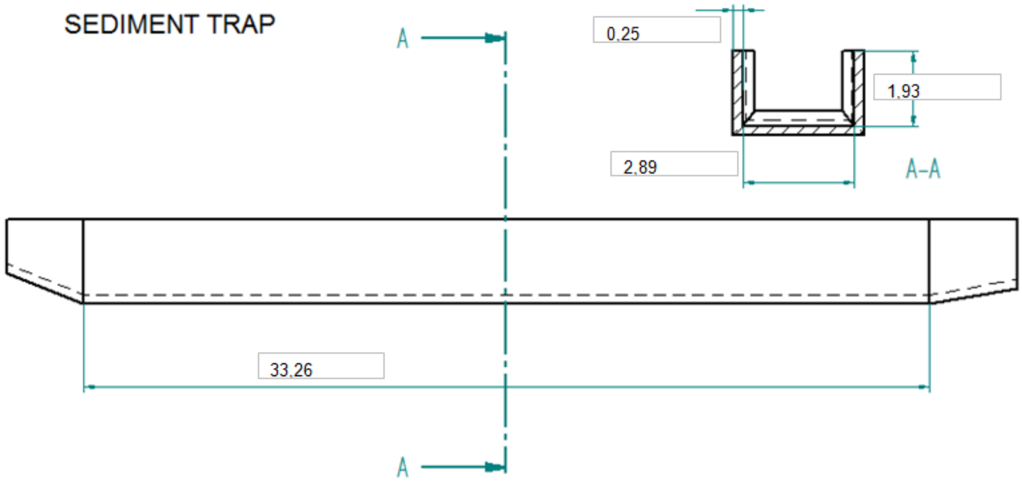



Figure 21.25.: Sediment trap dimensional drawing

The section of the 141 $m$ length channel is shown below, both the rectangular and trapezoid type, even if only the trapezoid have been used in this simulation. The channel runs down from the sediment trap to the forebay with the hydraulic gradient $(S)$ as a medium slope.

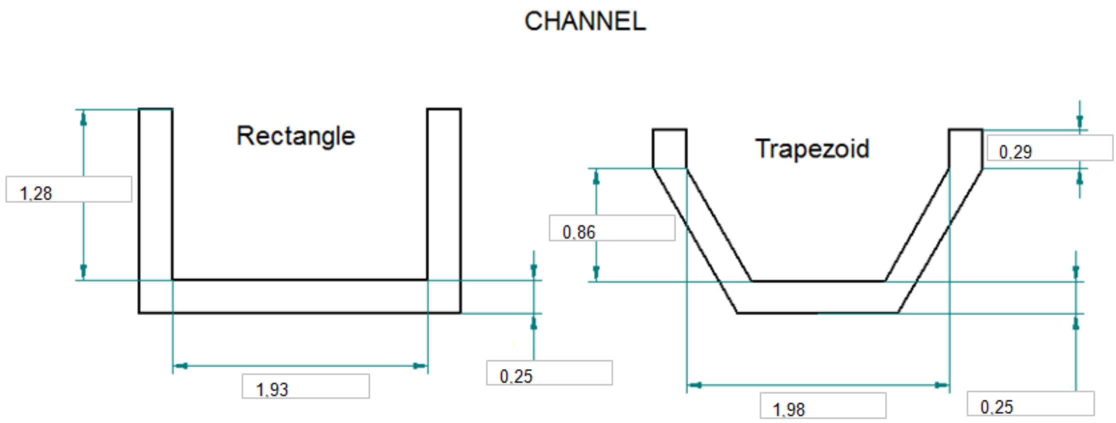



Figure 21.26.: Channel dimensional drawing

The forebay is a small water tank that is able to ensure the power continuity during small fluctuations of the water supply. The channel enters the forebay from one side, while on the bottom of the opposite side the power intake is located. Even the forebay is equipped with a flushing gate to periodically clean up its bottom from debris.

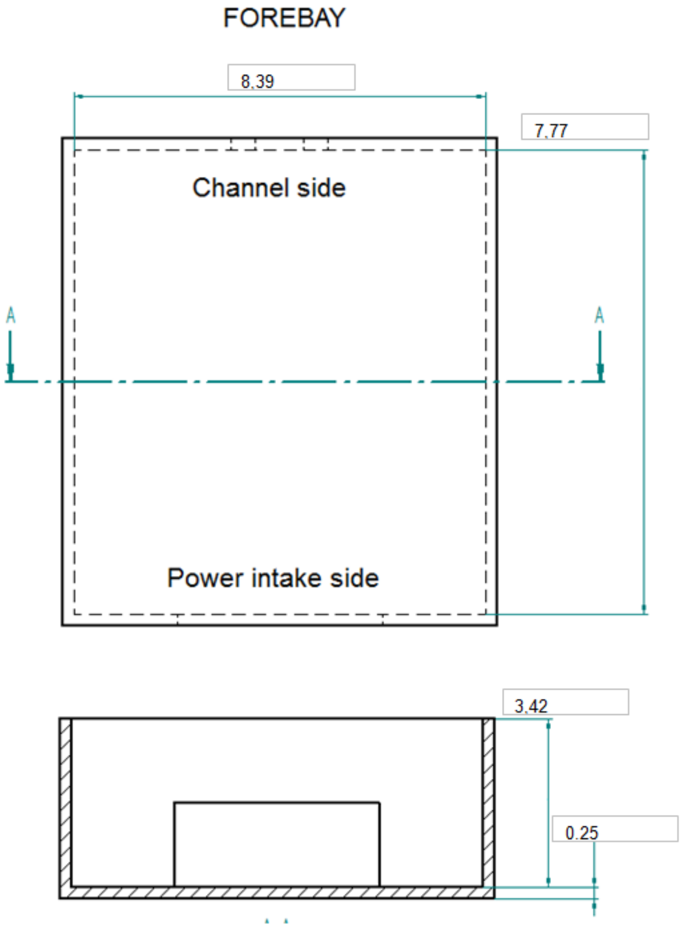



Figure 21.27.: Forebay dimensional drawing

The large side of the power intake is protected by a second trashrack, that prevents the remaining floating debris to enter the penstocks. On the small side, the inlets of penstocks are located side by side.

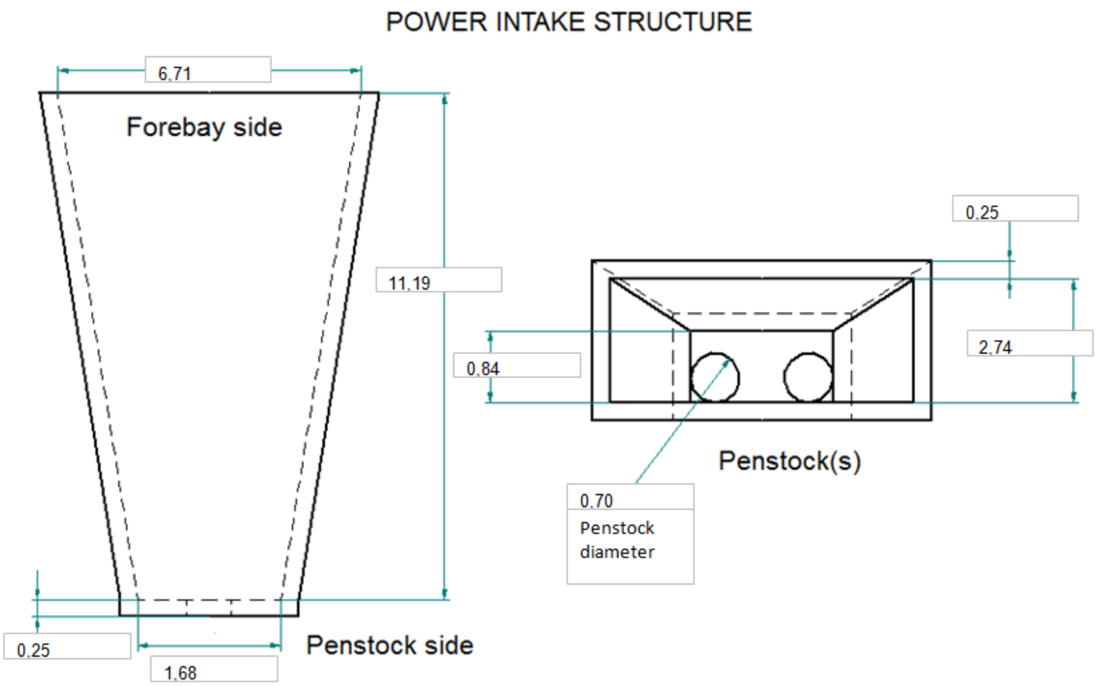



Figure 21.28.: Power intake dimensional drawing

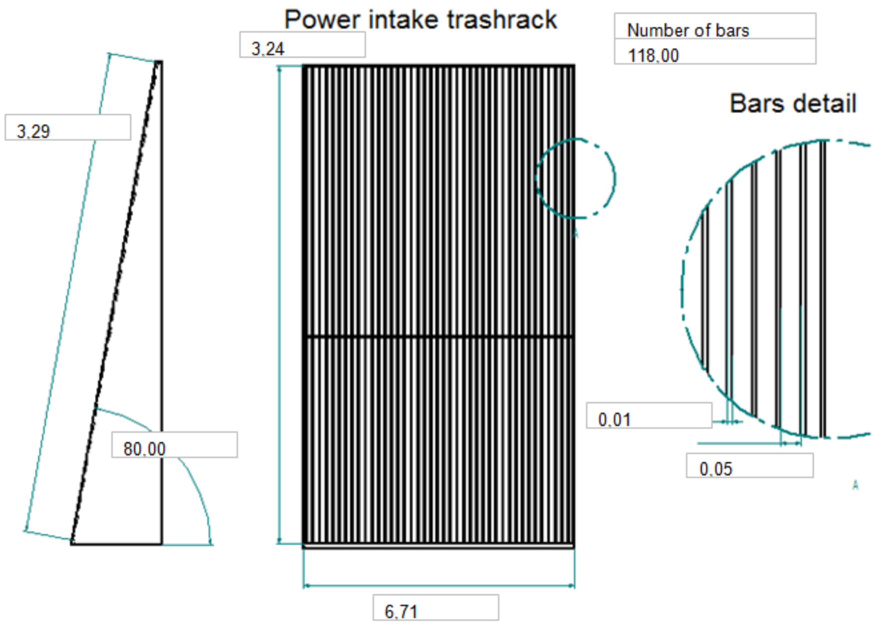



Figure 21.29.: Power intake dimensional drawing (trashrack)

The maximum gap between turbine axis and discharge water level indicates that, overcoming that value, the turbines will suffer cavitation problems. The building is divided into thow main sections: 'Control room' holding control systems and electrical equipment, 'Power room' holding turbines and generators. The small parallelepipeds represent the turbine groups, that are located side by side within the building. The spacing between the different groups allows to perform maintenance over the machines. The penstocks enter the building through the wall on which the turbines are laid.

