NTNU

Norwegian University of
Science and Technology

Dimensioning of Kirne Power Plant in Nepal

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Master of Science in Product Design and Manufacturing
Submission date: June 2009
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Norwegian University of Science and Technology
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Problem Description

The main objective of the thesis is to carry out a technical and economic analysis of the installation of unit 6 at Khimti Power Plant.

The following points should be included in the thesis:
1. The student should use hydrology data to investigate how much water that is available at all times through the year at Khimti Power Plant.
2. The student should get technical data for Khimti Power Plant, and information on power prices in Nepal, and HPL's agreements for delivering power.
3. An evaluation if a new tunnel and pressure shaft are necessary for the installation of unit 6.
4. A full study of unit 6 that should be used in the monsoon period should be carried out. This should mainly be done as a technical analysis. If information on the costs are available, an economic analysis should also be done.

Assignment given: 15. January 2009
Supervisor: Ole Gunnar Dahlhaug, EPT

Introduction

This is a master thesis written at the Hydro Power Laboratory at the Norwegian University of Science and Technology (NTNU) in cooperation with SN Power. The aim of the thesis is to do a rough design of Kirne Power Plant in Nepal. SN Power is a majority share holder in the company Himal Power Limited, who is going to build Kirne.

Kirne is a new plant that will utilize the same tunnel as the existing plant, Khimti I. In the start of the project, it was named Khimti I, Unit6, during the process the name was altered to Kirne Power Plant.

During the last year I have visited Khimti I and the site of Kirne two times. This has given me an advantage, as I can relate the thesis to what I have seen. It has also been motivating to work with a real project, that will be built some time.

The scope of the thesis is broad, and I have narrowed some aspects of it. I have also made use of a lot of simplifications and assumptions, due to reach a first estimate of Kirne. The main problems as power evacuation and agreements upon the power sale has not been addressed in the thesis. Those problems are of great concern for the project management.

During the work with the project, I have stayed at the office of SN Power at Lilleaker, in Oslo, and I have also spent some time at the office of Sweco in Oslo.

Line S. Drange

Line Sjødin Drange

Trondeheim 08.06.2009

Norges teknisk-
naturvitenskapelige universitet
NTNU

Fakultet for ingeniørvitenskap og teknologi
Institutt for energi- og prosessteknikk

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MASTEROPPGAVE

for

Line Sjødin Drange

Våren 2009

Ny turbin ved et kraftverk i Nepal
New turbine at a Power Plant in Nepal

Bakgrunn

Khimti Kraftverk ligger i Nepal og eies og drives av Himal Power Limited, HPL. SN-Power er majoritetseier av HPL og er derfor involvert i oppgraderinger ved Khimti Kraftverk. Khimti Kraftverk har 5 Pelton turbiner med til sammen 60 MW installert effekt. I monsunperioden er det mye vann tilgjengelig som det er mulig å benytte til ytterligere kraftproduksjon. Det er derfor ønskelig å se om det er mulig å utvide kraftverket med ytterligere en turbin og om dette er teknisk og økonomisk lønnsomt for HPL.

Mål

Gjennomføre en teknisk og økonomisk analyse for installasjon av unit 6 ved Khimti Kraftverk.

Oppgaven bearbeides ut fra følgende punkter:

1. Studenten skal benytte hydrologisk data for å se hvor mye vann som er tilgjengelig ved Khimti Kraftverk i hele året.
2. Studenten skal finne tekniske data for Khimti Kraftverk og informasjon om kraftpriser i Nepal og de HPL's avtaler om kraftleveranser.
3. Det skal evalueres om ny tunnell og trykksjakt er nødvendig for installasjon av unit 6.
4. Det skal gjennomføres et studie for unit 6 ved Khimti Kraftverk som skal benyttes i monsunperioden. Dette skal i hovedsak gjennomføres som en teknisk analyse. Dersom det finnes informasjon om kostnader for en ny turbin skal det også gjennomføres en økonomisk analyse.

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Senest 14 dager etter utlevering av oppgaven skal kandidaten levere/sende instituttet en detaljert fremdrift- og evt. forsøksplan for oppgaven til evaluering og evt. diskusjon med faglig ansvarlig/ veiledere. Detaljer ved evt. utførelse av dataprogrammer skal avtales nærmere i samråd med faglig ansvarlig.

Besvarelsen redigeres mest mulig som en forskningsrapport med et sammendrag både på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse etc. Ved utarbeidelsen av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelsen legges det stor vekt på at resultatene er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte, og at de er diskutert utførlig.

Alle benyttede kilder, også muntlige opplysninger, skal oppgis på fullstendig måte. (For tidsskrifter og bøker oppgis forfatter, tittel, årgang, sidetall og evt. figurnummer.)

Det forutsettes at kandidaten tar initiativ til og holder nødvendig kontakt med faglærer og veileder(e). Kandidaten skal rette seg etter de reglementer og retningslinjer som gjelder ved alle fagmiljøer som kandidaten har kontakt med gjennom sin utførelse av oppgaven, samt etter eventuelle pålegg fra Institutt for energi- og prosessteknikk.

I henhold til "Utfyllende regler til studieforskriften for teknologistudiet/sivilingeniørstudiet" ved NTNU § 20, forbeholder instituttet seg retten til å benytte alle resultater i undervisnings- og forskningsformål, samt til publikasjoner.

Ett -1 komplett eksemplar av originalbesvarelsen av oppgaven skal innleveres til samme adressat som den ble utlevert fra. (Det skal medfølge et konsentrert sammendrag på maks. en maskinskrevet side med dobbel linjeavstand med forfatternavn og oppgavetittel for evt. referering i tidsskrifter).
Til Instituttet innleveres to - 2 komplette, kopier av besvarelsen. Ytterligere kopier til evt. medveiledere/oppgavegivere skal avtales med, og evt. leveres direkte til, de respektive.
Til instituttet innleveres også en komplett kopi (inkl. konsentrerte sammendrag) på CD-ROM i Word-format eller tilsvarende.

Institutt for energi og prosessteknikk, 19. januar 2009

Johan Hustad
Instituttleder

for Ole G Dahlhaug
Faglig ansvarlig/veileder

Medveiledere: Torbjørn Nielsen
Morten Kjeldsen

Abstract

Kirne Power Plant is a planned expansion of Khimti I Hydro Power Plant in Nepal. During the monsoon period there is a lot of excess water, and the the plan is to utilize this water in an extra power plant during the monsoon. The same tunnel as for Khimti I is to be used for the whole volume flow. A new external pressure shaft is planned for the water down to the new power house of Kirne.

The hydrology is studied in this thesis, and a flow of 11 m^3/s can be utilized in Kirne through 80% of the monsoon, through the rest of the period, the flow is lower, on the average. The flow limit is found based on the head loss and surges in the water way.

The sediment basin will have to be doubled in size to handle the doubling of the volume flow. The placing of the basin can be on the opposite riverbank of the existing settling basin. Another possibility is to build the planned power plant Khimti II upstream Khimti I, and handle the sediments there.

Excavation of a volume of 170 m^3 is necessary at the top of the surge shaft, to give room for the upsurges. The down-surges are reduced by prolonging the opening time of the turbines and valves.

The new pressure shaft will be a 1800 m long external shaft of steel, with an optimal pipe diameter of $2,16$ m. The shaft will be external due to difficult conditions in the rock, and experiences of the building of Khimti I.

It will be shown that the best solution for Kirne is to install one Pelton turbine wiht five nozzles, or two Pelton turbines with three nozzles each, in the power plant. Two Pelton turbines will give a better production than one, but at the same time the costs of the power house, and the turbines will increase.

The size of the turbine will be 64 MW for one turbine, and 32 MW each, if two smaller turbines are chosen. The production will be about 240 GWh depending of the flow through the year, which can be up to 30% less than the average. The income of Kirne will be about $13 - 14$ MUSD, depending on the final choices.

In order to finish this thesis, a lot of assumptions are made. The power evacuation and agreements with locals and national governments are not investigated. This is done to narrow the scope of the thesis, but at these points, the largest risks of the project are placed.

Sammendrag

Kirne vannkraftverk er en planlagt utvidelse av det eksisterende Khimti I vannkraftverk. Gjennom en monsunperiode er det mye vann som går til spille ved Khimti I, og planen for Kirne er å utnytte noe av dette vannet. Inntaket og tunnelen vil være det samme for Khimti I og Kirne, men det er planlagt en ny trykksjakt fra enden av tunnelen og ned til Kirne.

Hydrologien for Kirne er studert i denne oppgaven, og det er kommet frem til at det kan benyttes en volumstrøm på 11 m^3/s, og denne volumstrømmen er overskredet 80% av en normal monsumperiode. Gjennom resten av perioden vil det produseres på en lavere volumstrøm.

Sedimentbassenget ved inntaket til Khimti I og Kirne må utvides, eller det må bygges et nytt basseng på motsatt side. En annen mulighet er å bygge et nytt sedimentbasseng i tilknytning til det mulige kraftverket Khitmi II, oppstrøms Khimti I.

I svingesjakten må det graves ut et volum på 170 m^3 på toppen, for å gjøre plass til ekstra oppsving, som følge av ekstra volumstrøm gjennom systemet. Nedsvinget kan begrenses ved å forlenge lukketider på turbiner og ventiler nedstøms svingesjakten.

Den nye rørgaten vil være circa 1800 m lang, og ha en optimal diameter på $2,16$ m. Grunnen til at en utvendig trykksjakt er valgt er de vanskelige fjellforholdene, som ble oppdaget, og skapte problemer under konstruksjonen av Khimti I.

Gjennom oppgaven blir det vist at det beste alternativet for Kirne er å installere en Pelton turbin med fem stråler, eller to mindre Pelton turbiner med 3 stråler hver. To turbiner vil produsere mer enn en, men dimensjoner og kostnader på de omkringliggende delene vil da økes.

Turbinstørrelsen vil være 64 MW for en turbin, og 32 MW hver for to mindre turbiner. Den totale produksjonen gjennom en monsunperiode vil være omtrent 240 GWh, avhengig av volumstrømmen gjennom sesongen. I et tørt år vil det kunne være 30% mindre produksjon. Inntjeningen fra Kirne

vil ligge på $13 - 14$ MUSD, basert på dagens estimerte kraftpris som er $0,055$ USD.

For å fullføre denne masteroppgaven er det gjort en rekke antakelser. En løsning for transport av den produserte strømmen, og avtaler med lokale myndigheter er det ikke tatt hensyn til, dette er for å begrense omfanget av oppgaven. Det er allikevel viktig å være klar over at det er ved disse aspektene at det er knyttet størst risiko og usikkerhet for byggingen av Kirne.

Acknowledgments

There are several people I would like to thank for helping me writing this thesis.

First I would like to thank SN Power and NTNU, who gave me the opportunity to write this interesting thesis. At SN Power I would like to thank Viggo Mossing, for supporting me, and always being positive.

Ole Gunnar Dahlhaug has been my supervisor at NTNU, we have had some contact through telephone and some meetings, and Ole Gunnar has always been supporting, and coming up with ideas for my work.

At Sweco, where I will start working when this thesis is finished, I would like to thank Per Erik Nevjen, Hans Aunemo, Håkon Kyrkjeeide and at least, but not last, Karen Helgeland Qvale.

The staff at Khimti also has to be thanked, the two visits to Kirne are unforgettable, and the service at site is excellent. I hope that I will get the possibility to go back some time.

I also owe my co-student, Mette Eltvik a huge thank. She is writing her own thesis for SN Power. We have had a lot of useful discussions, and I think that we have learned a lot from each other.

The other professors and students at the Hydropower Laboratory at NTNU also deserve a thanks. The environment at the Laboratory is the best I have ever met at NTNU, and we have much fun together.

In the end, I would like to thank my boyfriend Henrik Ruud, for reading through the thesis, and correcting it. And also for supporting me through the work.

Line S. Drange

Line Sjødin Drange

Trondeheim 08.06.2009

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List of symbols

Table 1: List of symbols used in this thesis.