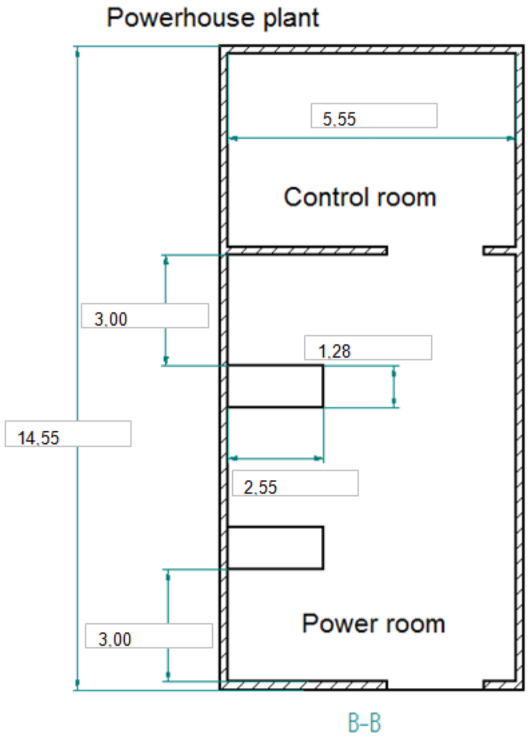



Figure 21.30.: Powerhouse dimensional drawing (plant)

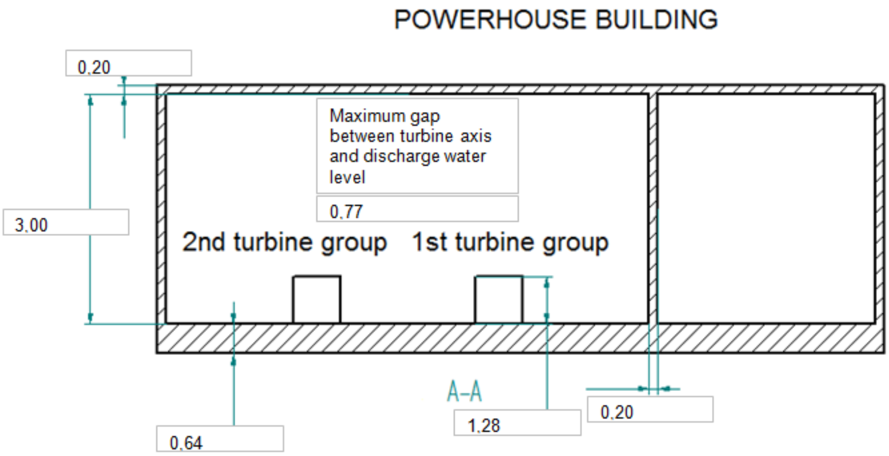



Figure 21.31.: Powerhouse dimensional drawing (section)

## 21.5. Third configuration

### 21.5.1. Layout

The last configuration provides the connection to the national grid. The connection would solve different problems, like supply continuity during dry season, unpredictable floods or maintenance, and displacement of the excess energy. The nearest connection point is located in the Makete village, around 48 $km$ from Tandala village. Adding the local grid of the second configuration a total value of 60,5 $km$ has been reached. Remember that the software uses for the MV connection a wood pole line with ACSR (Aluminium Conductors Steel Reinforced) cables, 100 $mm^2$ of section, with a specific cost of about 16600 $USD/km$, so the cost of the transmission grid for such configuration amounts around 1 million of $USD$.

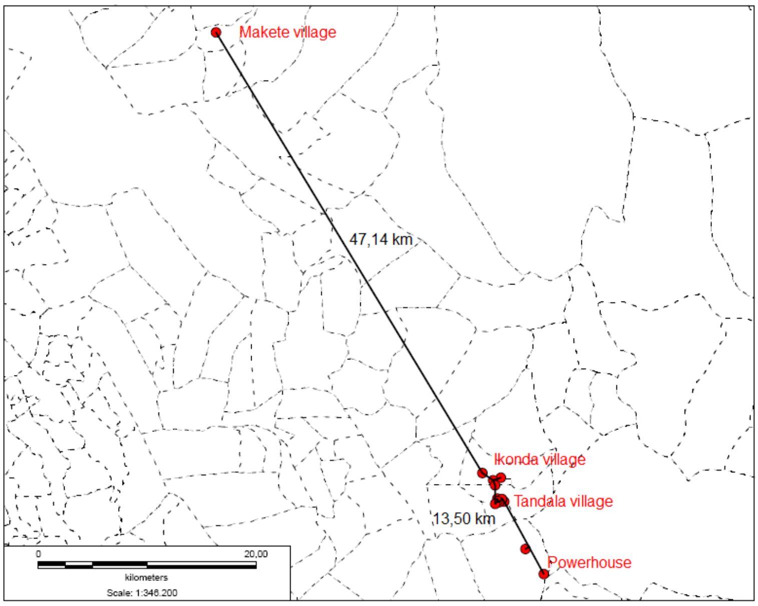



Figure 21.32.: Makete, third configuration grid map

At this point the hydropower plant supply continuity is no more a problem, so a single Francis turbine can be used instead of two parallel turbines. Besides, falling the utilities bound, the electrical power ($GP_{nom}$) that maximize the productivity is the same that optimizes the economic efficiency of the investment (Fig. 21.33).

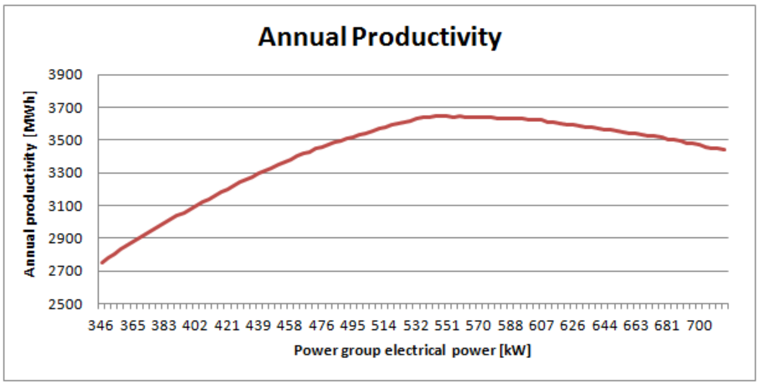



Figure 21.33.: Makete, third configuration *AP* trend

### 21.5.2. Results

The value of 540 $kW$ is indicated by the software as the optimum, but a rounded standard power of 500 $kW$ could be used with slight differences. Using the 500 $kW$ value the investment ($IC$) reaches the great amount of 2,27 million $USD$. As expected the transmission grid plays a main role in the cost distribution, as shown in the pie chart (Fig. 21.34).

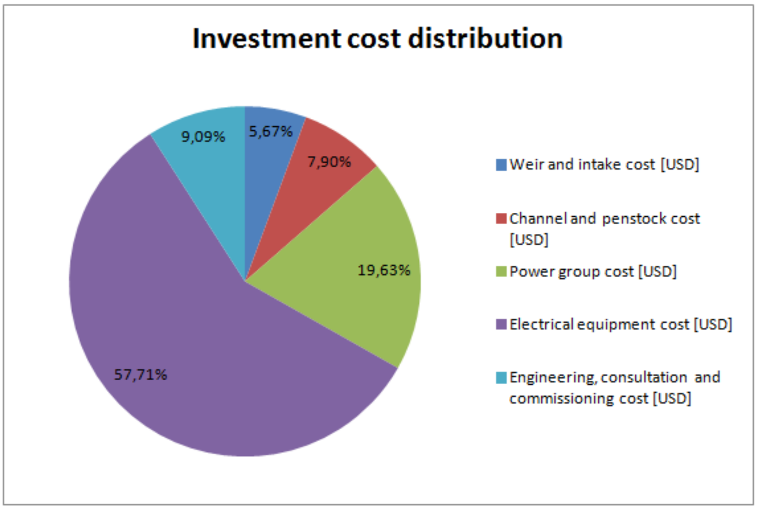



Figure 21.34.: Makete, third configuration cost distribution

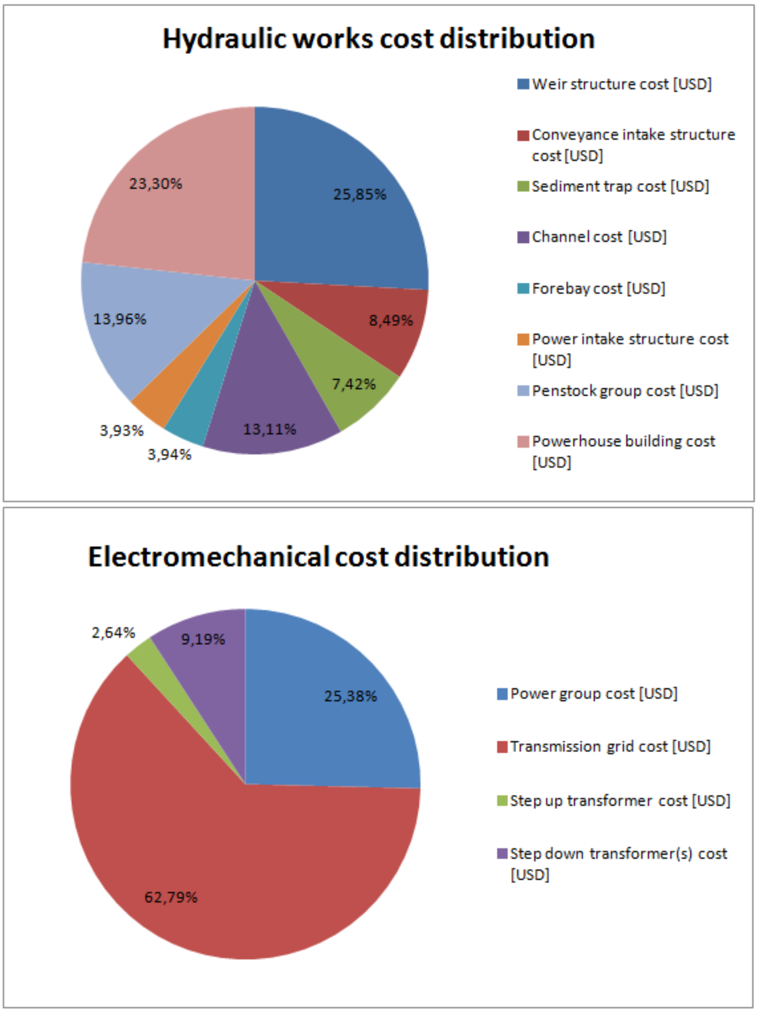



Figure 21.35.: Makete, third configuration detailed cost distribution

The power plant specific cost increase, from the second configuration, to the value of 4550 $USD/kW$, the $LEC$ returns a value of 0,076 $USD/kWh$, the $IRR$ results 8,21%; even in the last configuration the investment results quite profitable.

## 21.6. General conclusion

Summarizing: the second configuration maximizes the profitability of the investment, with an installed power of 340 $kW$ and an $IRR$ value of 12,78%; in the third configuration the $IRR$ decrease to 8,21% but the installed power of 500 $kW$ is the optimum value to take advantage of the whole river potential, besides the diaconical centre and nearby villages result connected to the national grid, according to the tanzanian national plan for rural electrification. At the end the third configuration seems to be the most suitable for the Makete hydropower project.

Only one big problem stands: can the rural utilities really afford the national price of electric energy? Some information about the 'Willingness to pay' of the rural utilities, have been taken from a prefeasibility study on the Zege village of about 3600 inhabitants, located within Usambara Mountains, in Tanga region. From interviews with local people an annual price of about 200 $USD$ for a 'One kiloWatt' connection for standard loads, and of about 320 $USD$ for business loads, have been extrapolated (Ref. [TaTEDO]).

Then applying the 'Power contract' in the second configuration, that is the most profitable, an $IRR$ negative value of -2,49% has been computed. Therefore the optimization can be always carried out to find the optimum 'Power group electrical power' ($GP_{nom}$) value, but to know with certainty if the investment will generate an appreciable financial gain, is essential to deal with the local utilities and quantify their willingness to pay.

Table below riassumes all the results for each configuration.

| Parameter | $1^{st}$config. | $2^{nd}$config. | $3^{rd}$config. |
|---|---|---|---|
| Optimum power [kW] | 160 | 340 | 500 |
| Equivalent hours [h] | 8461 | 8335 | 7069 |
| Operative hours [h] | 8760 | 8760 | 6552 |
| Power plant load factor | 1,00 | 1,00 | 0,75 |
| Annual productivity [MWh] | 1354 | 2834 | 3534 |
| Investment cost [million USD] | 0,98 | 1,36 | 2,27 |
| Specific plant cost [USD/kW] | 6103 | 3989 | 4549 |
| NPV [USD] | -372299 | 624542 | 63142 |
| PBT [y] | 7,84 | 5,20 | 6,99 |
| Levelized Energy Cost [USD/kWh] | 0,100 | 0,060 | 0,076 |
| IRR % | 3,08 | 12,78 | 8,21 |

Table 21.3.: Makete, simulation output

# 22. Application on other sites

## 22.1. Madaba in Rural Songea district

### 22.1.1. Site description

Madaba town is located along the Songea-Njombe highway in Songea district and the location of the mini hydro plant is at the Lingatunda falls in Lilondi River. The falls are very steep which make it suitable for the development of the hydro electrical power generation having a maximum head of 160 $m$.