Symbol	*Description*	*Unit*
A	Area of the tunnel	m^2
A_B	Area of settling basin	m^2
A_s	Area of settling basin	m^2
A_T	Cross sectional area of tunnel	m^2
A_{th}	Thoma cross section	m^2
a	Speed of sound	m/s
B	Bucket width	m
B	Inlet height/ vane height	m
$\beta_{1,2}$	Inlet and outlet angle Francis runner	$^\circ$
C_s	Safety coefficient	
c	Water velocity	m/s
D	Runner diameter	m
D_B	Fall distance	m
d	Diameter of pipe	m
d_j	Diameter of jet	m
E	Modulus of elasticity	MPa
η	Efficiency	%
ε	Roughness	mm
F	Forces	N
f	Friction factor	
f	Grid frequency	s^{-1}
g	Gravity constant	$\mathrm{m/s}^2$
H	Head	m
H_t	Pressure over turbine	m
h	Hour	
h_f	Head loss	m
h_{wh}	Pressure rise due to water hammer	m

Table 2: List of symbols used in this thesis, continued.

Symbol	*Description*	*Unit*
h_b	Atmospheric pressure	m
h_{va}	Vapour pressure	m
h_s	Submergence	m
I	Interest rate	%
K	Compressebility factor	
K_f	Cost of hydraulic losses	USD
K_t	Installation cost (pipe)	USD
K_{tot}	Total cost	USD
k	Overload koefficient	
kWh_{price}	Power price	USD/kWh
κ	Degree of turbine opening	
L	Length	m
L_B	Horizontal travel distance	m
L_p	Length of pipe	m
λ	Darcy Weisbach's friction factor	
M_p	Material price	\$/kg
M	Manning number	
m	Mass	kg
n	Frequency	rpm
n	Number of years	
n_s	Specific speed	
n_{sj}	Specific speed per jet	
ν	Viscosity	
Ω	Speed number	
ω	Rotational frequency	s^{-1}
P	Wetted perimeter	m
p	Internal pressure in pipe	MPa
p	Number of pole pairs	
Q	Volume flow	m^3/s
q	Volume flow in pressure shaft	m^3/s
$\underline{Q}$	Reduced volume flow	
R	Reaction degree	
Re	Reynolds number	-
R_h	Hydraulic radius	m
r	Pipe radius	m
ρ	Density	kg/m^3
ρ_m	Density of material	kg/m^3

Table 3: List of symbols used in this thesis, continued.

Symbol	*Description*	*Unit*
s	Second	
σ_T	Stresses in material	MPa
S_e	Energy gradient	
T	Time of operation	h
T	Period	s
T_C	Closing time	s
t	Pipe thickness	m
U_*	Shear velocity	m/s
u	Circumferential velocity	m/s
V	Volume	m^3
v	Water velocity in pipe	m^2
v_t	Horizontal transit velocity	m^2
W	Watt	
w	Fall velocity	m^2
Z	Number of nozzles, Pelton	
z	Number of buckets	
z	Height	m

Table 4: List of prefixes, super- and sub scripts

Symbol	*Description*	
1	Inlet	
2	Outlet	
B	Sediment Basin	
Corr	Corrected	
G	Giga	$1 \cdot 10^9$
gr	Gross	
gvi	Guide vane inlet	
gvo	Guide vane outlet	
gvs	Guide vane shaft	
h	hydraulic	
i	Inner	
j	Jet	
k	Kilo	$1 \cdot 10^3$
M	Mega	$1 \cdot 10^6$
m	Median	
n	Net	
O	Original	
sti	Stay vane inlet	
sto	Stay vane outlet	
T	Tunnel	
t	Turbine	
u	Radial direction	
*	BEP	

Table 5: List of abbreviations used in this thesis

Abbreviation	*Description*
BEP	Best Efficiency Point
BPC	Butwal Power Company
GDP	Gross Domestic Product
GUP	Glass Fiber reinforced Unsaturated Polyester plastic
HDI	Human Development Index
HMGN	His Majesty's Government of Nepal
HPI	Human Poverty Index
HPL	Himal Power Limited
KPP	Kirne Power Plant
masl	Meter above sea level
NPSH	Net Pressure Suction Head
NTNU	The Norwegian University of Science and Technology
NVE	The Norwegian Water Resources and Energy Directorate
PE	Polyethylene
PPP	Purchasing Power Parity
ROR	Run of River
S4	Serpent Sediment Sluicing System
SN Power	Statkarft Norfund Power Invest

Chapter 1

Background

1.1 Khimti I Power Plant

Khimti I Hydro Power Plant is a run-of-river (ROR) power plant situated in Nepal. Figure 1.1 shows Nepal on the world map, and figure 1.2 shows where Khimti I is situated in Nepal. Khimti I is owned and operated by Himal Power Limited (HPL), where SN Power has an ownership of 50,4%.

The planning of the Khimti I Hydro Power Project was started as early as 1985, when the Government in Nepal started to allow private parties to invest in development of hydro power projects. Butwal Power Company (BPC) started to do a feasibility study of Khimti I in 1991. In April 1993 the first feasibility study was ready from BPC and Norconsult. This was also when the new company HPL was set up. BPC, Statkraft SF, ABB Energi and Kværner Energy were the main shareholders. During 1994, 1995 and 1996 the necessary agreements between HPL and His Majesty Government of Nepal (HMGN) and Nepal Electricity Authority (NEA) were signed. The construction of the plant started in 1996 and was finished, and set in operation in year 2000. From the completion report, [5].

Khimti I consists of five pelton units, each of 12 MW and a total output of 60 MW. The yearly production is about 350 GWh.

In Nepal there is one dry season and one wet season, the monsoon period. The monsoon is defined to last from the start of June and until mid November. This climate leaves shortage of water during the dry season, and excess water during the monsoon. The main object of this thesis is to investigate how to utilize the excess water during the monsoon, in the best possible way.

Figure 1.1: The position of Nepal and Khimti on the world map, taken from Google maps, [26]

Figure 1.2: The position of Khimti in Nepal, taken from Google maps, [26]

Figure 1.3: Air photo over Khimti I and the junction between Khimti Khola and Tamakoshi Khola. Different places and items are marked on the photo. Taken from Google Earth 19.01.2009. [25]

1.2 Kirne Power Plant

Kirne Power Plant is a new power plant with one or more units that can utilize some of the excess water during the monsoon. When Khimti I was built, it was a project that included large risks, and it was not built to the full hydrological potential.

The plan for Kirne is to take water from the existing tunnel, and then build a new external pressure shaft down to the new power house. The new power station is planned to be placed near the Tamakoshi Bridge, and an old water canal is planned to be used for the tail race water.

One of the reasons why it is possible to build a new power plant now, is a new planned grid, to be build in 2010, for export of power to India. Today there are some doubts about the time of finishing of this grid, but it will certainly be up and running some time. The agreement for the power evacuation is not yet signed.

Kirne will be built as an independent power plant, and not a part of Khimti I. The reason for this is that HPL wishes to keep the new plant outside the existing agreements for.

1.3 Nepal

Figure 1.4: The flag of Nepal

This section will give some background information on Nepal. Nepal is a poor country in Asia, and is a small country between the two giants India and China, who has both influenced the culture of Nepal. Despite of this, Nepal has never been a colony. The border between China and Nepal is covered by the mountain range Himalaya, where Mount Everest is situated. In the south there is tropical lowlands. Nepal is a unique country, which also the special flag shown in figure 1.4 shows. [12]

Due to the Himalayas that stretches along the border of Nepal, there is a vast potential for developing hydro power projects in the country. It is estimated that there exist a total potential of 83000 MW where the half of this is economic feasible.

Nepal has a population of nearly 30 million inhabitants, and 80% of these are Hinduists.

Figure 1.5: Mountains in Nepal

Nepal has had some problems through the years, and an unstable political situation. Between 1996 and 2006 there was a bloody civil war going on in Nepal, between the Governments Army and the Communist Party of Nepal (The Maoists). In December 2007, it was decided in the Parliament that the kingdom of Nepal should be abolished, and replaced by a republic. Now the Maoists have formed a government, and they have a two years time to write the new Constitution for Nepal.

Another political problem in Nepal is the high level of corruption in the country. This makes legal business difficult to run, and it is difficult for foreign investors to enter the market without being a part of the corruption. On the Corruption perceptions index made by Transparency International, Nepal holds a 121th place out of the 180 countries that are ranked. And the score is 2,7 out of 10. [15]

In Appendix C there are included several pictures from trips to Nepal and Khimti I.

1.3.1 Human Development Index

In the United Nations Development Programme, indexes that show the country's position in the world, are made. The Human Development Index (HDI), is measuring the average progress of a country in human development. It is made to give a more complex picture of the living standard in a given country, looking beyond the Gross Domestic Product (GDP) which is often used for the same purpose. The HDI is measured by four different parameters;

life expectancy, adult literacy rate, primary, secondary and tertiary gross enrolment ratio and GDP per capita (purchasing power parity, PPP, USD). Nepal is ranked at 145^{th} place out of 179 countries in this index. At another index, called the Human Poverty Index, HPI, Nepal ranks 99 among 135, which also tells us that 33,3 % of Nepals population lives below a defined threshold of poverty. These figures show that Nepal has a long way to go before becoming an industrial country.

[21]

Chapter 2

Theory

2.1 Economy and agreements

In order to commission a power plant, several agreements have to be signed. This section will briefly describe how the sales are organized at Khimti I, and how the possibilities are for Kirne.

2.1.1 Economic agreements for Khimti I

For Khimti I there is a Power Purchase Agreement, PPA, between HPL and NEA. This agreement regulates the amount and price of the power that HPL is obliged to produce and sell to NEA. The agreement also states that after twenty years of operation, in year 2020, 50% of Khimti I is to be transferred to NEA. After another 30 years of operation the whole plant is to be transferred.

2.1.2 Economic agreements for Kirne

At this stage in the project of building Kirne Power Plant, all the details and agreements for the power sales are not decided and agreed upon. There are several elements of uncertainty about the power evacuation from Kirne. But there are also many possibilities. The plan is to sell the power to India through new transmission lines that are to be built, but there has to be backup plans if the transmission lines are delayed. Also agreements and plans for how to cooperate with Khimti I are to be discussed. For this thesis it will be assumed that the practical agreements and power evacuation will cause no problems to the technical solutions.

2.1.3 Power price

The power price is assumed to be 4 Nepal Rupees, this is based on the opinion of the SN Power employee in Nepal, Khadk Bahadur Bisht. That is the price offered by NEA. The exchange rate from Nepal Rupees to United State Dollar is 0,0135 \$/Rupee, thus the power price is 5, 5 \$/kWh. It is possible to negotiate for a higher peak-hour price, but that will not be used in this thesis. It is also possible that the power will be sold to India, where other rates may apply, but that is not agreed upon, and hence not used in this thesis.

The planned grid to India is shown in figure 2.1.

Figure 2.1: The planned power grid from Bhutan to New Delhi, where Khimti is attached. Taken from Google maps [26]

2.2 Hydrology

Nepal has one wet season and one dry season during the year. The wet season lasts from the start of June and until the middle of November. The rest of the year is defined as the dry season. The purpose of Kirne Power Plant is to operate only in the wet season, when there is excess water. Figure 2.2 shows the flow through the year at the intake of Khimti I. The wet season is clearly seen.

Rasnalu gauging station is situated a few kilometers upstream the intake of Khimti I. A nearly complete measure series exists from 1968 and up to today.

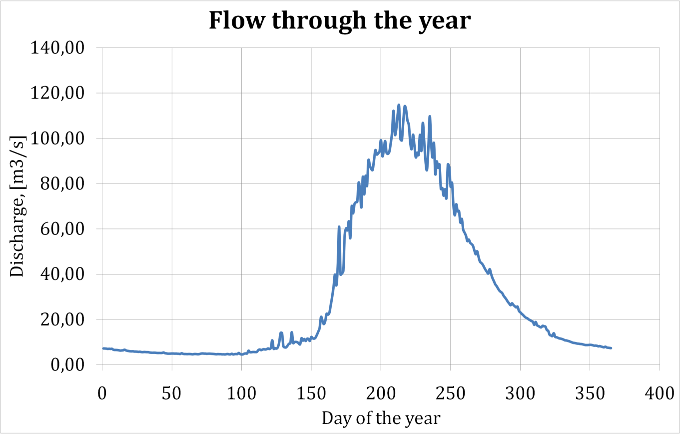


Figure 2.2: The flow through the year at Kirne.