On the right river bank, from the falls to downstream, exists a very steep slope through a head difference of about 200 $m$ (Fig. 22.1). However, this side is not suitable based on the fact that the construction would be very difficult, as it will require sophisticated machinery for the installation of the penstock and its supports. On the left side of the river bank, there is a slight gentle slope which makes it easy to access the proposed powerhouse location as well as rather simple to construct the hydropower components. On this side there is also a possibility of providing an access path or road to the power house. It is on this side through which the team members managed to walk down to the proposed power house locations.


Figure 22.1.: Madaba falls

There are three options for powerhouse placement (Fig. 22.2):

1. With the powerhouse placed in P1 the head is maximum, equal to 160 $m$ and the penstock length is about 560 $m$.
2. With the powerhouse placed in P2 the head is equal to 120 $m$ and the penstock length is about 484 $m$.
3. With the powerhouse placed in P3 the head is equal to 80 $m$ and the penstock length is about 430 $m$.

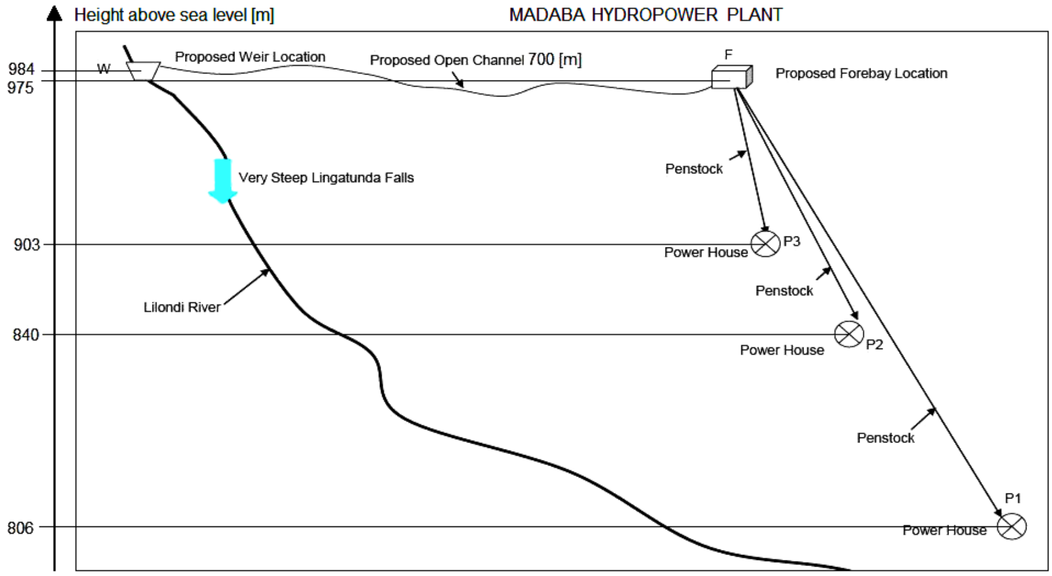



Figure 22.2.: Madaba, pre-feasability layout

The rainfall season in the catchment area of Lilondi River is from December to April. The low flows in the river are observed in the months of October and November. However, based on the experience obtained from the villagers, it is believed that the low flows does not fall to more than half of the normal flow during the rain season. The flow reported here of 2,5 $m^3/s$ is based on an estimate made during the site visit in May, an so it can be considered the maximum flow. The low flow has been computed as half of the maximum flow, that is 1,25 $m^3/s$. The soil formation is composed of rocks and stiff soils which is suitable for power house foundation.

Madaba is economically a very active centre. Institutions also exist, like the Livestock Training Institute (LITI), banks, a health centre, primary and secondary Schools and some government offices. Commercial businesses are also substantial in number including grain milling machines, residential houses, communication towers and small shops and workshops. The GPS coordinates of these load centers were registered during the pre-feasability study, and their distances computed using the GIS software *Map_ Info_* ®, the possible transmission grid layout is shown in the figure below.

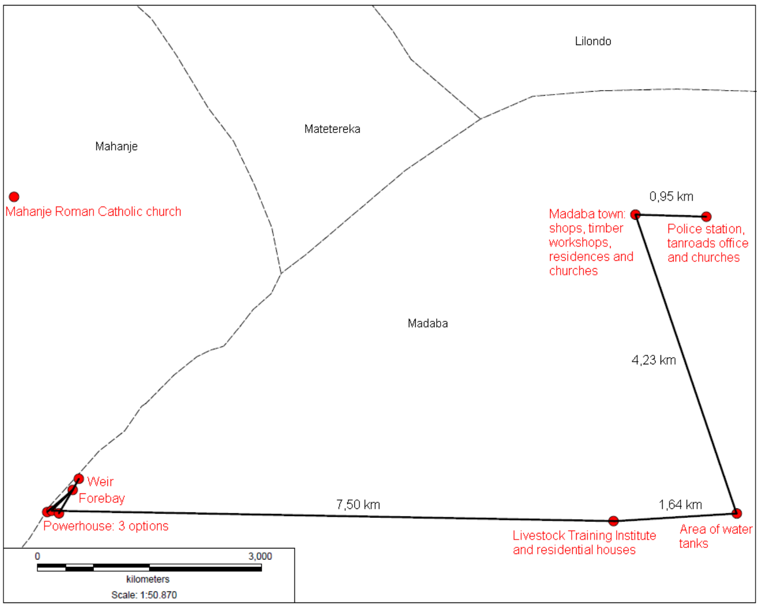



Figure 22.3.: Madaba, grid map

It was decided not to connect the isolated Mahanje Roman Catholic church on the left because extending the transmission grid, for such a low load, would have been economically unsustainable.

### 22.1.2. Sensitive data

The table below summarizes the input used in the hydropower plant simulations, the data linked to utilities are the same for the different configurations, while the ones linked to the plant layout change from case to case and they will be listed at the beginning of the related section (Ref. [DIT2]).

| Location | | River features | |
|---|---|---|---|
| Latitude | -9,920908 | Hydrograph input type | Computed |
| Longitude | 35,282466 | Min g. flow ($HY_{min}$) [$m^3/s$] | 1,25 |
| Weir altitude A.M.S.L. [$m$] | 984 | Minimum gauge period | October |
| Gross project Head ($GH$) [$m$] | 160 | Max g. flow ($HY_{max}$) [$m^3/s$] | 2,50 |
| Project head loss % ($hl_{nom}$) | 8% | Maximum gauge period | May |
| | | Residual flow ($rf$) % | 10% |
| **Power group** | | **Electrical equipment** | |
| Turbine type | Pelton | Grid length ($L_{grid}$) [$km$] | 14,33 |
| Turbine number ($TN$) | 2 | Utilities acces points ($UA$) | 4 |
| Nominal power group electrical power ($GP_{nom}$) [$kW$] | - | Electrical equipment transport cost coefficient ($tf$) | 1,10 |
| Turbine tr. cost coefficient ($tf$) | 1,30 | Annual maintenance hours [$h$] | 400 |
| **Weir and intake** | | **Channel and Penstock** | |
| Ground type | Medium | Channel layer material | Concrete |
| Weir lenght ($WL$) [m] | 5,00 | Channel section shape | Trapezoid |
| Weir height ($WH$) [m] | 2,00 | Channel length [$m$] | 200 |
| Weir material | Armed concrete | Channel hyd. grad. ($S$) [$m/m$] | 0,0450 |
| Trashrack bars shape | Circular | Penstock material | Steel |
| Building material transport cost coefficient ($tf$) | 1,30 | Penstock length [$m$] | 560,00 |
| | | Penstock deposition type | External |
| **Economic parameters** | | **Utilities** | |
| Estimated service life ($SL$) [$y$] | 30 | Utilities min power ($UMP$) [$kW$] | 150 |
| Discount rate % ($r$) | 8% | Utilities peak power ($UPP$) [$kW$] | 275 |
| Engineering, consultation and commissioning cost % ($ecc$) | 10% | Utilities load factor ($LF_{utilities}$) | 0,60 |
| Energy price valuation ($EP$) [$USD/kWh$] | 0,0920 | Connection price for preferential loads ($PCP$) [$USD/kW$] | - |
| | | Connection price for standard loads ($SCP$) [$USD/kW$] | - |

Table 22.1.: Madaba sensitive data

The table 22.2 shows in the first row the rainfall data collected by the Madaba gauging station, in the second the 'Rainfall to Hydrograph' results, monthly discretized. Besides the obtained hydrograph curve and flow duration curve are shown in the figure 22.4.

| Month | January | February | March | April | May | June |
|---|---|---|---|---|---|---|
| Rainfall ($RA_{(t)}$) [$l/m^2$] | 253 | 218 | 302 | 263 | 63 | 5 |
| Hydrograph ($HY_{(t)}$) [$m^3/s$] | 2,33 | 2,49 | 2,43 | 2,55 | 2,50 | 2,00 |
| Month | July | August | September | October | November | December |
| Rainfall ($RA_{(t)}$) [$l/m^2$] | 2 | 3 | 3 | 9 | 63 | 167 |
| Hydrograph ($HY_{(t)}$) [$m^3/s$] | 1,35 | 1,17 | 1,25 | 1,25 | 1,48 | 2,00 |

Table 22.2.: Madaba Hydrograph

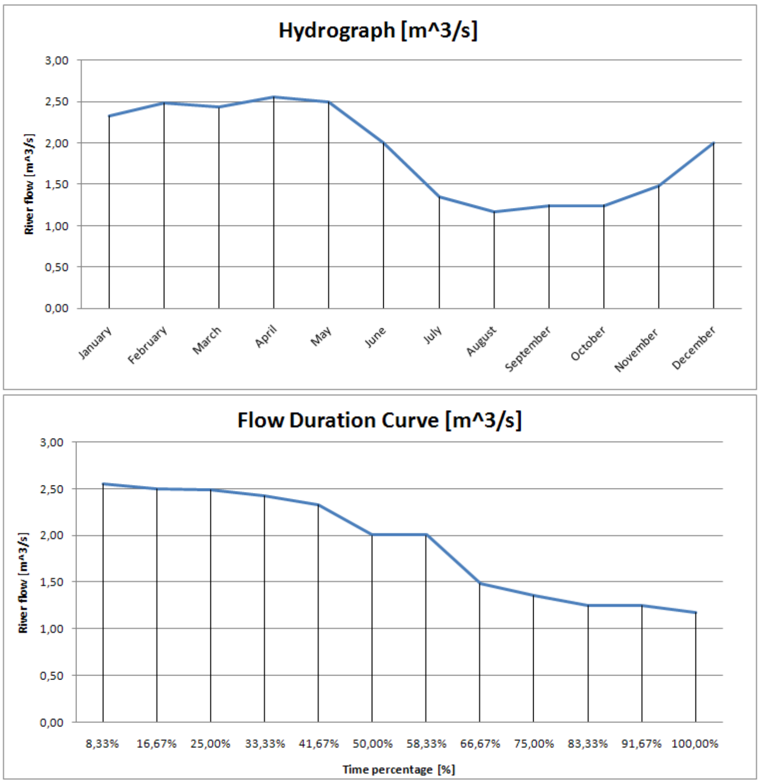



Figure 22.4.: Hydrograph and FDC for Lilondi river

The power required by the utilities was estimated as follows:

- Livestock Training Institute (25 kW).
- Timber workshops (50 kW).

- Madaba Health Centre (15 kW).
- Primary and secondary schools (60 kW).
- Banks (20 kW).
- Milling machines (50 kW).
- Police station (5 kW).
- Tanroads office (5 kW).
- Two churches (10 kW).
- Madaba town (population: 8800 ; 660 $kW$).

All the utilities except for the 80% of Madaba town has been set to preferencial loads, for a total of 397 $kW$. The maximum utilities power demand (including standard load) is equal to 925 $kW$.

### 22.1.3. First configuration

In this configuration the powerhouse il located in position P1 (Fig. 22.2), that means a gross head of 160 $m$ and a penstock length of 560 $m$. The great head is suitable for a pelton turbine and because of the relevant river potential two machines were installed, this increases a bit the investment cost but facilitate the transport, since the site is not well connected with big roads.

The choice of the 'Power group electrical power' ($GP_{nom}$) falls to 568 $kW$ (284 $kW$ for each turbine), which maximize both the $NPV$ (about 2,5 million $USD$) and $IRR$ (26,07%), over this value the annual productivity does not increase anymore because the energy purchase limit is reached.

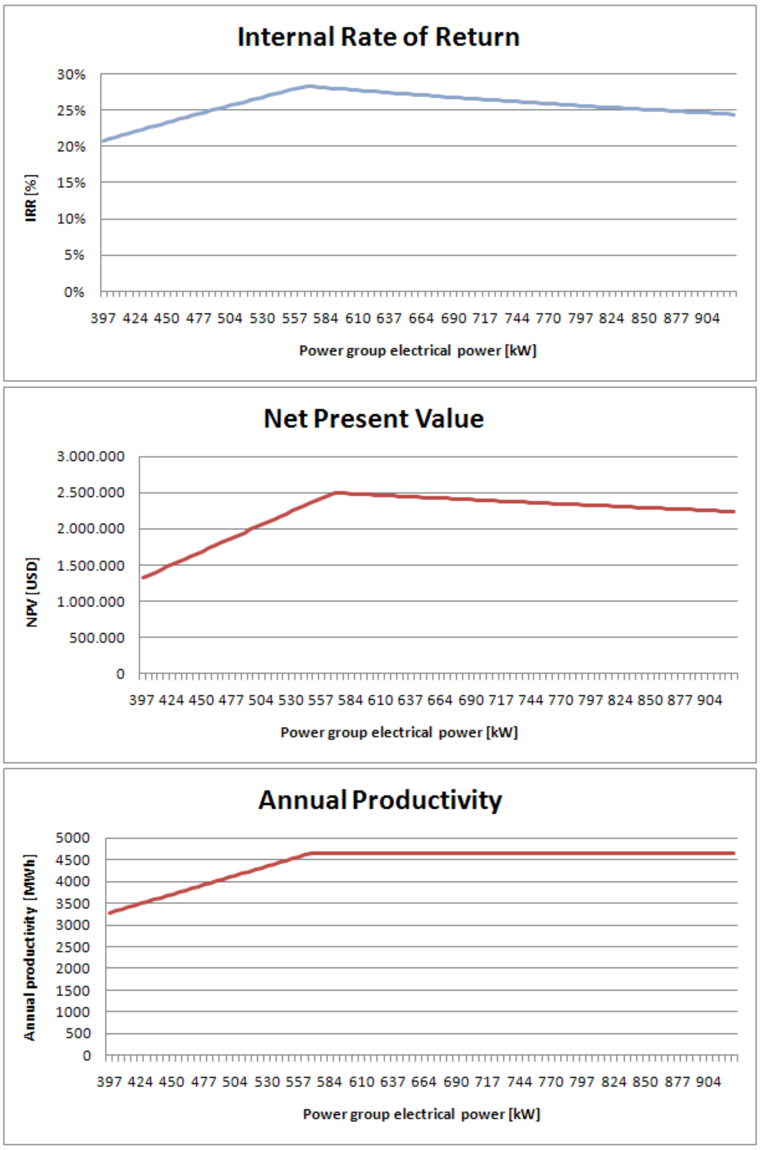



Figure 22.5.: Madaba, IRR, NPV and Productivity

In this simulation the TANESCO energy price for general usage of 157 $TZS/kWh$ or 0,092 $USD/kWh$ was used.

Due to the great income produced by the investment and shown by the high $IRR$ value, cheaper tariff could be assumed for these rural utilities in further simulations.

Other output of the economic analysis for $GP_{nom}$ equal to 568 $kW$ are the $PBT$ with a value of 3,1 years and the Levelized Energy Cost of 0,034 $USD/kWh$ . The investment cost ($IC$) is about 1,32 million $USD$, therefore the specific plant cost is 2332 $USD/kW$, this makes the project economically sustainable.

The investment cost distribution through different parts is shown below in the first pie chart, while the second chart shows the detailed electro-mechanical cost distribution.

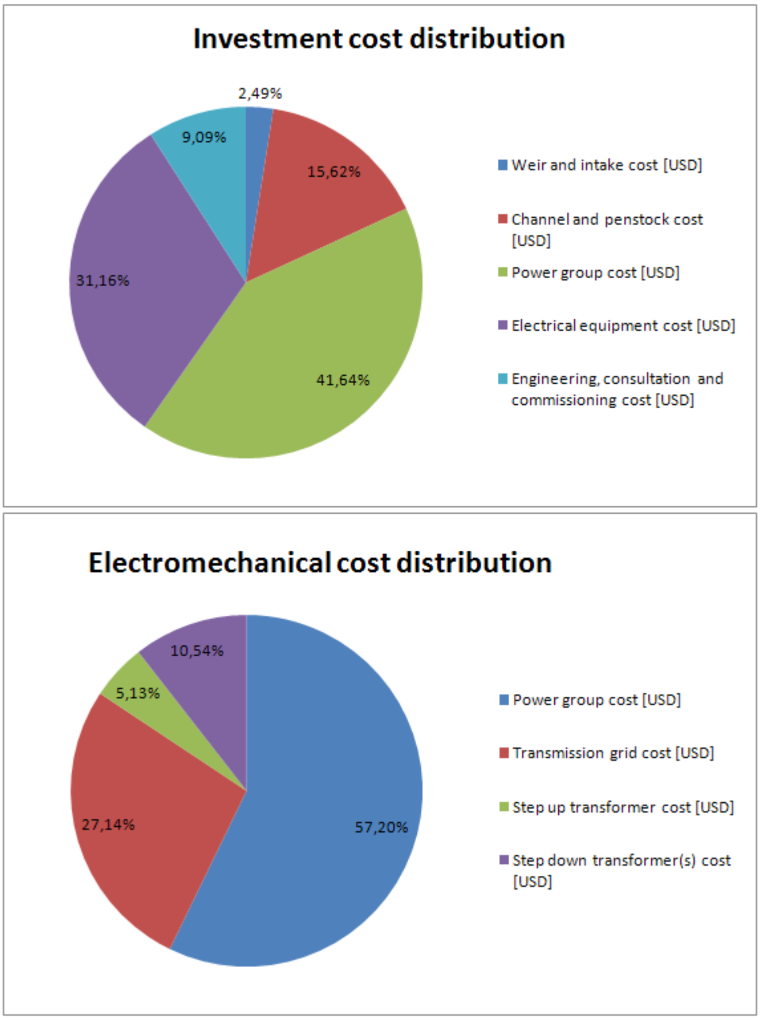



Figure 22.6.: Madaba, first configuration cost distribution

Analyzing the plant productivity is possible to notice that the power group doesn't takes advantage of the maximum river potential, in fact the energy producted every month is quite stable (except for the manteinance period in October), because it doesn't suffer the water shortage during the dry season.

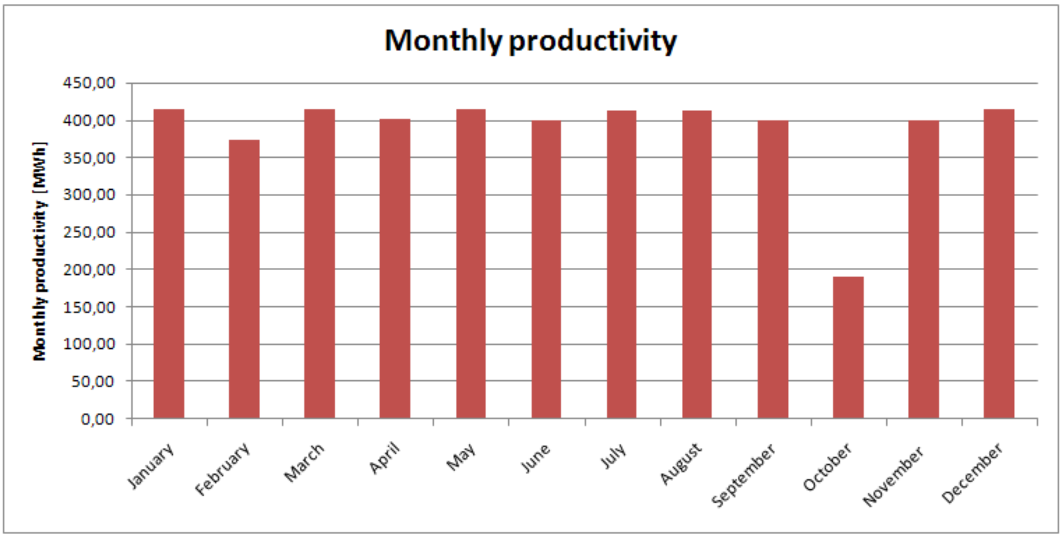



Figure 22.7.: Madaba, first configuration productivity

### 22.1.4. Second configuration

In this configuration the powerhouse in position P2, with a gross head of 120 $m$ and a penstock length of 484 $m$, and the powerhouse in position P3, with a gross head of 60 $m$ and a penstock length of 430 $m$ are analized together. The choice of two pelton turbines and other settings are manteined.

Decreasing the head from 160 to 120 $m$, and then from 120 to 80 $m$, it can be noticed that the optimum power is still 568 $kW$, the $IC$ increases slightly (1,36 and 1,42 million $USD$) because the decrease in penstock cost is balanced by the increase of turbine cost (to produce the same power with lower head turbines will need bigger discharge and therefore bigger dimensions). This makes the choice of placing the powerhouse in position P1 the best.

### 22.1.5. Third configuration

This option is characterized by the powerhouse in position P3 (therefore a penstock length of 430 $m$). The lower head (80 $m$) allows the installation of two francis turbines (the optimum power remains the same). Comparing this configuration with the first one (head of 160 $m$ with two pelton), again the decrease in penstock cost is balanced by the increase of turbine cost, resulting in very similar economic output. The investment cost increases by 45000 $USD$ and $IRR$ decrease by 0,8% but remains still very high with a value of 25,30% confirming the idea that a fees reduction is possible.

### 22.1.6. Fourth configuration

This configuration is identical to the first one except for the electricity contract type: here a power contract was chosen, so the standard loads will pay 200 $USD/kW$ while preferential ones will pay 320 $USD/kW$. These fees are more affordable for the user than the energy contract proposed by TANESCO (0,092 $USD/kWh$) and used in the previous simulation. Mantaining the power which minimize the Levelized Cost of Electricity (568 $kW$), the investment cost is obviously the same of the first configuration but incomes decrease causing a drop in $IRR$ value (from 26,1% to 7,8%) and increasing$PBT$ from 3,1 to 7,2 years.

### 22.1.7. General conclusion

As said in section 22.1.5, the choice between two pelton with a head of 160 $m$ or two francis with a head of 80 $m$ is pretty the same, thus developers could choose the turbine type which is most available from suppliers.