The catchment area was calculated in the Feasibility Report [11], commissioned during 1996. The report gives a correlation factor for conversion between the flow at the gauging station, and the actual intake. The factor is found as the ratio between the catchment area at the gauging station, and the catchment area at the intake.

The Khimti River is also supposed to have an ecological flow of 0,5 m^3/s at all times, due to the agreements with HPL. The volume flow to the intake can be calculated by formula 2.1.

$$Q_{\text{Khimti}} = \text{correlation factor} \cdot Q_{\text{Rasnalu}} - \text{Irrigation flow} \quad [\text{m}^3/\text{s}] \tag{2.1}$$

2.3 Sediment handling

The theory in this section is taken from the Hydropower development series, Hydraulic design, Chapter nine; Sediment transport and handling [6]. Figure 2.3 shows a world map where the sediment concentration is plotted for different areas.

Sediments are fragments of rocks and minerals, and occur naturally in all rivers in Nepal, and other parts of the world. The sediments vary in size and hardness, as shown in figure 2.4. When dimensioning a power plant it is important to think of optimal sediment handling through the whole life of the plant.

When the regulation of a river is altered, by for example introducing a power plant, the conditions for the sediment transport will also be altered. When

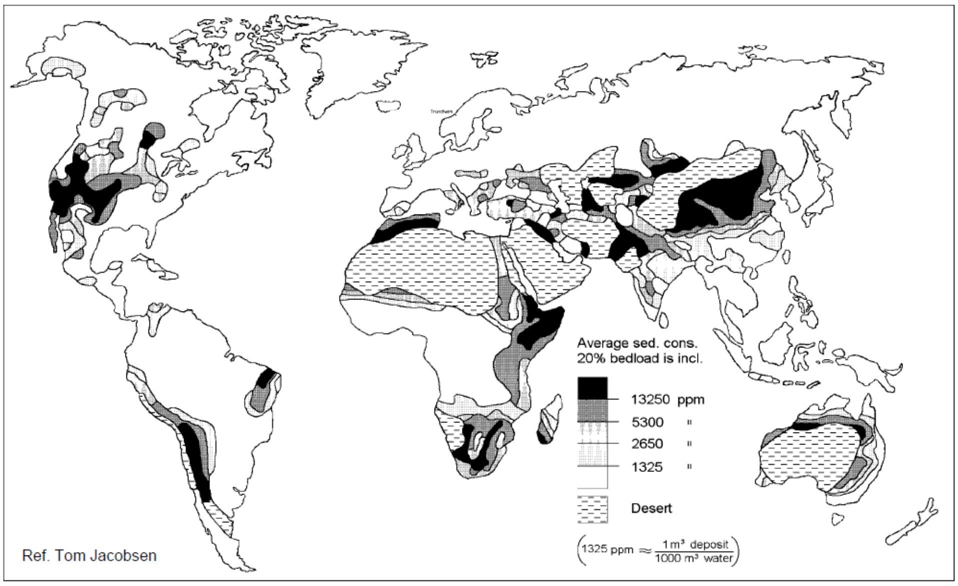


Figure 2.3: Sediment loaded rivers around the world. Taken from a presentation by Dynavec, [23].

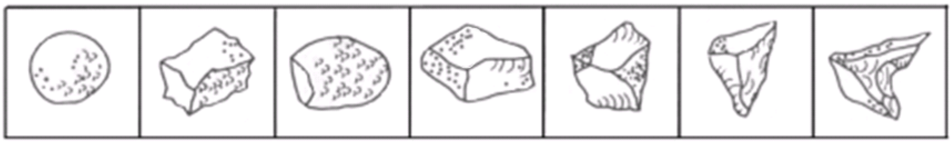


Figure 2.4: The sediments can have a lot of different sizes and hardnesses. Taken from lecture notes by Ole Gunnar Dahlhaug, [7].

water is diverted from the river to a tunnel system, often more water than sediments are diverted. Hence the sediment-water ratio in the river will increase. This might lead to extra deposition along the river. In the other end, when the water leaves the power plant, the increased amount of water in the river will lead to a flushing, and possible erosion.

In the literature two types of sediments are described, that is bed load and suspended load. Bed load is the particles that moves along the river bed, by sliding, rolling or jumping. The velocity of the bed load is much less than the water velocity. The suspended load are particles that are carried by the volume flow, and the velocity of these particles is about the same as the water. Only the bed load particles tends to settle and deposit.

The sediment load in the river will vary from year to year, and it is therefore not possible to rely on short time observations when the sediment datas are analyzed. There are also large variations in the sediment transport through the year, during the wet season the load is heavy, while in the dry season there might be periods of practically no sediments. The sediment transport is depending on many factors, and not solely on the volume flow.

2.3.1 Settling basin

Hydro power plants operating in heavy sediment loaded areas often install a settling basin at the intake. The object of a settling basin is to remove coarse sediments before entering the waterway and machinery.

The settling basin is an enlargement of the cross sectional area, and thus reducing the transient velocity of the water flow. The sediments are now allowed to deposit at the bottom. Usually a design velocity of $0,2$ m/s is used through the basin. It is difficult to remove the lightest suspended sediments, due to the long settling time.

The efficiency of the settling basin is decreasing as the basin is filled up. The trapped sediments have to be flushed through a flushing system. This system is described in section 2.3.2

There are several reasons why the sediments are desired removed. The maintenance of the hydraulic transport capacity of the water ways is one important reason, together with the reduction of the sediment erosion in the machinery. When designing the turbine, it is important to take the sediments into account.

A settling basin is often split into two or more basins, so that the flushing or inspection of one basin could be done in parallel with the other working. It is important that a uniform flow is secured, this will increase the efficiency of the trapping process. Figure 2.5 shows a typical layout of a settling basin.

Back flow and separations can be avoided if the largest angles allowed in the basin is about 10-12 °. The trap efficiency is a function of the size of the basin.

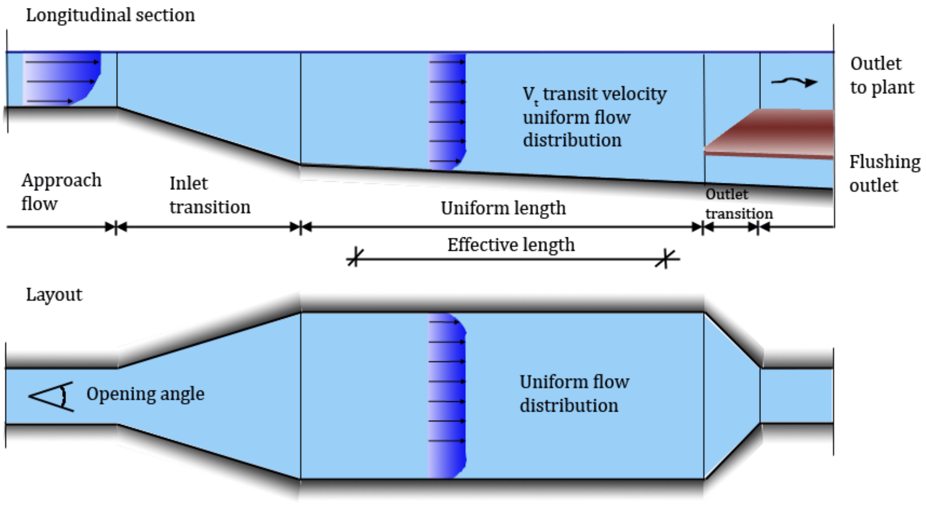


Figure 2.5: Definition sketch of a settling basin. [6]

In order for a particle to be trapped it has to have a certain fall velocity, w.

$$\frac{w}{v_t} = \frac{D}{L} \tag{2.2}$$

Where v_t is the horizontal transit velocity, D is the fall distance and L is the horizontal travel distance. All particles that have a higher velocity than w in equation 2.2, will be trapped.

$$w = \frac{D_B \cdot v_t}{L_B} = \frac{Q}{A_B} \quad [\text{m/s}] \tag{2.3}$$

Where Q is the volume flow through the basin, and A_B is the net surface of the basin, only including the area where the flow is uniform.

The efficiency calculation of a settling basin is shown in Appendix B.

2.3.2 Flushing of the settling basin

The trapped sediments will need a flushing arrangement. The four main methods are summarized in table 2.1.

Settling basin flushing arrangements			
Close down during flushing		In operation during flushing	
1	2	3	4
Conventional gravity flow flushing	Excavators and manual unloading	Continuous flushing	Intermittent flushing

Table 2.1: Flushing methods for the settling basin. Table from Hydropower development [6]

Serpent Sediment Sluicing System

The flushing system used at the intake of Khimti I is a system called Serpent Sediment Sluicing System, S4. This is classified in the fourth method of table 2.1.

The serpent is a heavy-duty rubber tube. The serpent can be filled and emptied with water. When it is filled, the serpent will cover the slit above the flushing canal. The serpent moves back and fourth in the basin as it is filled and dewatered. When the serpent is lifted, low pressure is created just above the slit, and the sediments will be sucked into the slit. The serpent is continuously moving, and the flushing process is going on at all times when it is necessary. [6].

2.3.3 Sediments in the turbine

The sediments that pass the intake and settling basin, will eventually reach the turbine. In the turbine the sediments will cause erosion. The amount of erosion depends on the size and hardness of the sediments. Figure 2.6 shows how small and large particles will follow the water in the buckets of a Pelton turbine, and where the particles will hit the bucket and cause erosion.

A table of the different minerals that are contained in the Khimti River is given in Appendix A.

2.4 Head losses

Head losses are the losses that are encountered in the water way, due to friction and shear stresses between the water and the tunnel walls. The head losses will reduce the head available for the power plant.

For Kirne, the extra losses in the tunnel, will also be extra losses for the existing Khimti I plant. In the following sections the theory for the head

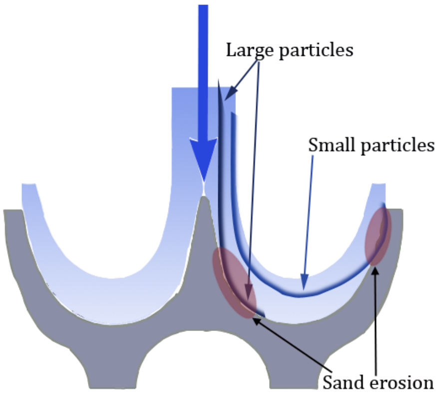
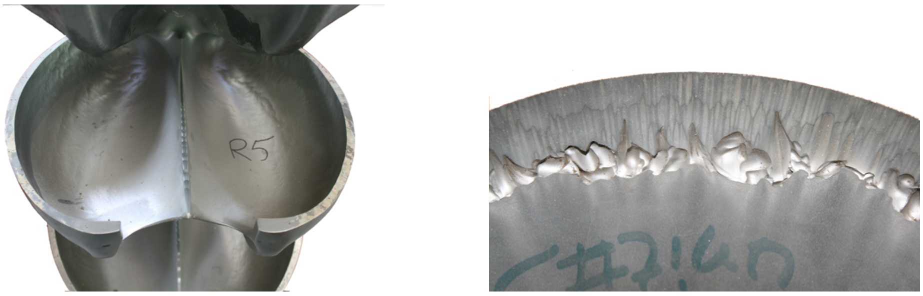


Figure 2.6: The track of small and large sediment particles in a pelton bucket.


(a) Erosion in a Pelton bucket.

(b) Erosion in the Pelton nozzle.

Figure 2.7: Sanderosion in Khimti I

losses in the tunnel and shafts will be reviewed.