Regarding the tariffs, power contract is recommended because, as said in section 22.1.6, it's economically more sustainable for rural users. Moreover in this project, the high values of the investment $IRR$ allow the developers to reduce tariffs to make the electricity service more affordable also for low income households.

| Parameter | $1^{st}$config. | $2^{nd}$config. | $3^{rd}$config. | $4^{th}$config. |
|---|---|---|---|---|
| Max annual productivity power [kW] | 568 | 568 | 568 | 568 |
| Equivalent hours [h] | 8173 | 8173 | 8173 | 8173 |
| Operative hours [h] | 8760 | 8760 | 8760 | 8760 |
| Power plant load factor | 1,00 | 1,00 | 1,00 | 1,00 |
| Annual productivity [MWh] | 4640 | 4640 | 4640 | 4640 |
| Investment cost [million USD] | 1,32 | 1,36 | 1,37 | 1,32 |
| Specific plant cost [USD/kW] | 2332 | 2395 | 2413 | 2332 |
| NPV [USD] | 2495950 | 2448471 | 2439560 | -13996 |
| PBT [y] | 3,10 | 3,19 | 3,21 | 7,20 |
| Levelized Energy Cost [USD/kWh] | 0,034 | 0,035 | 0,035 | 0,034 |
| IRR % | 26,07 | 25,39 | 25,30 | 7,78 |

Table 22.3.: Madaba, simulation output

## 22.2. Macheke in Ludewa district

### 22.2.1. Site description

The Macheke hydropower plant is located in Ludewa District. The project is in Macheke village surrounded by other villages which can benefit from the project. There is also nearby a Roman Catholic mission with several social services such as a nursery school.

Some developments have been made as regards to this project: during the pre-feasability visit, an access road to the site and a bridge were under construction (see picture below).

Figure 22.8.: Macheke, bridge construction

The intake is located in the Likingo River just upstream of the falls. During the visit it was reported that once another pre-feasibility study was conducted for the same area by another team. The present team (DIT) was led to the locations proposed by the previous team. The following were the findings:

- The location for the powerhouse is near the flooding area of the river which may need a well designed protection structure. As a result it can increase the cost of construction.
- The location of the forebay is far distant from the intake point which calls for construction of an open channel of at least 500 $m$.
- The available gross head will be about 46 $m$.
- The location of the intake was chosen where there is a firm and rocky base and side banks.

The problem for powerhouse flooding led the DIT team to decide another suitable location for the powerhouse and forebay which will avoid the addressed problems but maintaining the gross head equal to or slightly above 46 $m$. Moreover the new location for the powerhouse has relatively a good foundation regardless of the fact that still will need foundation treatment, but not as the old option. Both configurations (Fig. 22.9) will be analyzed in the following sections.

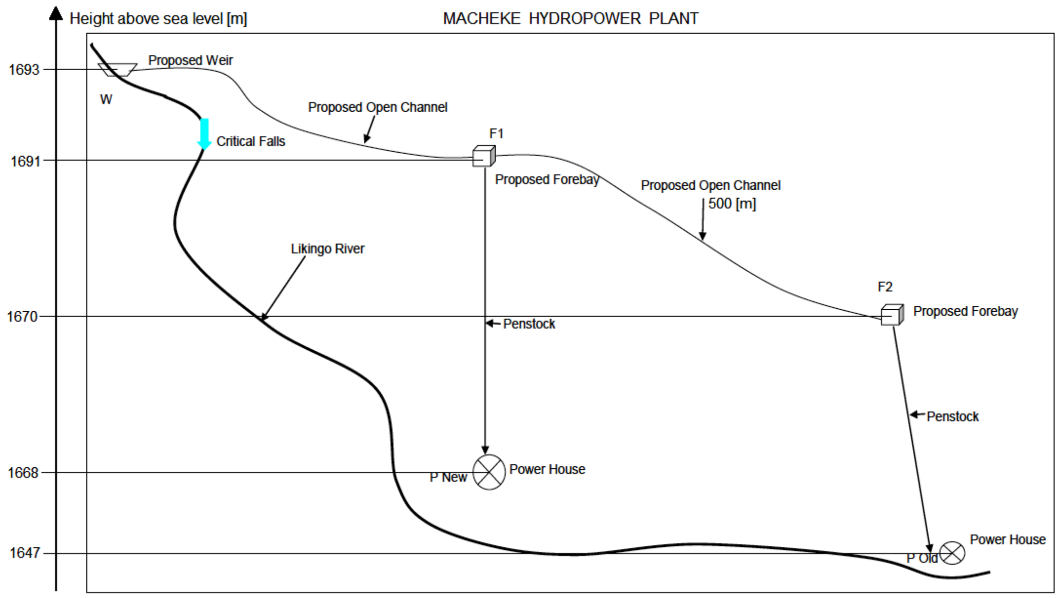



Figure 22.9.: Macheke, pre-feasability layout

The catchment area for Likingo River is characterized by heavy rainfall. The rain season is from late November to April and sometimes May. As result the variation low flow (during dry season) to maximum flow (during rainfall season) can vary by 50%. The river discharge was estimated in rain season at 1,5 $m^3/s$.

The power transmission line is proposed to originate from the proposed powerhouse location to Mlangali centre. In the way, there will be tee-off point at Mlangali Roman Catholic church to a neighbouring village of Utiriri. The common load centres in Mlangali town are the primary and secondary schools, dispensaries, residential houses, shops and small workshops, garages, communications towers and water pumps.

The GPS coordinates of these load centers were registered during the pre-feasability study, and their distances computed using the GIS software *Map_Info_*®, the possible transmission grid layout is shown in the figure below.

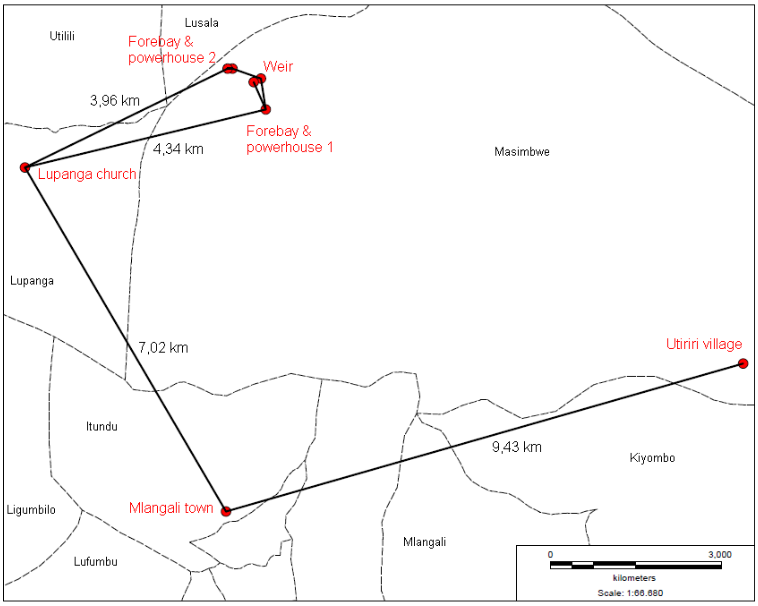



Figure 22.10.: Macheke, grid map

### 22.2.2. Sensitive data

The table below summarizes the input used in the hydropower plant simulations, the data linked to utilities are the same for the different configurations, while the ones linked to the plant layout change from case to case and they will be listed at the beginning of the related section (Ref. [DIT2]).

| **Location** | | **River features** | |
|---|---|---|---|
| Latitude | -9,703496 | Hydrograph input type | Computed |
| Longitude | 34,52374 | Min g. flow ($HY_{min}$) [$m^3/s$] | 0,7 |
| Weir altitude A.M.S.L. [$m$] | 1693 | Minimum gauge period | September |
| Gross project Head ($GH$) [$m$] | 48 | Max g. flow ($HY_{max}$) [$m^3/s$] | 1,5 |
| Project head loss % ($hl_{nom}$) | 55% | Maximum gauge period | April |
| | | Residual flow ($rf$) % | 10% |
| **Power group** | | **Electrical equipment** | |
| Turbine type | Francis | Grid length ($L_{grid}$) [$km$] | 20,79 |
| Turbine number ($TN$) | 1 | Utilities acces points ($UA$) | 3 |
| Nominal power group electrical power ($GP_{nom}$) [$kW$] | - | Electrical equipment transport cost coefficient ($tf$) | 1,10 |
| Turbine tr. cost coefficient ($tf$) | 1,10 | Annual maintenance hours [$h$] | 400 |
| **Weir and intake** | | **Channel and Penstock** | |
| Ground type | Soft | Channel layer material | Concrete |
| Weir lenght ($WL$) [m] | 8 | Channel section shape | Trapezoid |
| Weir height ($WH$) [m] | 3 | Channel length [$m$] | 552 |
| Weir material | Armed concrete | Channel hyd. grad. ($S$) [$m/m$] | 0,042 |
| Trashrack bars shape | Circular | Penstock material | Steel |
| Building material transport cost coefficient ($tf$) | 1,10 | Penstock length [$m$] | 526,00 |
| | | Penstock deposition type | External |
| **Economic parameters** | | **Utilities** | |
| Estimated service life ($SL$) [$y$] | 30 | Utilities min power ($UMP$) [$kW$] | 70 |
| Discount rate % ($r$) | 8% | Utilities peak power ($UPP$) [$kW$] | 443 |
| Engineering, consultation and commissioning cost % ($ecc$) | 10% | Utilities load factor ($LF_{utilities}$) | 0,60 |
| Energy price valuation ($EP$) [$USD/kWh$] | 0,0920 | Connection price for preferential loads ($PCP$) [$USD/kW$] | 320 |
| | | Connection price for standard loads ($SCP$) [$USD/kW$] | 200 |

Table 22.4.: Macheke sensitive data

Notice that the 'Project head loss %' ($hl_{nom}$) has been set to an high value of 55% because the channel is very long and sloping, therefore it introduces great head losses. Only one francis turbine has been chosen because the construction of the new road and bridge should make the transport quite simple. This is why also the turbine and building material transport coefficient have been set to a low value of 1,1.

The table 22.5 shows in the first row the rainfall data collected by the Macheke gauging station, in the second the 'Rainfall to Hydrograph' results, monthly discretized. Besides the obtained hydrograph curve and flow duration curve are shown in the figure 22.11.

| Month | January | February | March | April | May | June |
|---|---|---|---|---|---|---|
| Rainfall ($RA_{(t)}$) $[l/m^2]$ | 233 | 215 | 239 | 186 | 62 | 5 |
| Hydrograph ($HY_{(t)}$) $[m^3/s]$ | 1,47 | 1,50 | 1,48 | 1,50 | 1,45 | 1,24 |
| Month | July | August | September | October | November | December |
| Rainfall ($RA_{(t)}$) $[l/m^2]$ | 2 | 1 | 2 | 8 | 84 | 206 |
| Hydrograph ($HY_{(t)}$) $[m^3/s]$ | 0,88 | 0,77 | 0,70 | 0,77 | 0,94 | 1,30 |

Table 22.5.: Macheke Hydrograph

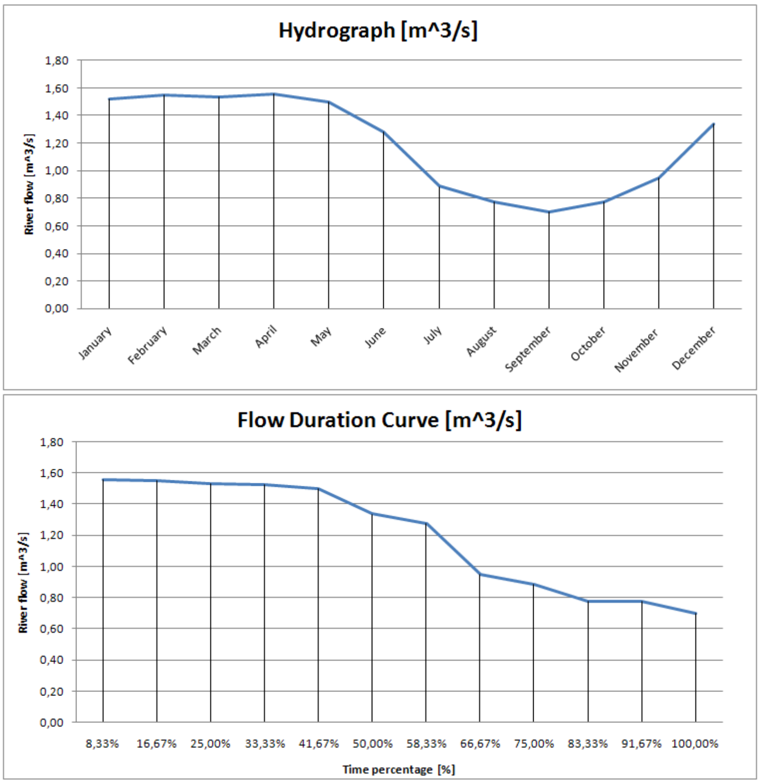



Figure 22.11.: Hydrograph and FDC for Likingo river

The power required by the utilities was estimated as follows:

- Lupanga church (5 $kW$).
- Mount Masusa Secondary School (10 $kW$).
- Mlangali Roman Catholic church (5 $kW$).
- Mlangali CCM Office (3 $kW$).
- Primary school (10 $kW$).
- Secondary School (10 $kW$).
- Dispensaries x3 (15 $kW$).
- Shops x20 (20 $kW$).
- Small workshops x10 (30 $kW$).
- Garages x3 (15 $kW$).
- Communication towers x2 (10 $kW$).

- Pumps x5 (15 $kW$).
- Utiriri village (population: 1654 ; 124,1 $kW$).
- Mlangali town (population: 2279 ; 170,9 $kW$).

Due to the low river potential and to avoid a 'Plant load factor' less than 1, only 70 $kW$ have been set as preferential loads, this include: schools, dispensaries, communication towers and pumps.

### 22.2.3. First configuration

In the first configuration the forebay and powerhouse were considered in the new location (Powerhouse 1, Fig. 22.10).

The choice of the 'Power group electrical power' ($GP_{nom}$) falls to 250 $kW$, which maximize the annual productivity (about 1570 $MWh$) and minimize the $LEC$ (0,10 $USD/kWh$). For this power the $IRR$ is equal to 3,62% and $PBT$ is 8,26 years.

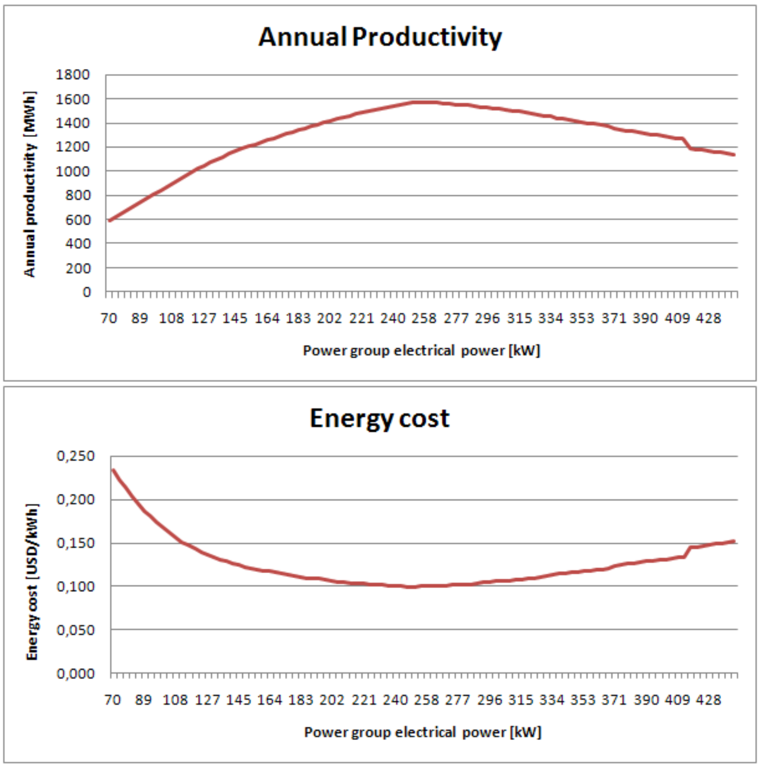



Figure 22.12.: Macheke, Productivity and LEC

In this simulation the TANESCO energy price for general usage of 157 $TZS/kWh$ or 0,092 $USD/kWh$ was used. The quite low value of $IRR$ (3,62%) doesn't not allow to decrease the tariffs, for example using a cheaper power contact, because the $IRR$ would become negative.

The investment cost (IC) is about 1,19 million $USD$, therefore the specific plant cost is 4741 $USD/kW$, this makes the project quite expensive but still doable.

The investment cost distribution through different parts is shown below in the first pie chart, while the second chart shows the detailed electro-mechanical cost distribution.

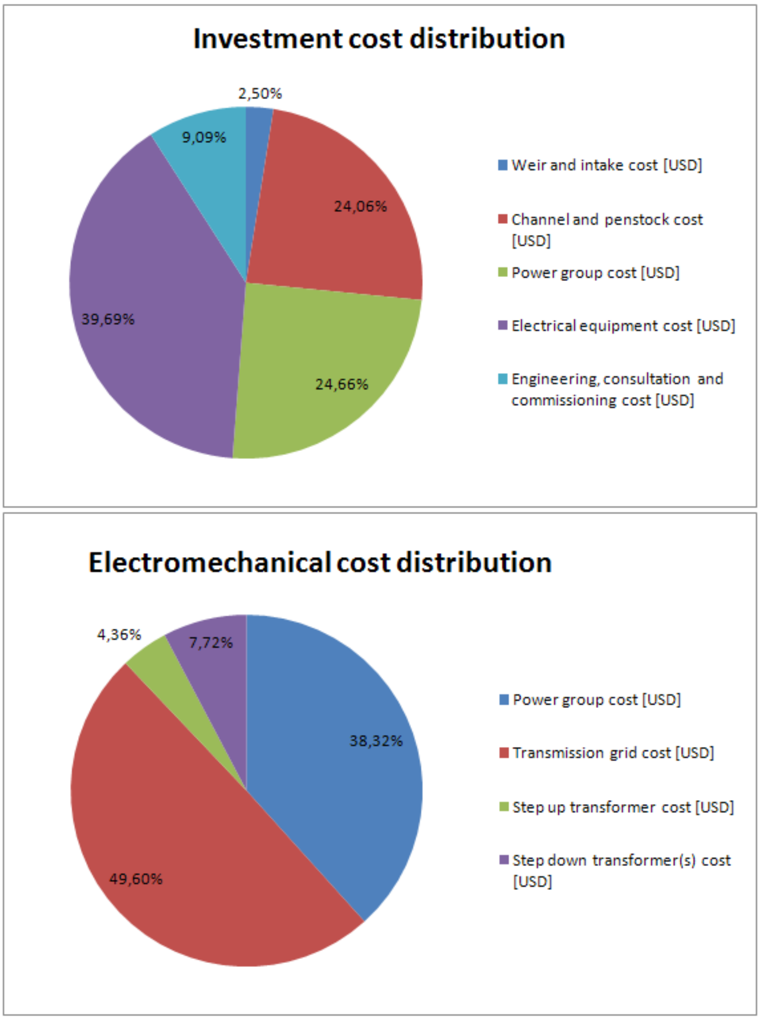



Figure 22.13.: Macheke, first configuration cost distribution

Analyzing the plant productivity is possible to notice that the power group takes advantage of the maximum river potential, in fact the energy producted every month suffer the water shortage during the dry season.

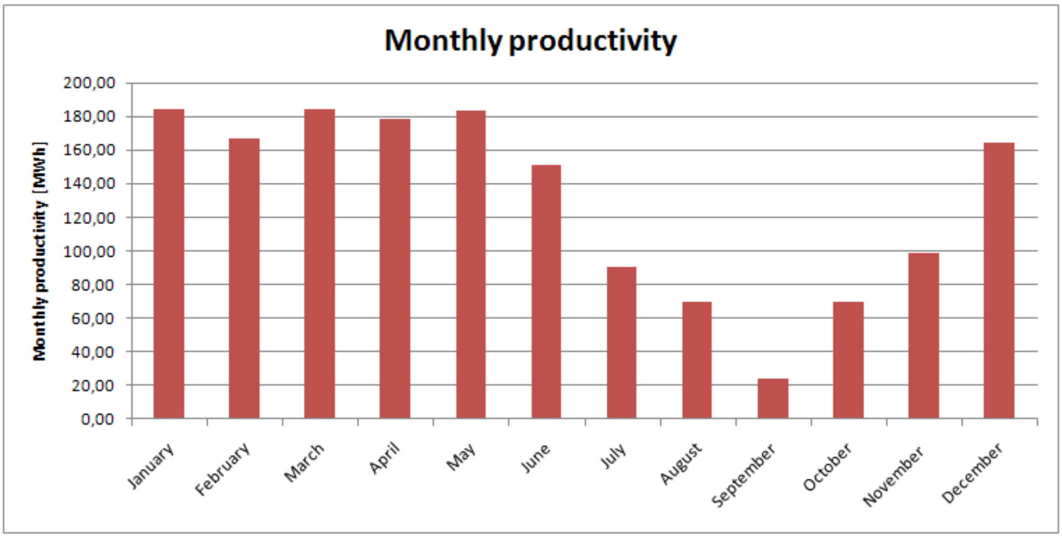



Figure 22.14.: Macheke, first configuration productivity

### 22.2.4. Second configuration

In this second option the forebay and powerhouse in the old location were considered (Powerhouse 2, Fig. 22.10). The transmission grid is a bit shorter with 20,41 $km$.

The 'Power group electrical power' ($GP_{nom}$) which maximize the annual productivity (about 1512 $MWh$) and minimize the $LEC$ (0,089 $USD/kWh$) is 240 $kW$. For this power the $IRR$ increases to the value of 5,54% while specific plant cost (4308 $USD/kW$) and $PBT$ (7,43 years) are both better than the previous simulation, all this make the second configuration winning on the economical aspect.

### 22.2.5. General conclusion

If more detailed idro-geological studies confirmed the problems in flooding and hard foundation treatment for the old location of powerhouse (Powerhouse 2, Fig. 22.10), the first configuration would be the best solution. Otherwise, if these problems could be easily solved, the second configuration should be adopted because it's economically better.

| Parameter | $1^{st}$config. | $2^{nd}$config. |
|---|---|---|
| Max annual productivity power [kW] | 250 | 240 |
| Equivalent hours [h] | 6240 | 6301 |
| Operative hours [h] | 8760 | 8760 |
| Power plant load factor | 1,00 | 1,00 |
| Annual productivity [MWh] | 1565 | 1512 |
| Investment cost [million USD] | 1,19 | 1,03 |
| Specific plant cost [USD/kW] | 4741 | 4308 |
| NPV [USD] | -412433 | -217885 |
| PBT [y] | 8,26 | 7,43 |
| Levelized Energy Cost [USD/kWh] | 0,010 | 0,089 |
| IRR % | 3,62 | 5,37 |

Table 22.6.: Macheke, simulation output

## 22.3. Mpando in Njombe district

### 22.3.1. Site description

The proposed Mpando hydropower plant is located in Imalinyi Village, Njombe District. The plant is about 30 $km$ from Njombe town and about 5 $km$ from Mangula secondary school. The proposed site was once being used by a failed mini hydroelectric plant. The site has a constructed open channel which is about 500 $m$ long, a forebay as well as a powerhouse. The previous power plant was locally fabricated. It was reported that the failure was due to the flooding of the powerhouse which resulted into short circuiting of the generator. The open channel was constructed in such a way that at one section it crosses the river downstream of the intake location as result at one time it was washed away by floods. When this happened also the powerhouse was flooded. Figure below shows the breached channel as well as the failed power plant.