2.4.1 Head loss in the tunnel

The head loss in a tunnel is calculated using the Manning number. This is a method mostly used by the civil engineers.

$$h_f = \frac{L \cdot Q^2}{M^2 \cdot A^2 \cdot R_h^{4/3}} \quad [\mathrm{m}] \tag{2.4}$$

The hydraulic radius, R_h is found from equation 2.5.

$$R_h = \frac{A}{P} \quad [\mathrm{m}] \tag{2.5}$$

Where A is the cross-sectional area, and P is the wetted perimeter of the tunnel. [27]

The maximum head loss that can be accepted in the tunnel will be the head loss corresponding to the maximum down surge. If the head loss increases above this, air will be sucked into the tunnel. Illustrated in figure 2.8.

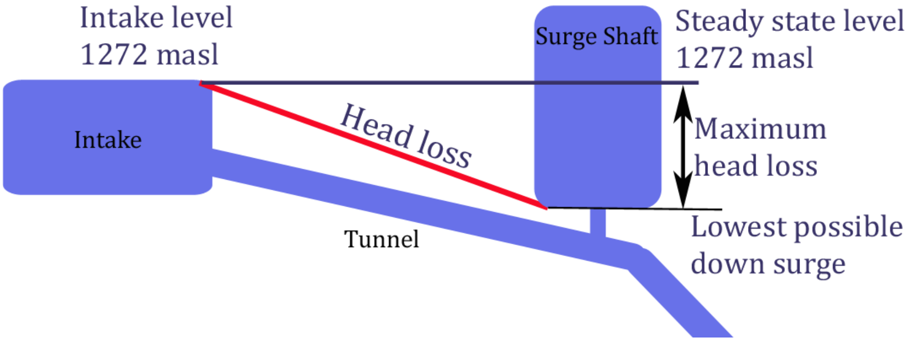


Figure 2.8: The maximum head loss.

2.4.2 Head loss in a pipe

The head losses in a pipe is calculated by using the head loss formula given in equation 2.6.

$$h_f = f \cdot \frac{L}{d} \cdot \frac{v^2}{2g} \quad [\mathrm{m}] \tag{2.6}$$

$$Re = \frac{v \cdot L}{\nu} \tag{2.7}$$

The friction factor is found from the Moody diagram, based on the Reynolds number, equation (2.7). The Moody diagram is enclosed in Appendix D. The other parameters are the length of the pipe, L, the water velocity in the pipe, v, and the diameter of the pipe, d. Figure 2.9 shows the principle of head loss.

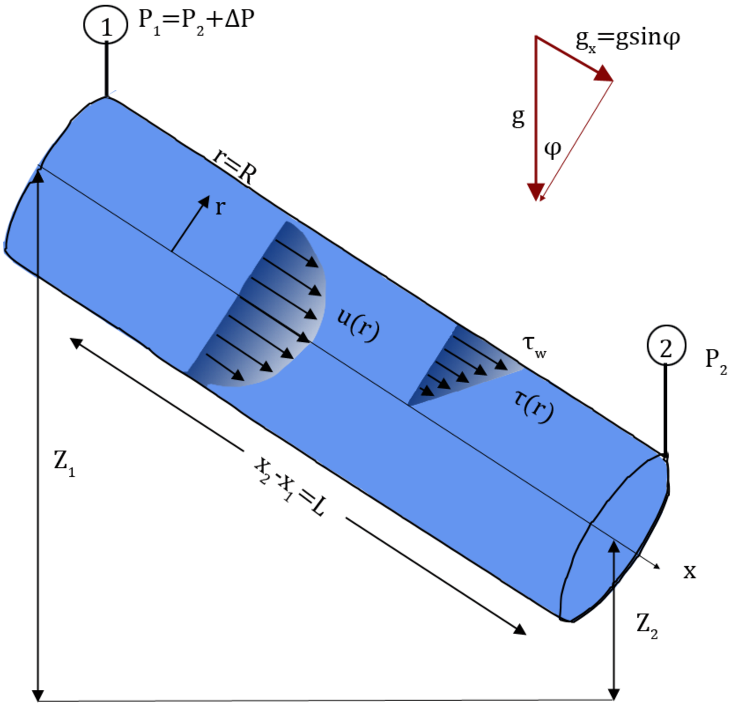


Figure 2.9: The principle of head losses in pipes, based on a figure from White [27]

2.5 Stability

This section will go through the stability elements of the power plant. The theory is taken from *Dynamic dimensioning* by Torbjørn Nielsen, [18].

2.5.1 Surges

Khimti I is equipped with a surge shaft, originally designed for the flow of Khimti I. When increasing the flow in the tunnel, the surges need to be recalculated. Modifications to the procedures of closing and opening the turbine, or modifications to the surge shaft might be necessary, to satisfy the surge limits.

When the power plant is running at constant load, there is no surges, first when the load is changing, surges will occur. The surges arises due to the inertia of the water masses.

The surges have to be within certain limits so that flooding, nor air suction into the tunnel will occur. Figure 2.10 shows what will happen at the summit points in the tunnel if the surges are larger than the limit stated. This will lead to vacuum in the tunnel.

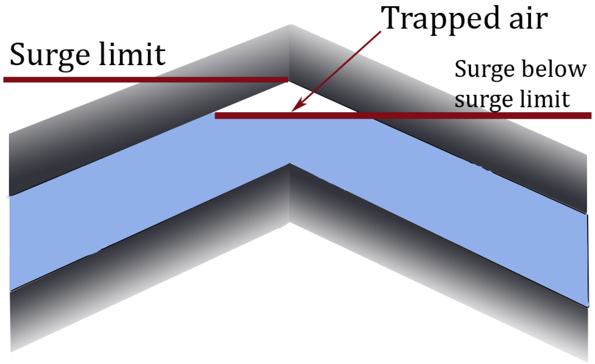


Figure 2.10: Illustration of surges below surge limit, air-trapping.

The two main equations used for the calculation of the surges are the continuity, and the the equation of motion, equation 2.8 and 2.9.

$$\frac{\delta H}{\delta t} + \frac{a^2}{g}\frac{\delta v}{\delta x} = 0 \tag{2.8}$$

$$g\frac{\delta H}{\delta x} + \frac{\delta v}{\delta t} + \lambda\frac{v\,|v|}{2D} = 0 \tag{2.9}$$

Where a is the speed of sound, $a = \sqrt{\frac{K}{\rho}}$, K is the compressibility factor, and λ is Darcy-Weisbachs friction factor. In water the the speed of sound is usually about 1450 m/s.

The dimensioning pressure for the surge shaft is when the load is rejected, or when the gates are opened suddenly. The pressure wave in the pressure shaft will propagate with the speed of sound, and the period is shown in equation 2.10.

$$T = \frac{4L}{a} \quad [\mathrm{m}] \tag{2.10}$$

The elasticity in the pipe can be taken into account, and the speed of sound is then shown in equation 2.11.

$$a = \sqrt{\frac{E_{eq}}{\rho}} \quad [\mathrm{m/s}] \tag{2.11}$$

$$E_{eq} = \frac{1}{\frac{1}{K} + \frac{d}{TE}} \quad [\mathrm{Pa}] \tag{2.12}$$

Where d is the pipe diameter, T is the period, and E is the modulus of elasticity. When the elasticity is accounted, the pressure rise in front of the turbine is given in equation 2.13. This is in worst case a doubling of the pressure rise calculated without the elasticity.

$$\Delta h = 2 \cdot \frac{\Delta Q}{T_C} \cdot \frac{L}{A} \quad [\mathrm{m}] \tag{2.13}$$

Where T_C is the closing time of the turbine or the valve.

Surge shaft and surge limits

The purpose of the surge shaft is to reduce the retardation pressure at the turbine, and to increase the stability of the governing.

The surge shaft reduces the distance from the turbine to the nearest free water surface, and thus also the water volume that has to be retarded. Changes in the load will result in surges. The surges at a load rejection is shown in figure 2.11.

It is the turbine that defines the change of load in the system. In the calculations it will be assumed that the turbine acts like a valve with a given characteristic.

The degree of opening of the turbine, κ, is given in equation 2.14.

$$\kappa = \frac{Q}{Q_n} \cdot \frac{\sqrt{2gH_n}}{\sqrt{2gH}} \tag{2.14}$$

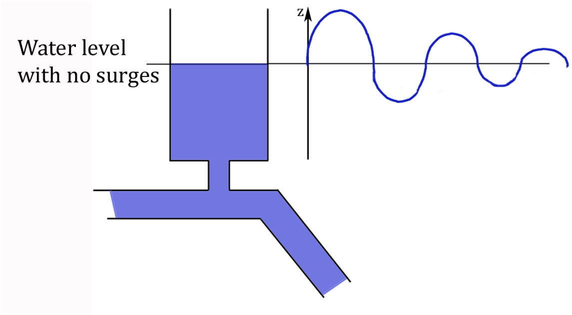


Figure 2.11: The up- and down surge in the surge shaft at load rejection.

The pressure over the turbine is then given in equation 2.15.

$$H_t = H_n \left(\frac{Q}{\kappa \cdot Q_n} \right)^2 \quad [\mathrm{m}] \tag{2.15}$$

Where Q_n and H_n is denoting the nominal volume flow, and the nominal head.

Figure 2.12, shows the different elements that will affect the surges in the surge shaft. The following equations, equation 2.16 to 2.18, refer to the numbers and variables in figure 2.12. The equations are derived from the continuity equation, and the equation of motion.

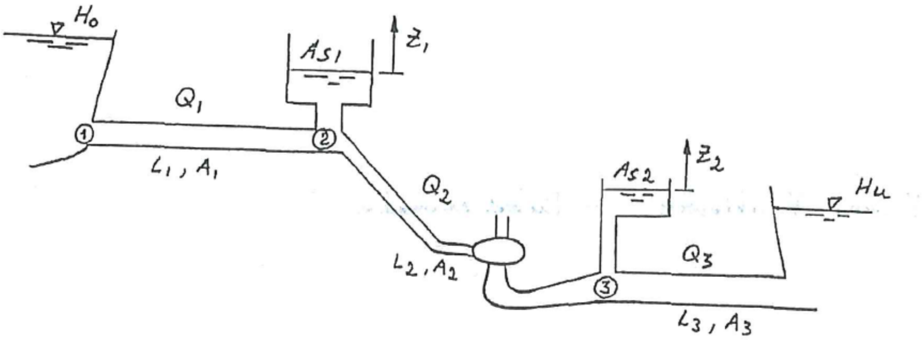


Figure 2.12: Showing the elements of hydro power plant, [18].

$$\frac{dQ_1}{dt} = \frac{g \cdot A_1}{L} (H_0 - z_1 - k_1 Q_1 |Q_1|) \tag{2.16}$$

$$\frac{dQ_2}{dt} = \frac{g \cdot A_2}{L_2} \left(z_1 - H_u - H_n \left(\frac{Q_2}{\kappa \cdot Q_n} \right)^2 - k \cdot Q_2 |Q_2| \right) \tag{2.17}$$

$$Q_s = Q_1 - Q_2 \quad [\mathrm{m}^3/\mathrm{s}] \tag{2.18}$$

$$\frac{dz}{dt} = \frac{1}{A_s} \cdot Q_s \tag{2.19}$$

This leaves 4 equations and 4 unknowns, which can be solved by Euler's method.

Estimated surges

A rough estimate of the surges can be found by using the u-tube oscillation between the dam and the surge shaft. The equation of motion can then be set up as shown in equation 2.20

$$\frac{L}{g \cdot A_T} \frac{dQ}{dt} = \Delta z \quad [\mathrm{m}] \tag{2.20}$$

The continuity between the tunnel and the surge shaft is given in equation 2.21:

$$A_s \frac{dz}{dt} = Q - q \tag{2.21}$$

Where Q is the volume flow in the tunnel, and q is the volume flow continuing in the pressure shaft. When there is a load rejection, q is approaching zero.

For the estimate, the following assumptions will be done:

- $dz \approx \Delta z$
- $dv \approx \Delta v$
- $dt \approx \Delta t$

The lossless equation for the up- and down surges is derived, and expressed in equation 2.22.

$$\Delta z = \pm \Delta Q \sqrt{\frac{L/A_T}{g \cdot A_s}} \quad [\mathrm{m}] \tag{2.22}$$

If the losses are included the equation for the up surge is given in equation 2.23, and in equation 2.24 for the down surge.

$$\Delta z = +\Delta Q\sqrt{\frac{L/A_T}{g \cdot A_s}} + \frac{1}{3}h_f \quad [\mathrm{m}] \tag{2.23}$$

$$\Delta z = -\Delta Q\sqrt{\frac{L/A_T}{g \cdot A_s}} - \frac{1}{9}h_f \quad [\mathrm{m}] \tag{2.24}$$

2.5.2 The Thoma cross section

The Thoma cross section is the smallest cross section that gives stable u-tube oscillations. The oscillations are given by the continuity equation and Newton's second law, equation 2.25 and 2.26.

$$A_s\frac{dz}{dt} = v \cdot A - q \tag{2.25}$$

$$\frac{dv}{dt} = \frac{g}{L}(z - \alpha v|v|) \tag{2.26}$$

Where $\alpha v|v|$ is the head loss.

If a small disturbance in the volume flow is studied, the equations can be linearized. If the eigenvalues of the set of equations are found, and the requirement of a negative real part is followed, the stable u-tube oscillation is given by equation 2.27.

$$A_{th} \geq \frac{L \cdot f}{2 \cdot g \cdot \alpha(H_0 - z_0)} \quad [\mathrm{m}^2] \tag{2.27}$$

If the Manning friction factor is included, the Thoma area will be as in equation 2.28.

$$A_{th} \approx 0,0085 \cdot \frac{M^2 \cdot A_{\mathrm{T}}^{5/3}}{H_0} \quad [\mathrm{m}^2] \tag{2.28}$$

For the u-tube oscillations to be stable, $A_s > A_{th}$, has to be fulfilled. The surface area in the shaft has to be larger than the Thoma area. A safety factor of 1,5 is often used; $A_s = 1,5 \cdot A_{th}$.

2.6 The elements of the power plant

2.6.1 Intake

The intake at Kirne will be the same as the intake for Khimti I. The intake consist of trash racks, diversion weir, and the sediment basin, which is already described in section 2.3.1.

An overview of the intake can be seen in the picture in figure 2.13. The actual intake is indicated with the white arrow, the minimum release flow (500 l/s) is shown in the red box, and the diversion weir is shown in the orange box. The picture is taken during the dry season, in the beginning of March, and the situation would be quite different if it was taken during the wet season.

Figure 2.13: The intake at Khimti I/Kirne Power Plant

The diversion weir has a crest elevation of 1272 masl, and the length is 42 meter. The height of the weir is at maximum two meters above the original river bed. At the left of the weir there is a fish passage, (not seen in the picture).

2.6.2 Tunnel

The tunnel of Khimti I is 7885 m long, with an average diameter of 11,6 m^2. The tunnel has several summit and valley points along the way. The summit points will settle the limit for the down surge in the surge shaft, and this is calculated in the final design report, [17], to be at 1249 masl. Surges below

Figure 2.14: The intake seen from helicopter.

this limit will suck air into the tunnel. The tunnel is also dealt with in the head loss section, 2.4, and in the surges section, 2.5.1.

2.6.3 Sand trap

There is an additional sand trap at the junction of Adit 4 in the tunnel. The purpose of this sand trap is to remove bed load that come from the tunnel invert, and eventual rock falls in the tunnel. It is not the purpose to remove suspended load here. The trap can be hydraulically flushed through Adit 4. There is installed a sediment flushing system, called a Slotted Pipe Sediment Slucier (SPSS).

2.6.4 Surge shaft

The existing surge shaft has a diameter of 4670-5000 mm through the main section. The lower part of the surge shaft has a diameter of 2150 mm, and connects the surge shaft to the branch tunnel. In the branch tunnel, a 1050 mm steel lined orifice is introduced to reduce the surges, and to increase the stability. The branched arrangement enables excavating the shaft without disturbing the tunnel.

The water intake level is maximum 1274 masl, and the minimum level is 1269 masl. The corresponding surge limits are:

- Upsurge maximum = 1300 masl, this gives 2 meter clearance to the top of the surge tank.

- Down surge minimum = 1249 masl, this leaves 4 meter margin to the tunnel roof.

The surge limits are given that the assumed tunnel roughnesses are correct.

2.6.5 Pressure shaft

The pressure shaft is the inclined pipe connecting the tunnel and the power house.

Kirne Power Plant

The new pressure shaft of Kirne Power Plant, is planned to be an external pipe. It will be taken out from the Adit 4 tunnel. The pipe should be supported by anchor blocks and support piers. The reason for why an external pipe will be chosen is the unstable geological conditions in the rocks in the Khimi area. When building the shafts at Khimti I, there were a lot of challenges, and the shafts and tunnels had to be re-directed, and rebuilt several times due to rock fall.

Pipes in hydro power plants

The pipes used in power plants can be of several different materials, depending on the required properties. The most common used ones are shown in the list below.

- Steel
- Polyethylene, PE
- Glass-fiber reinforced Unsaturated Polyester plastic, GUP
- Wood
- Concrete

Two tables containing the physical properties of the different materials are enclosed in Appendix E.

Only the steel pipes are suited for the high pressures that will be encountered at Kirne.

Maximum pressure in pipes

There are several aspects that makes the total picture of the maximum pressure in the pipes and shafts:

- Static head.
- Water hammer, Δh_{wh}.
- Deflection between pipe supports.
- Friction in the axial direction.

It is neccesary to avoid the water hammer effect in the pipe. The water hammer is introduced when the closing time of the valve or guide vanes is faster than the reflection time of the pressure pulse, equation 2.29.

$$\Delta h_{\mathrm{wh}} = \frac{a \cdot c_{\max}}{g}, \quad [\mathrm{m}] \quad \text{if} \quad T_C << \frac{2L}{a} \tag{2.29}$$

Where Δh_{wh} is the pressure rise due to the water hammer, a is the speed of sound in the penstock and $c_{\max}$ is the maximum velocity in the pipe. T_C is the closing time for the main valve, the guide vanes, or the nozzles of the turbine.

If the reflection time is shorter than the closing time, the pressure rise equation is shown in equation 2.30:

$$\Delta h_{\mathrm{wh}} = \frac{a \cdot c_{\max}}{g} \cdot \frac{2L/a}{T_C} = \frac{c_{\max} \cdot 2L}{g \cdot T_C} \quad [\mathrm{m}] \quad \text{if} \quad T_C \geq \frac{2L}{a} \tag{2.30}$$

The pipe thickness can be calculated based on the pressure and the material properties, given in Appendix E. Figure 2.15 illustrates the stresses in the materials, and pressures in the pipe.

The internal pressure is calculated by formula 2.31. The equilibrium of the stress and pressure result in equation 2.32, and the resulting equation for the pipe thickness is shown in equation 2.33.

$$p = \rho \cdot g \cdot (H_{\mathrm{gr}} + h_{\mathrm{wh}}) \quad [\mathrm{Pa}] \tag{2.31}$$

$$L \cdot D_i \cdot p \cdot C_s = 2\sigma_t \cdot L \cdot t \tag{2.32}$$

$$t = \frac{p \cdot r_i \cdot C_s}{\sigma_t} \quad [\mathrm{m}] \tag{2.33}$$

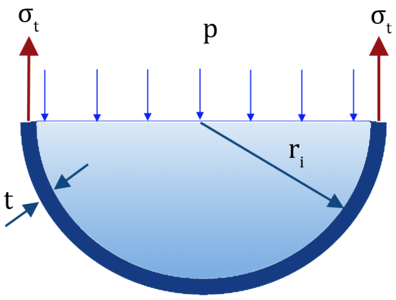


Figure 2.15: Pressure and stresses in the pipe, taken from lecture notes by Torbjørn, [19].

D_i is the inner diameter of the pipe, p is the pressure inside the pipe, σ_t is the stresses in the pipe material, t is the thickness, and C_s is the safety coefficient, which is often set to 1,2, [19].

2.6.6 Economic correct pipe diameter

The relation between head losses in the pipe, and costs of a larger pipe has to be optimized, so that the total cost can be minimized. An economic correct pipe diameter can be ensured by formula 2.34.

$$\frac{dK_{tot}}{dD} = \frac{d(K_f + K_t)}{dD} = 0 \tag{2.34}$$

Equation 2.34 is describing when the correct economical diameter of the pipe can be expected. K_f is the cost for the hydraulic losses in the pipe, K_t is the installation costs of a new pipe and K_{tot} is the combined costs of losses and installation.

$$P_{loss} = \rho \cdot g \cdot Q \cdot h_f = \rho \cdot g \cdot Q \cdot f \frac{L}{2r} \frac{Q^2}{2 \cdot g \cdot \pi^2 \cdot r^4} = \frac{C_2}{r^5} \quad [\mathrm{W}] \tag{2.35}$$

Here C_2 is the calculation coefficient, shown in equation 2.36.

$$C_2 = \frac{\rho Q^3 f L}{4\pi^2} \tag{2.36}$$

$$K_f = P_{\text{loss}} \cdot T \cdot kWh_{\text{price}} = \frac{C_2}{r^5} \cdot T \cdot kWh_{\text{price}} \quad [\mathrm{USD}] \tag{2.37}$$

In equation 2.37, T is the production time, and kWh_{price} is the energy price.

In order to get the total price of the head loss costs, the net present value of K_f has to be calculated. As shown in formula 2.38

$$K_{\text{f, npv}} = \sum_{i=1}^{n} \frac{K_f}{(1+I)^i} = \sum_{i=1}^{n} \frac{\frac{C_2}{r^5} T \cdot kWh_{\text{price}}}{(1+I)^i} \quad [\text{USD}] \tag{2.38}$$

Where n is the lifetime in number of years, and I is the interest rate.

K_t is calculated from the material price of steel, equation 2.39, but can also be found from the NVE tables Appendix E.

$$K_t = M_p \cdot m = M_p \cdot C_1 \cdot r^2 \quad [\text{USD}] \tag{2.39}$$

Where C_1 is a calculation coefficient given in equation 2.41, based on equation 2.40.

The mass of a pipe is given in equation 2.40:

$$m = \rho_m \cdot V = \rho_m \cdot 2 \cdot \pi \cdot r \cdot t \cdot L = \rho_m \cdot 2 \cdot \pi \cdot r \cdot \frac{pr}{\sigma} L = C_1 \cdot r^2 \quad [\text{kg}] \tag{2.40}$$

$$C_1 = \frac{2 \cdot \rho_m \cdot \pi \cdot p \cdot L}{\sigma_m} \tag{2.41}$$

Now the economic correct diameter can be summarized in equation 2.43, by the use of equation 2.39 and equation 2.38 through derivation, 2.42.

$$\frac{d(K_t + K_f)}{dr} = 2 \cdot M_p \cdot C_1 \cdot r - \frac{5}{r^6} \sum_{i=1}^{n} \frac{C_2 \cdot T \cdot kWh_{\text{price}}}{(1+I)^i} = 0 \tag{2.42}$$

$$r = \sqrt[7]{\frac{5}{2} \cdot \sum_{i=1}^{n} \frac{C_2 \cdot T \cdot kWh_{\text{price}}}{M_p \cdot C_1 \cdot (1+I)^i}} \tag{2.43}$$

The theory about pipes in the hydro power plants is taken from the lecture notes of Torbjørn Nielsen, [19].

2.6.7 Power house

The size and requirements for the power house are depending on the type and number of turbines to be installed.

2.6.8 Draft tube

A draft tube is only necessary if the turbine installed is a Francis turbine. The draft tube will recover the lost energy, this can be seen in the energy diagram for a Francis turbine, shown in figure 2.16.