Figure 22.15.: Mpando, failed plant equipment

It was decided to use the present plant layout with an alteration of the powerhouse location as well as the intake. The location of the intake is proposed to be at the breached channel (Fig. 22.16). The improvement will include the design of the weir to direct water to the existing following part of the channel, after the breach. The new powerhouse location is away from the flooding zone of the river. Also, with the new location, the head is improved of a couple of meter (15 $m$).

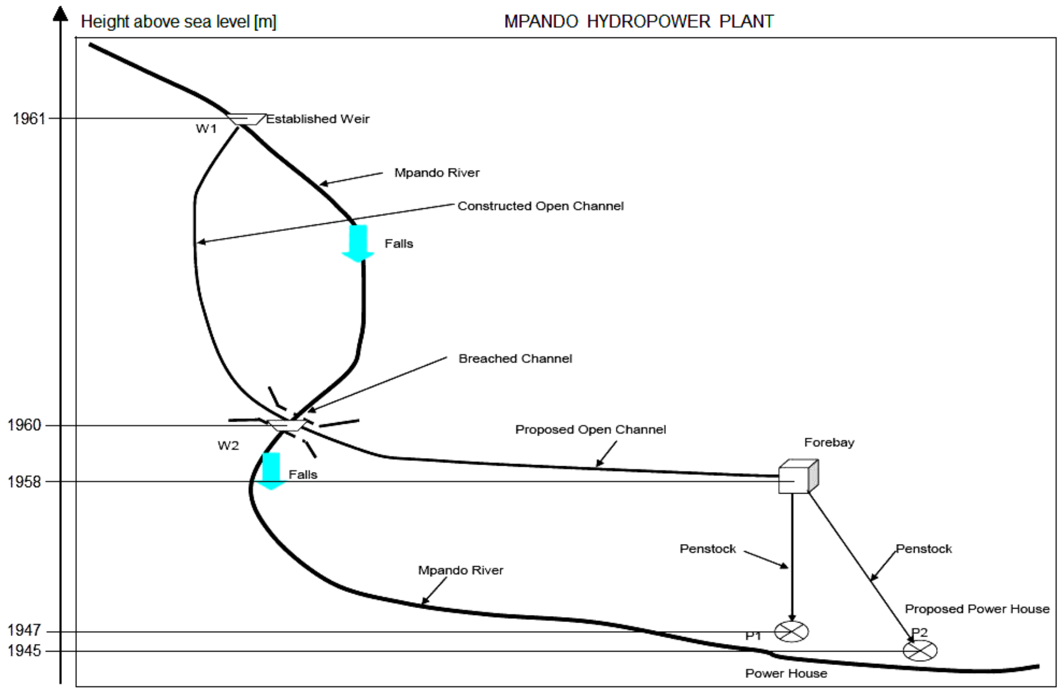



Figure 22.16.: Mpando, pre-feasability layout

The rainfall characteristics for Mpando catchment area is seasonal extending from December to April. The river experiences low flows starting from October to November and some years from September depending of the amount of rainfall. It is reported that the Mpando River low flows go down to almost quarter of the maximum base flow. During the site visit, the river discharge was estimated at 3 $m^3/s$, this was during the rain season. Based on that discharge, the low flow can be estimated at 0,75 $m^3/s$. For detailed design purposes a physical low flow measurement must be conducted.

The project area is composed of loam soil with a high possibility of erosion. Rocks were observed in the river course. This implies that the weir to be constructed will definitely lie in the river bed rocks which make a good foundation. However, the identified location for the power house will require a foundation treatment.

The power line transmission route will originate from the proposed powerhouse location to the Phillip Mangula secondary school, about 3 $km$ away. From there, will be a tee-off point to other load centers and to Imalinyi village.

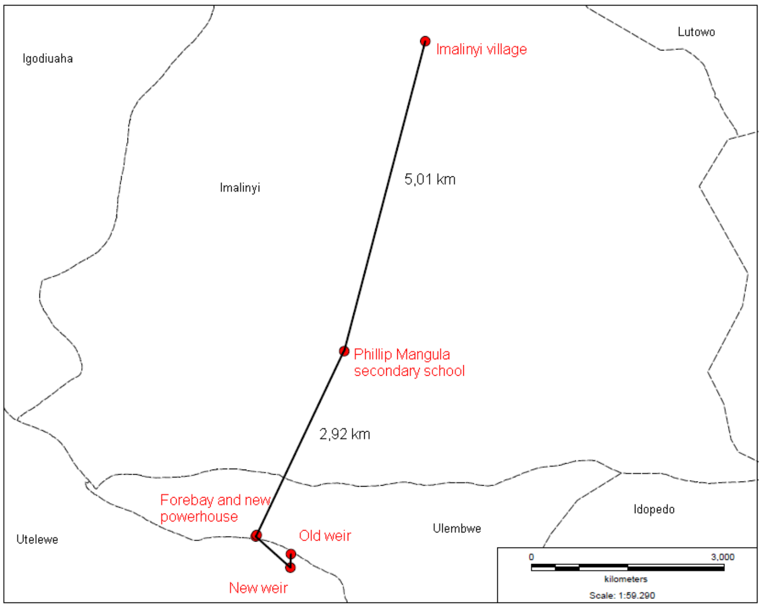



Figure 22.17.: Mpando, grid map

### 22.3.2. Sensitive data

The table below summarizes the input used in the hydropower plant simulations (Ref. [DIT2]).

| **Location** | | **River features** | |
|---|---|---|---|
| Latitude | -9,261247 | Hydrograph input type | Computed |
| Longitude | 34,60767 | Min g. flow ($HY_{min}$) [$m^3/s$] | 0,75 |
| Weir altitude A.M.S.L. [$m$] | 1961 | Minimum gauge period | September |
| Gross project Head ($GH$) [$m$] | 15 | Max g. flow ($HY_{max}$) [$m^3/s$] | 3 |
| Project head loss % ($hl_{nom}$) | 20% | Maximum gauge period | April |
| | | Residual flow ($rf$) % | 10% |
| **Power group** | | **Electrical equipment** | |
| Turbine type | Francis | Grid length ($L_{grid}$) [$km$] | 7,93 |
| Turbine number ($TN$) | 2 | Utilities acces points ($UA$) | 2 |
| Nominal power group electrical power ($GP_{nom}$) [$kW$] | - | Electrical equipment transport cost coefficient ($tf$) | 1,10 |
| Turbine tr. cost coefficient ($tf$) | 1,20 | Annual maintenance hours [$h$] | 400 |
| **Weir and intake** | | **Channel and Penstock** | |
| Ground type | Soft | Channel layer material | Rocks |
| Weir lenght ($WL$) [m] | 10 | Channel section shape | Rectangle |
| Weir height ($WH$) [m] | 3 | Channel length [$m$] | 726,4 |
| Weir material | Rocks | Channel hyd. grad. ($S$) [$m/m$] | 0,0028 |
| Trashrack bars shape | Circular | Penstock material | Steel |
| Building material transport cost coefficient ($tf$) | 1,10 | Penstock length [$m$] | 33,2 |
| | | Penstock deposition type | External |
| **Economic parameters** | | **Utilities** | |
| Estimated service life ($SL$) [$y$] | 30 | Utilities min power ($UMP$) [$kW$] | 40 |
| Discount rate % ($r$) | 8% | Utilities peak power ($UPP$) [$kW$] | 453 |
| Engineering, consultation and commissioning cost % ($ecc$) | 10% | Utilities load factor ($LF_{utilities}$) | 0,60 |
| Energy price valuation ($EP$) [$USD/kWh$] | 0,0920 | Connection price for preferential loads ($PCP$) [$USD/kW$] | - |
| | | Connection price for standard loads ($SCP$) [$USD/kW$] | - |

Table 22.7.: Mpando sensitive data

Weir and channel layer material was set on 'rocks' (which are cheaper than concrete), to reduce the cost of this two components in the investment cost computation. This because the location of the new weir is proposed to be at the breached canal point, and this will make the construction easier, while the channel already exists, and it will need only some renovation work.

The table 22.8 shows in the first row the rainfall data collected by the Mpando gauging station, in the second the 'Rainfall to Hydrograph' results, monthly discretized. Besides the obtained hydrograph curve and flow duration curve are shown in the figure 22.18.

| Month | January | February | March | April | May | June |
|---|---|---|---|---|---|---|
| Rainfall ($RA_{(t)}$) [$l/m^2$] | 263 | 221 | 256 | 105 | 12 | 4 |
| Hydrograph ($HY_{(t)}$) [$m^3/s$] | 3,02 | 3,02 | 2,89 | 3,00 | 2,40 | 1,40 |
| Month | July | August | September | October | November | December |
| Rainfall ($RA_{(t)}$) [$l/m^2$] | 1 | 1 | 5 | 28 | 145 | 262 |
| Hydrograph ($HY_{(t)}$) [$m^3/s$] | 1,06 | 0,75 | 0,75 | 1,12 | 1,73 | 2,60 |

Table 22.8.: Mpando Hydrograph

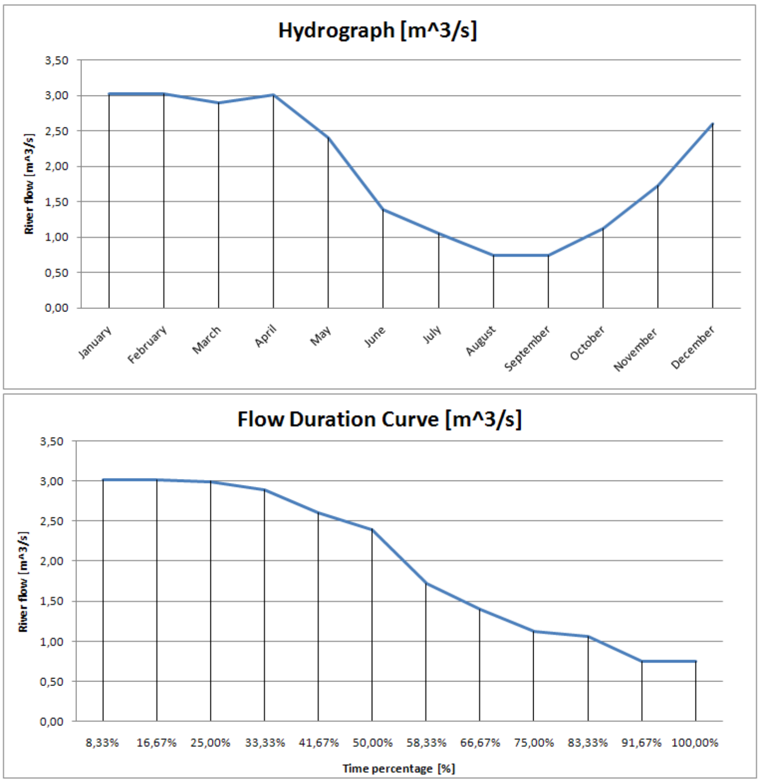



Figure 22.18.: Hydrograph and FDC for Mpando river

The power required by the utilities was estimated as follows:

- Philip Mangula secondary school (10 $kW$).
- Dispensary x3 (15 $kW$).
- Village government offices x3 (15 $kW$).
- Primary schools x3 (30 $kW$).
- Imalinyi village (population: 5107 ; 383 $kW$).

Due to the low river potential and to avoid a 'Plant load factor' less than 1, only the schools for a total of 40 $kW$ have been set as preferential loads.

### 22.3.3. First configuration

In the first configuration the powerhouse was considered in the new location (Powerhouse 2, Fig. 22.16), with a gross head of 15 $m$ and a penstock length of 33,2 $m$.