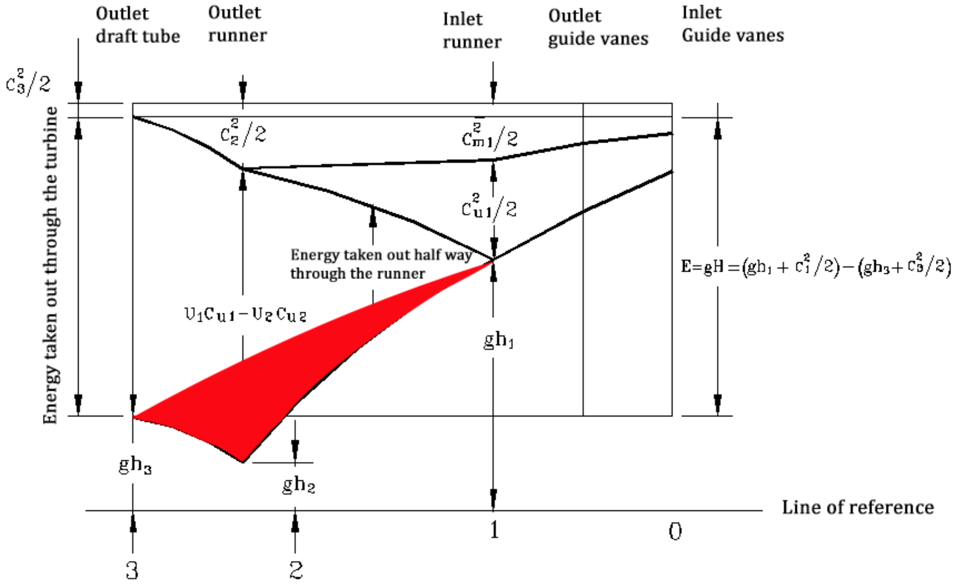


Figure 2.16: The energy diagram of a Francis turbine, where the recovered energy in the draft tube is marked in red.

2.7 Turbines

This section will give the theory of the two main types of turbines, the Francis turbine and the Pelton turbine, which also are the two relevant types for Kirne Power Plant.

The power equation of turbines in hydro power plants is given in equation 2.44, and the equation 2.45 shows the production.

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot H_n \quad [\mathrm{W}] \tag{2.44}$$

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot H_n \cdot \text{number of days} \cdot 24 \text{ hours} \quad [\mathrm{Wh}] \tag{2.45}$$

Where P is the power, η is the efficiency, and ρ is the density of water.

2.7.1 Speed number

The speed number is a dimensionless value that gives some criteria for the turbine. There are speed number limits between the different types of turbines, as shown in figure 2.17.

The maximum speed number for a Pelton turbine is 0,22, which can be derived from the formulas given below, together with the requirement of zero reaction ratio, $u_1/c_{u1} \leq 0,5$.

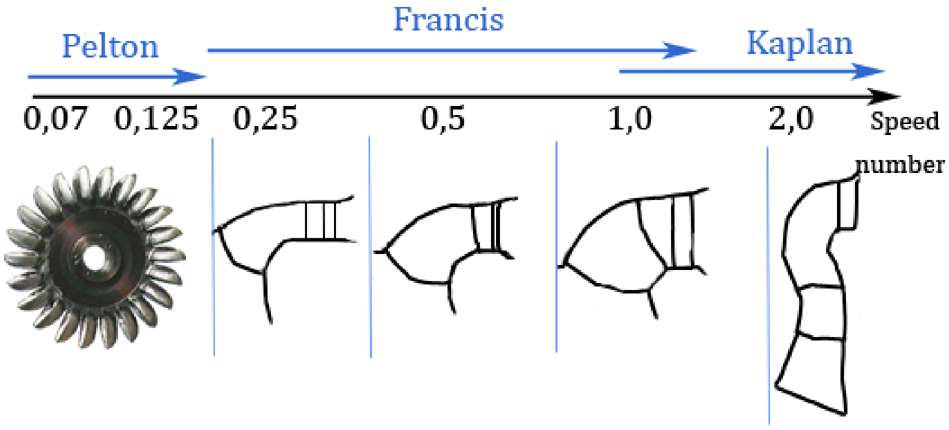


Figure 2.17: The speed number limits between the different type of turbines, taken from [3].

The speed number of a turbine is defined as in equation 2.46.

$$\Omega = \underline{\omega}\sqrt{\underline{Q}} \tag{2.46}$$

For a pelton turbine with several nozzles, the speed number, Ω can include the number of nozzles, equation 2.47.

$$\Omega = \underline{\omega}\sqrt{Z \cdot \underline{Q}} \tag{2.47}$$

The angular speed is defined in formula 2.48

$$\omega = \frac{n\pi}{30} \quad \text{[rad/s]} \tag{2.48}$$

The reduced angular speed, $\underline{\omega}$, is given in equation 2.49

$$\underline{\omega} = \frac{\omega}{\sqrt{2gH}} \tag{2.49}$$

The reduced volume flow, $\underline{Q}$, is defined in the same way, equation 2.50.

$$\underline{Q} = \frac{Q}{\sqrt{2gH}} \tag{2.50}$$

Figure 2.18 shows the correlation between the maximum speed number of a Pelton turbine, and the number of nozzles, for a runner with a volume flow of 10 m^3/s and a diameter ratio, D/d_j, of 12.

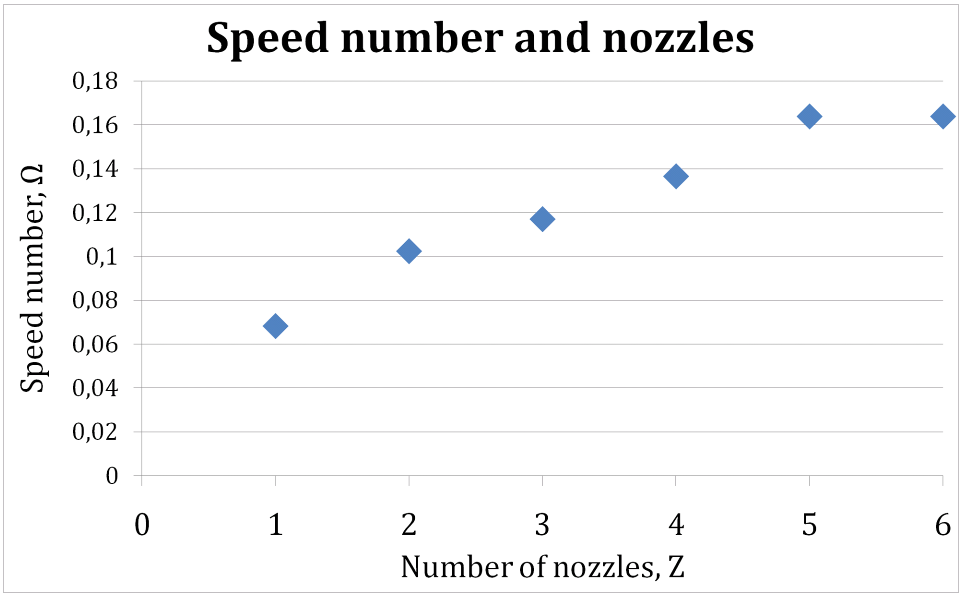


Figure 2.18: The speednmuber of a Pelton turbine as a function of number of nozzles.

2.7.2 Pelton turbine

The Pelton turbine is an impulse turbine, all the pressure energy is converted to mechanical energy before the water enters the runner. Only the impulse force between the water and the buckets is causing the conversion between mechanical energy and electrical energy. The Pelton turbines are most commonly used for high heads. Figure 2.19 shows one of the existing turbines at Khimti I.

Design of a Pelton turbine

The theory in this section is taken from lecture notes by Torbjørn Nielsen, [20], and from *Pumps and turbines* by Hermod Brekke, [2].

Figure 2.19: One of the old pelton runners at Khimti I.

The main dimensions of a Pelton turbine are shown in figure 2.20.

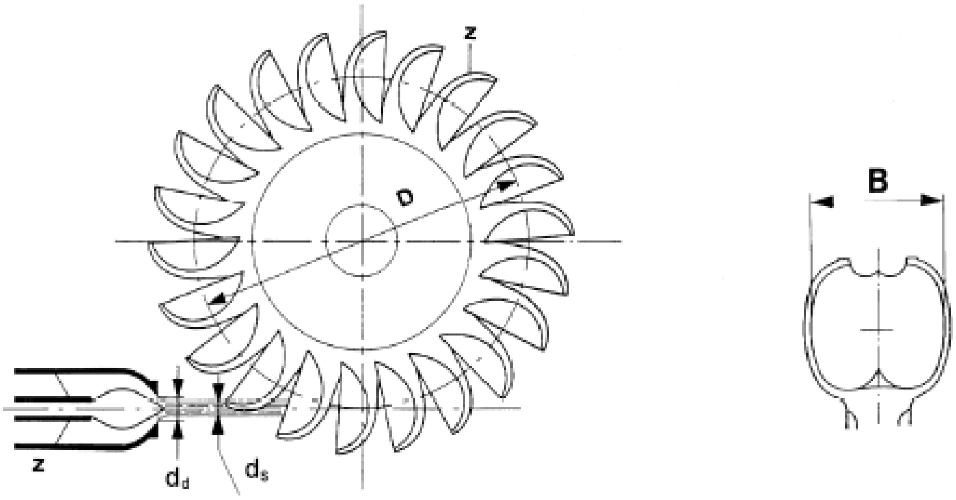


Figure 2.20: The main dimensions of a pelton turbine, [20].

When the designing process is started, the head and volume flow are known, a procedure can be followed to derive the main dimensions of the turbine.

The ideal Pelton runner

The absolute water velocity from the nozzle, c_1, is found from equation 2.51. In figure 2.21, c_1 along with the other variables in the following calculations are shown.

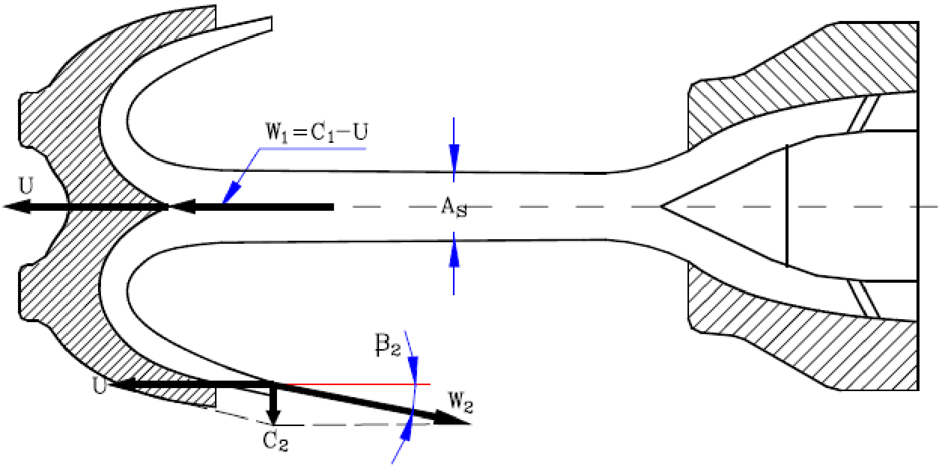


Figure 2.21: The different velocity in the pelton bucket. [20]

$$c_1 = \sqrt{2 \cdot g \cdot H_n} \quad [\mathrm{m/s}] \tag{2.51}$$

Hence the reduced absolute velocity will equal 1, equation 2.52.

$$\underline{c}_1 = \frac{c_1}{\sqrt{2 \cdot g \cdot \ H_n}} = 1 \tag{2.52}$$

Now the circumferential speed can be derived, equation 2.53.

$$u_1 = \frac{c_{u1}}{2} = \frac{1}{2} \cdot \sqrt{2 \cdot g \cdot H_n} \quad [\mathrm{m/s}] \tag{2.53}$$

From this it follows that the reduced circumferential speed is $\underline{u}_1 = 0,5$.

The equations derived so far are for an ideal turbine, with an efficiency equal to one in the Euler's turbine equation, equation 2.54

$$\eta_h = 2(\underline{u}_1 \cdot \underline{c}_{1u} - \underline{u}_2 \cdot \underline{c}_{2u}) \quad [\%] \tag{2.54}$$

From figure 2.21 and through the equations 2.51 to 2.54 it can be seen that $\underline{c}_{u1} = 1$, and $\underline{c}_{u2} = 0$.

A real Pelton runner

In reality the efficiency of a Pelton turbine does not equal 1, but is often set to 0,96 in order to include some losses in the calculations. The absolute velocity from the nozzles will usually be in the interval; $0,99 \leq \underline{c}_{u1} \leq 0,995$, for the design purpose it is set equal to one.

From the Euler equation, 2.54 the reduced circumferential speed is derived in equation 2.55:

$$\underline{u}_1 = \frac{\eta_n}{2 \cdot \underline{c}_{1u}} = \frac{0,96}{2 \cdot 1,0} = 0,48 \tag{2.55}$$

The following design process is much based on experience and empirical values. The sequence of the steps can change places, and the results can be rechecked in other ways.

The bucket width is dependent on the number of jets and the jet diameter, as follows:

- $B = 3,1 \cdot d_j$, 1 nozzle
- $B = 3,2 \cdot d_j$, 2 nozzle
- $B = 3,3 \cdot d_j$, 4-5 nozzle
- $B = 3,3 - 3,4 \cdot d_j$, 6 nozzle

The jet diameter is dependent on the continuity and the number of nozzles and is given in equation 2.56. The number of nozzles is decided based on empirical datas, and experiences. The desired efficiency curve can be used to select the appropriate number of nozzles. An example of such an efficiency curve is shown in figure 2.22. All the dimensions of the runner is dependent on the number of nozzles chosen.

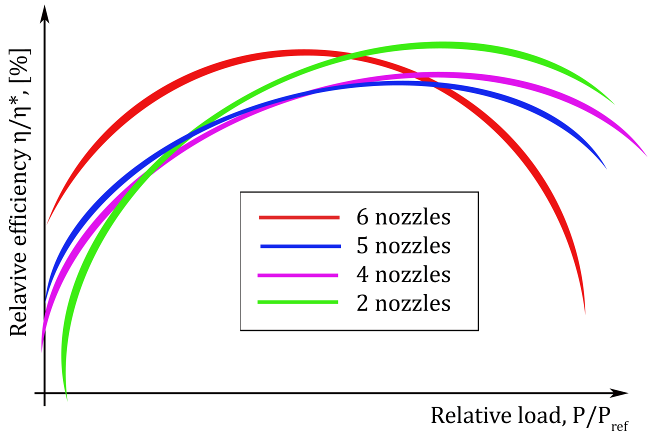


Figure 2.22: The efficiency curves of a Pelton runner, dependent on the number of nozzles.

$$d_j = \sqrt{\frac{4 \cdot Q}{Z \cdot \pi \cdot c_{u1}}} \quad [\text{m}] \tag{2.56}$$

The number of buckets, z, is also decided based on empirical values, but it is given that the number of nozzles should be equal to 17 or more. For the existing Pelton runners at Khimti I, the number of buckets are 22.

The next dimension to decide is the diameter of the runner. The rule of thumb used is;

- $D = 10 \cdot d_j$ when $H_n \leq 500\text{m}$
- $D = 15 \cdot d_j$ when $H_n \leq 1300\text{m}$

Between the values, the correlation is found by interpolation. The ratio used can also be adjusted to higher values if this will be beneficial for the final design. To increase the ratio can help reducing the pitting at the bucket inlet. The pitting will occur if the angle between the relative water velocity and the first contact with the bucket is too big. The rule of thumb is that this angle should not be bigger than 1 to 2° for high head turbines. The angle can be increased towards the sides of the bucket.

The speed of the runner is calculated by equation 2.57.

$$u_1 = \omega \cdot \frac{D}{2} = \frac{2 \cdot \pi \cdot n}{60} \cdot \frac{D}{2} \quad [\text{m/s}] \tag{2.57}$$

The rotational frequency, equation 2.58.

$$n = \frac{u_1 \cdot 60}{\pi \cdot D} \quad [\text{rpm}] \tag{2.58}$$

The rotational frequency has to be synchronous with the frequency in the grid. In Nepal the frequency is 50 Hz. A correct rotational frequency can be described by equation 2.59.

$$n = \frac{50 \cdot 60}{P} \tag{2.59}$$

Where P is the number of pole pairs, and equal to a whole number. The final number of pole pairs are given in equation 2.60.

$$P = \frac{3000}{n} \approx \text{whole number} \tag{2.60}$$

The number of pole pairs is rounded to the nearest whole number. The next steps are then to recalculate the rotational frequency to match the number of poles. And also to recalculate the runner diameter so that it is correct concerning the circumferential speed.

The speed number of an optimal Pelton runner is about 0,1. That is the point where the optimal design of the runner is found. [8]

The runner diameter as a function of the rotational frequency is shown in figure 2.23.

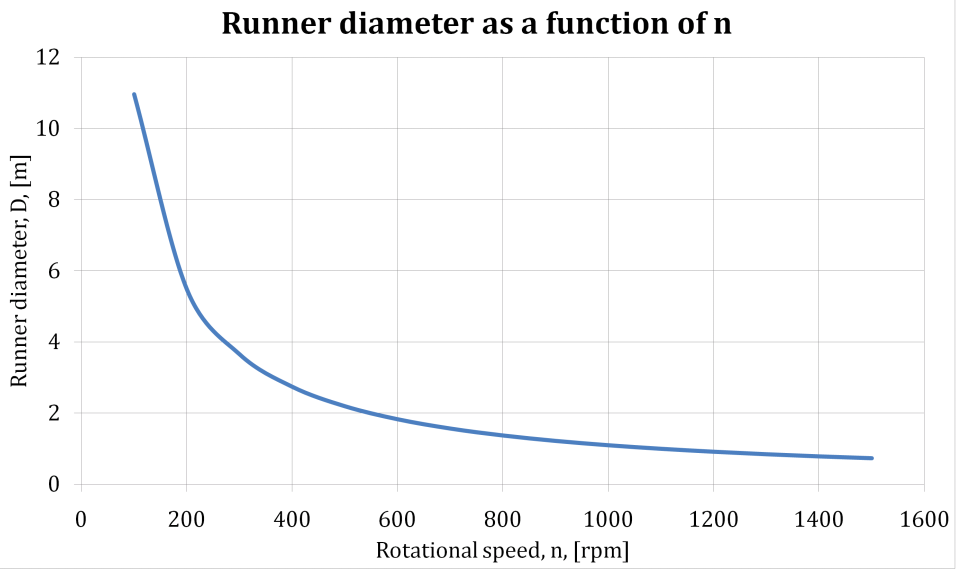


Figure 2.23: Diameter of Pelton runner, based on the reduced angular velocity, and the assumption that reduced circumferential speed equals 0,5.

Maintenance Pelton turbines

1 mm degrading of the splitter corresponds roughly to the loss of 1% of the efficiency.

2.7.3 Francis turbine

This section will present the theory for designing a Francis turbine, and the properties of the turbine. The literature used for this section is lecture notes and discussions with Ole Gunnar Dahlhaug, [7] and [8]. In addition, a report written by Håkon Hjort Francke, a PhD student at the hydro power lab, is used, [13].

The Francis turbines are usually used for a lower head range, and larger, but more narrow flow rates than the Pelton turbines. A drawing of a Francis

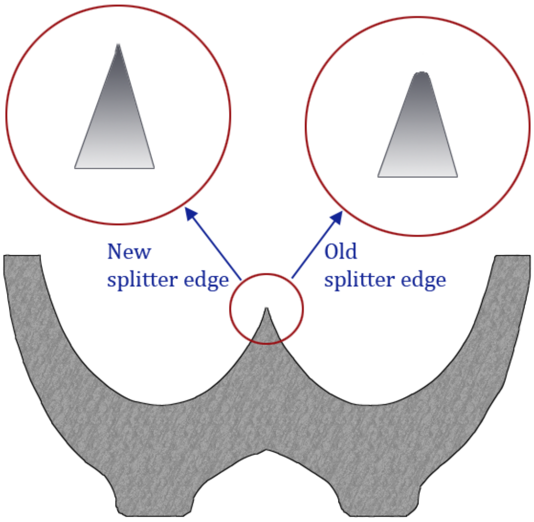


Figure 2.24: The degrading of the splitter edge will reduce the efficiency of the pelton turbine

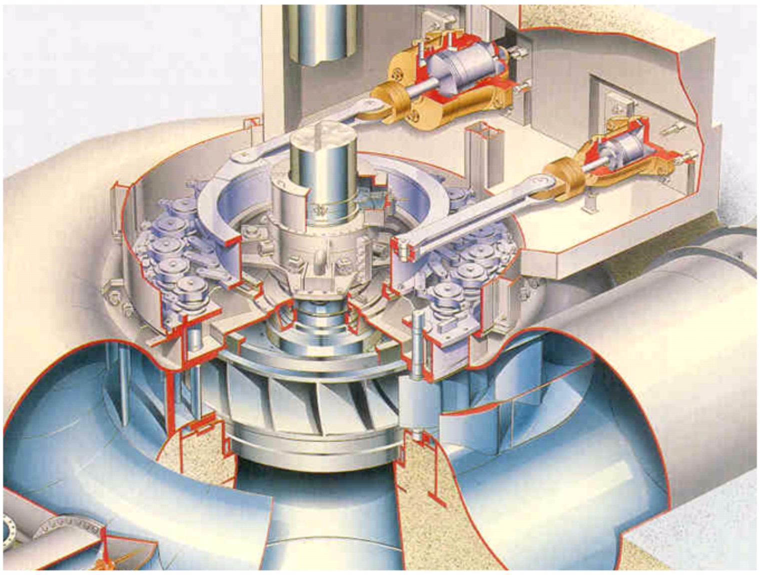


Figure 2.25: A Francis drawing, made by Kværner, taken from lecture notes, [7].

turbine, made by Kværner, is shown in figure 2.25.

The Francis turbine is a reaction turbine, which means that the energy is converted from pressure energy to mechanical energy through the runner. Illustrated by the energy diagram shown in figure 2.26.

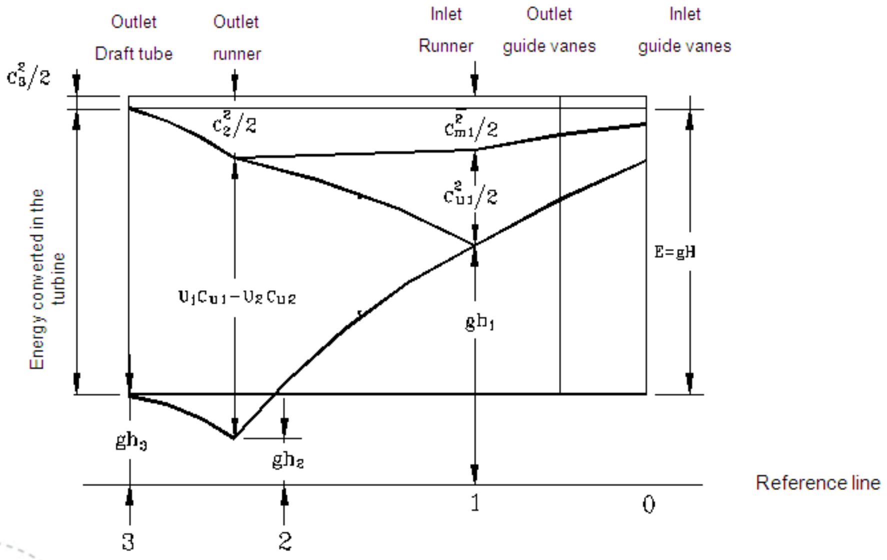


Figure 2.26: The energy diagram of a Francis turbine

Design of a Francis

Before the design process of a Francis turbine is started, some main data are needed. That is the head, the flow of the Best Efficiency Point (BEP), the frequency of the grid, and the turbine center line. The general layout of a Francis turbine is shown in figure 2.27.

Some of the design theory is also taken from Brekke's *Pumps and turbines*, [2].