The choice of the 'Power group electrical power' ($GP_{nom}$) falls to 265 $kW$, which minimize the $LEC$ (0,102 $USD/kWh$) and maximize the $NPV$. For this power the $IRR$ is equal to 3,22% and $PBT$ is 8,57 years. Moreover the load factor chart in the picture below shows that it's not convenient to choose a power over 265 $kW$, because a bigger turbine could not work with the lowest discharge values during dry season and would not supply the minimum power requested by preferential loads, causing the drop of the 'plant load factor'.

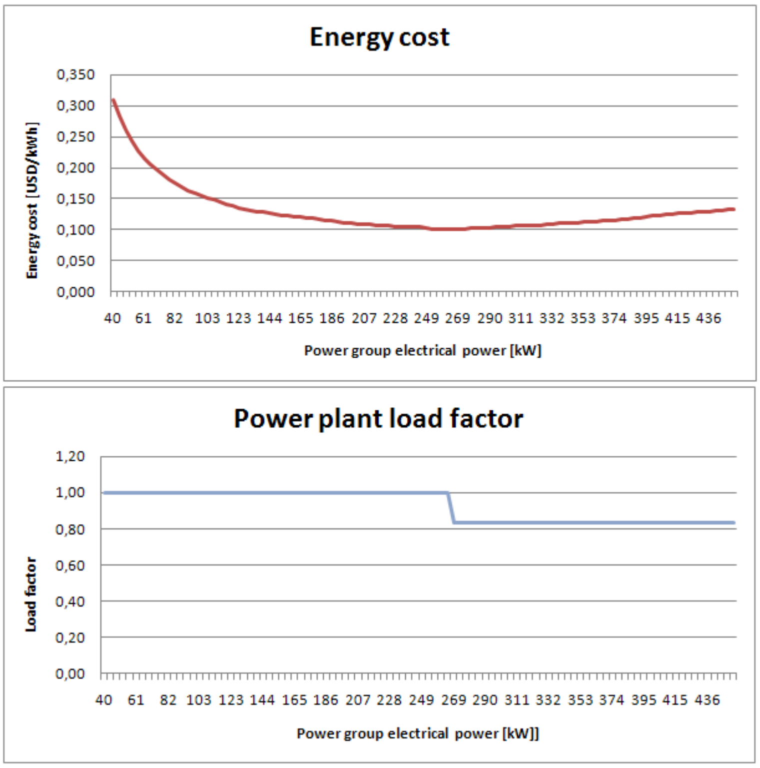



Figure 22.19.: Mpando, LEC and load factor

In this simulation the TANESCO energy price for general usage of 157 $TZS/kWh$ or 0,092 $USD/kWh$ was used. The quite low value of $IRR$ (3,22%) doesn't not allow to decrease the tariffs, for example using a cheaper power contact, because the $IRR$ would become negative.

The investment cost (IC) is about 1,17 million $USD$, therefore the specific plant cost is 4433 $USD/kW$, this makes the project quite expensive but still feasible.

The investment cost distribution through different parts is shown below in the first pie chart, while the second chart shows the detailed electro-mechanical cost distribution.

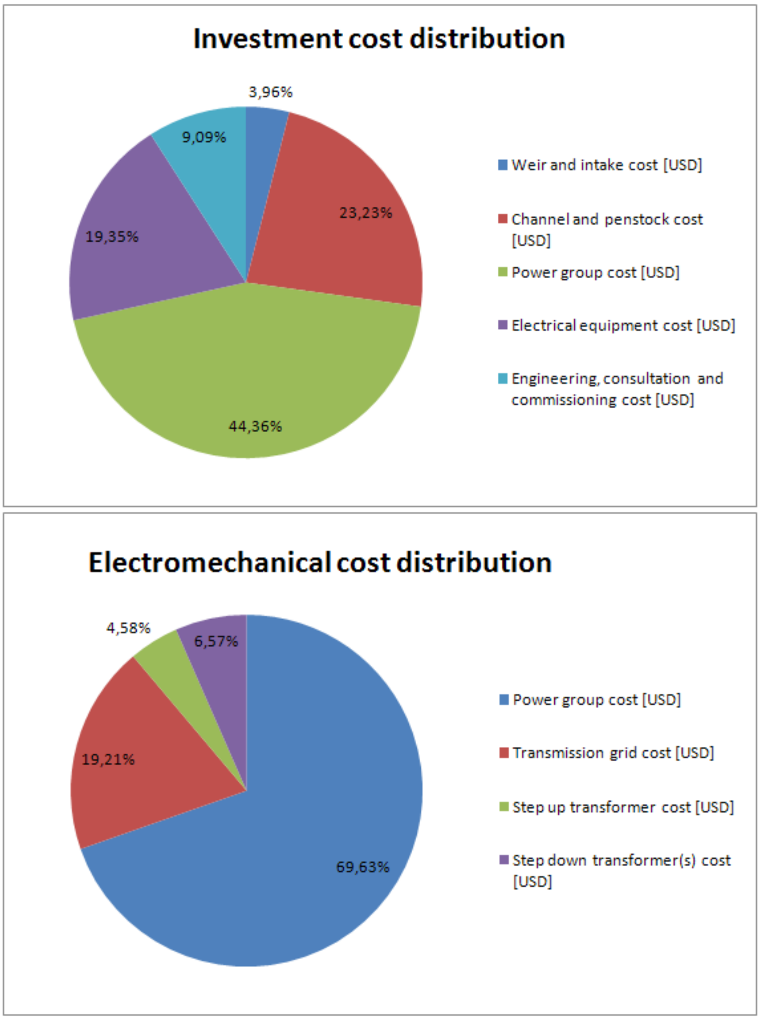



Figure 22.20.: Mpando, first configuration cost distribution

Analyzing the plant productivity is possible to notice that the power group takes advantage of the maximum river potential, in fact the energy producted every month suffer the water shortage during the dry season.

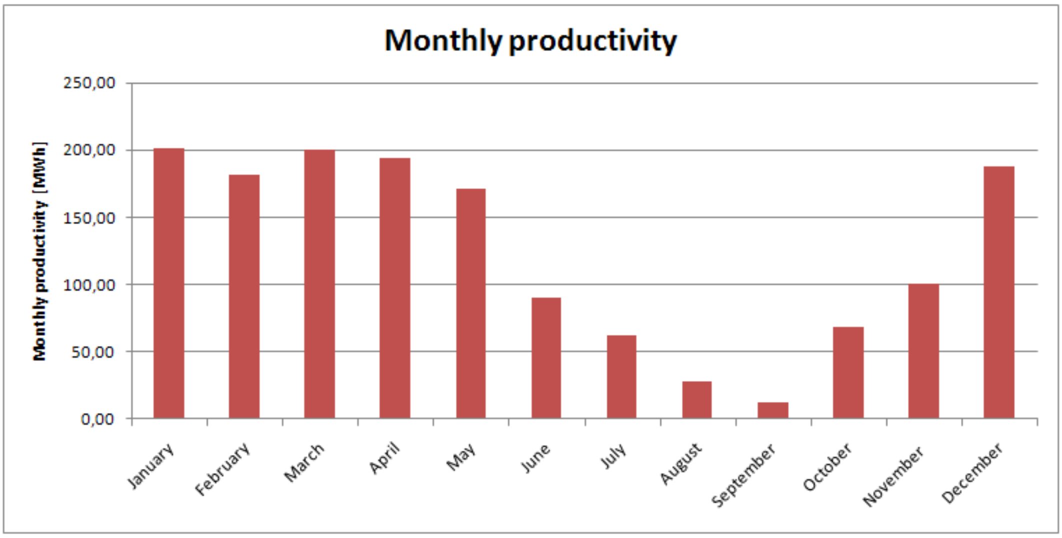



Figure 22.21.: Mpando, first configuration productivity

### 22.3.4. Second configuration

There would be the possibility to connect the plant to the nearby national grid, but this wouldn't bring great benefits, because with these utilities connected, the plant takes already advantage of the maximum river potential (Fig. 22.21).

### 22.3.5. General conclusion

The only possible solution for Mpando hydropower plant is the first configuration without connection to the national grid. This solution, using about half of the already constructed channel and the existing forebay, allow potential developers to save money in the civil works.

| Parameter | $1^{st}$config. |
|---|---|
| Max annual productivity power [kW] | 265 |
| Equivalent hours [h] | 5620 |
| Operative hours [h] | 8760 |
| Power plant load factor | 1,00 |
| Annual productivity [MWh] | 1489 |
| Investment cost [million USD] | 1,17 |
| Specific plant cost [USD/kW] | 4433 |
| NPV [USD] | -441258 |
| PBT [y] | 8,57 |
| Levelized Energy Cost [USD/kWh] | 0,102 |
| IRR % | 3,22 |

Table 22.9.: Mpando, simulation output

# 23. Conclusions

According to the main thesis objectives the following tasks have been achieved:

- The model has been developed following the main reference document "Guide on How to Develop a Small Hydropower plant" of the 'European Small Hydropower Association' (ESHA), which provides plant scheme, sizing formulas and advices on the mini hydro technology. The model has been inplemented in the software *Mini hydro plants simulator*, based on *Microsoft excel 2007 ®*. This software collects several sizing formulas taken from the ESHA, but also provides original algorithms developed to simulate carefully the features of the power plant. The *Mini hydro plants simulator* makes use of some input data, obtainable by a single survey on the desired location, to generate:

  1. An optimization of the installed electrical power, that best fits the features of both the river and the connected utilities.
  2. A first-attempt sizing of each power plant component, besides dimensional drawings of the hydraulic structures are provided by the software.
  3. A careful estimation of the power plant productivity, limited to the availability of input data.
  4. A cost valuation of each component of the hydropower plant.
  5. An economic analysis considering the cost of the power plant and the purchase ability of the connected utilities.

- During the time spent in Tanzania the model has grown taking information from the local contest. Many informations about building standards, availability and cost of components, have been taken from the DIT university and related partners. Finally the model has been tested upon the Madunda power plant, a mini hydro installation recently built by the italian NGO 'Rural Cooperation in Africa and Latin America' (ACRA). The software *Mini hydro plants simulator*, has been built attempting to make it as user friendly as possible. It follows a logical scheme to arrange the informations through the different sheets, and also the striclty structure of each sheet helps to bring on changes or developments. Besides the software has been equipped with a related 'User guide' which explains all the steps for use.

## 23.1. Matching the needs

To lead the simple users in the software utilization, an 'User guide' has been written. It's addressed to the Dar Es Salaam Institute of Technology and its connected operators: Rural Energy Agency or other sponsoring societies. The user guide provides the information needed to fill the INPUT DATA, run the simulation and read the output correctly.

In order to make clear the steps through which the software has been developed, the master thesis will be made available to the DIT team who cooperated to the project, and later to all those who will adapt the software to a different country, or will improve it.

The software *Mini hydro plants simulator* and the thesis together will provide to the Dar Es Salaam Institute of Technology the building capacity to structure the decision making about mini hydro technologies, making them a reference institution inside the Tanzanian scenery. It is hoped that these tools can lead to increase hydropower production in the country and at the same time improve rural areas access to electricity, involving in the project the DIT, sponsoring societies and tanzanian government.

### 23.1.1. Sites analisys

Of the nine investigated sites only four have been selected: Makete, Madaba, Macheke, Mpando, each one with different configuration. Makete is the most important site, because DIT and REA are already working on its design stage. Carrying out the simulations, Madaba first configuration (Ref. 22.1.3) has been found to be the most economically sustainable because allows to obtain an IRR value equal 26%, using TANESCO tariffs.

## 23.2. Software improvement

The software is open to improvement. Its shortcomings are mainly due to lack of data, then collecting more informations, the reliability of software results could be easily improved. The main possible improvement are listed below:

1. Changing the discretization of hydrograph from monthly to daily.
2. Check the specific costs used for building material by contacting several local producers.
3. Set up the first cost coefficient of cost functions, investigating several existing tanzanian hydropower plants.
4. Collects detailed informations about the 'Willingness to pay' of local rural utilities.

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