The rotational speed of the runner at the outlet is denoted U_2, and is estimated based on empirical data and experience. Another assumption used for the design purpose is the zero rotation, and zero losses at the outlet, and hence the absolute peripheral velocity at the outlet, c_{u2}, equals zero. The outlet angle of the runner vane, β_2, is also assumed based on experience. The two parameters are in the following ranges:

- $13° < \beta_2 < 22°$
- $35 \text{ m/s} < U_2 < 43 \text{ m/s}$

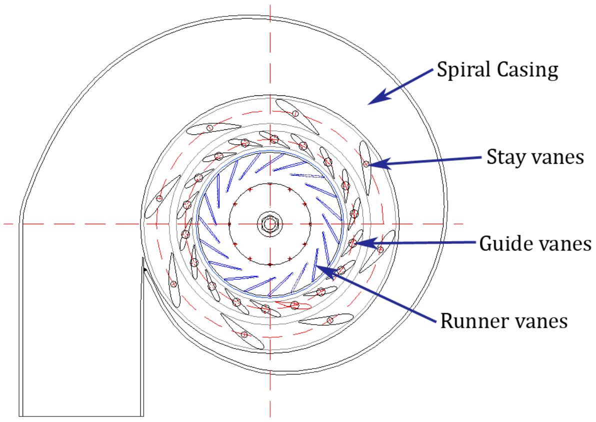


Figure 2.27: The general layout of a Francis turbine, showing the runner, guide vanes, stay vanes and the spiral casing, [7].

[7]

The velocity diagrams for the inlet, and the outlet of the runner vanes are shown in figure 2.28.

Figure 2.28 and figure 2.29 gives some relations; The absolute velocity at the outlet, c_{m2}, is given in equation 2.61.

$$c_{m2} = U_2 \cdot \tan(\beta_2) \quad [\mathrm{m/s}] \tag{2.61}$$

An over load coefficient is often set to $k = 1,2$. And thus the volume flow for the BEP can be decided, equation 2.62.

$$Q^* = \frac{Q_n}{k} \quad [\mathrm{m^3/s}] \tag{2.62}$$

The next step is to calculate the diameter at the outlet of the runner, D_2. That is done by continuity, equation 2.63.

$$D_2 = \sqrt{\frac{4 \cdot Q^*}{\pi \cdot c_{m2}}} \quad [\mathrm{m}] \tag{2.63}$$

Now the rotational frequency, n, in rotations per minute can be found through equation 2.64.

$$n = \frac{60 \cdot U_2}{\pi \cdot D_2} \quad [\mathrm{rpm}] \tag{2.64}$$

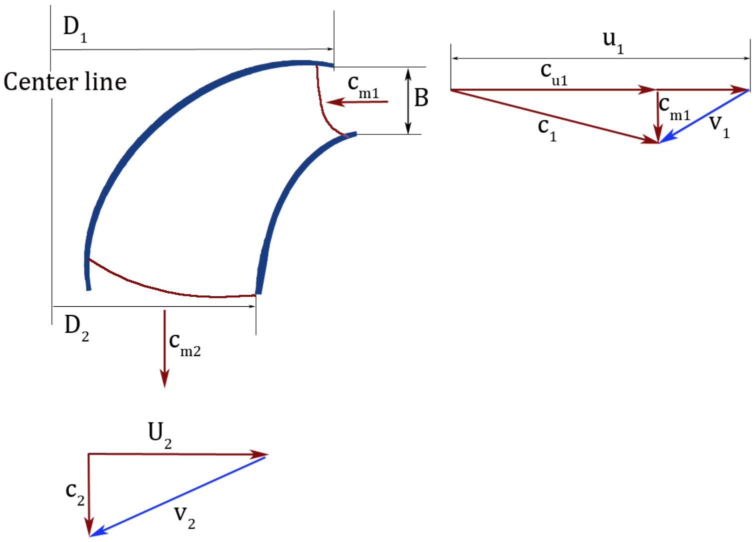


Figure 2.28: The velocity diagrams of the Francis runner.

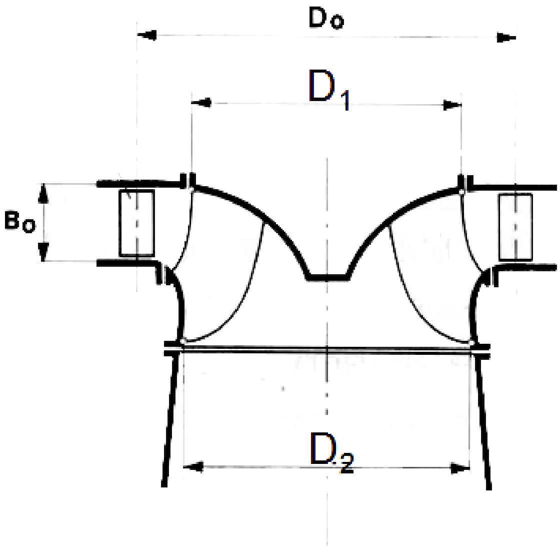


Figure 2.29: The axial view of a Francis runner, and the main dimensions, [7].

This rotational frequency is not necessarily correct, according to the synchronous rotational frequency. Thus it has to be corrected with formula 2.65.

$$n = \frac{60 \cdot f}{p} \quad \text{[rpm]} \tag{2.65}$$

Where f is the grid frequency, and p is the number of pole pairs. In both Norway and Nepal, the frequency is 50 Hz.

The other values already decided also have to be corrected. The outlet triangle should keep it's original shape, and thus the correction formula will be as shown in equation 2.66

$$\tan \beta_2 = \frac{c_{m2}}{U_2} = \frac{c_{\mathrm{m,corr}}}{U_{2,\mathrm{corr}}} = \frac{\frac{4Q}{\pi \cdot D_2^2}}{\frac{\pi}{60} \cdot n \cdot D_2^2} = \frac{\frac{4Q}{\pi \cdot D_{\mathrm{corr}}^2}}{\frac{\pi}{60} \cdot n_{\mathrm{corr}} \cdot D_{\mathrm{corr}}^2} \tag{2.66}$$

$$\rightarrow n_{\mathrm{corr}} \cdot D_{2,\mathrm{corr}}^3 = n \cdot D_2^3$$

$$\rightarrow D_{2,\mathrm{corr}} = \sqrt[3]{\frac{n \cdot D_2^3}{n_{\mathrm{corr}}}} \quad \text{[m]}$$

A Francis turbine is often submerged, in order to avoid cavitation at the runner outlet. The amount of submergence is decided based on equation 2.67

$$NPSH < \frac{c^2}{2 \cdot g} - f_{\text{draft tube friction}} = h_{\mathrm{b}} - h_{\mathrm{va}} - h_{\mathrm{s}} \quad \text{[m]} \tag{2.67}$$

NPSH is the net pressure suction head, this is the flow losses through the draft tube. The water velocity is denoted c, h_b is the atmospheric pressure, h_{va} is the vapour pressure, and h_s is the submergence of the turbine. It might be difficult to calculate the water velocity c, but an empirical formula can be used instead, equation 2.68.

$$NPSH = a \cdot \frac{c_{m2}^2}{2 \cdot g} - b \cdot \frac{U_2^2}{2 \cdot g} \tag{2.68}$$

Here a and b is found based on experience, while c_{m2} is the median velocity at the outlet. The constants a and b are depending on the speed number, which has been derived in section 2.7.1.

- $1,05 < a < 1,15$

- $0,05 < b < 0,15$

The inlet diameter of the runner , D_1, and the peripheral velocity at the inlet, U_1, is found based on the assumption that the reaction degree is equal to 0,5. The equation expressing the degree of reaction is shown in equation 2.69.

$$R = 2\underline{U}_1 \cdot \underline{c}_{u1} - \underline{c}_{u2}^2 \tag{2.69}$$

Combining equation 2.69 with Euler's turbine equation 2.54, the reduced peripheral velocity of the water can be calculated, equation 2.70.

$$\underline{c}_{u1}^2 = \eta_h - R \tag{2.70}$$

Now the reduced peripheral velocity, $\underline{U}_1$, and the inlet diameter, D_1 is found in equation 2.71 and 2.72.

$$\underline{U}_1 = \frac{\eta_h}{2 \cdot \underline{c}_{u1}} \tag{2.71}$$

$$D_1 = \frac{60 \cdot U_1}{\pi \cdot n} \quad [\mathrm{m}] \tag{2.72}$$

In order to secure no back flows through the runner vanes, a 10% increase in the area is used, equation 2.73.

$$A_{\text{inlet}} = 1,1 \cdot A_{\text{outlet}} \quad [\mathrm{m}^2] \tag{2.73}$$

Now it is time to calculate the inlet height of the runner vanes, B_1. This is done based on the inlet and outlet area, shown in equation 2.74.

$$B_1 = \frac{A_{\text{inlet}}}{\pi \cdot D_1} \quad [\mathrm{m}] \tag{2.74}$$

In the end the inlet absolute peripheral velocity of the water, c_{u1}, and the inlet angle, β_1, is found from the geometry of the velocity triangles shown in figure 2.28. In equation 2.75 and 2.77, c_{u1} and β_1 are derived.

$$c_{u1} = \frac{Q^*}{\pi \cdot B_1 \cdot D_1} \quad [\mathrm{m/s}] \tag{2.75}$$

The outlet absolute median velocity is 10% higher than at the inlet. At the inlet c_{m1} is shown in equation 2.76.

$$c_{m1} = \frac{c_{m2}}{1,1} \quad [\mathrm{m/s}] \tag{2.76}$$

$$\beta_1 = \arctan \frac{c_{m1}}{u_1 - c_{u1}} \quad [^\circ] \tag{2.77}$$

Design of Francis guide vanes

The purpose of the guide vanes of a Francis turbine is to regulate the volume flow through the turbine. It is important that the guide vanes are capable of stopping the volume flow. The number of guide vanes in a Francis turbine can vary, but normally the number is about 24 vanes. Figure 2.30 shows a plot of guide vanes against the speed number, taken from the lecture notes, [7].

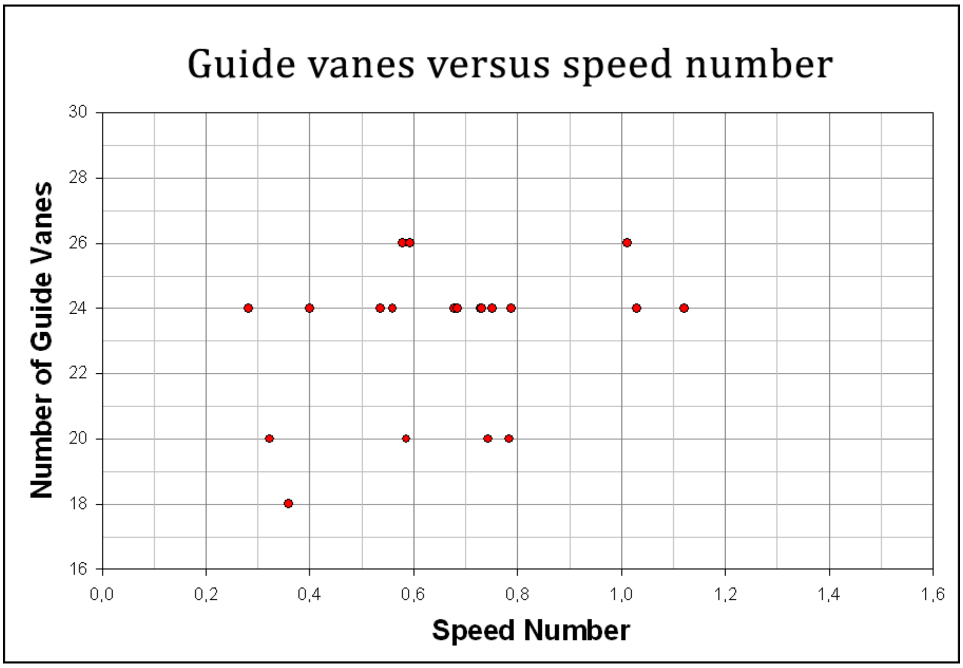


Figure 2.30: The number of guide vanes as a plot against the speed number. Taken from the lecture notes by Ole Gunnar Dahlhaug, [7]

The gap between the runner and the guide vanes is often set to a 5% increase of the runner diameter, equation 2.78

$$D_{\text{Guide vanes outlet}} = D_1 \cdot 105\% \quad [\mathrm{m}] \tag{2.78}$$

The height at the outlet of the runners is often set 1 mm higher than the runner inlet, to ensure accelerating flow, shown in equation 2.79.

$$B_0 = 0,005 + B_1 \quad [\mathrm{m}] \tag{2.79}$$

Figure 2.31 gives an overview of the different diameters in the Francis turbine.

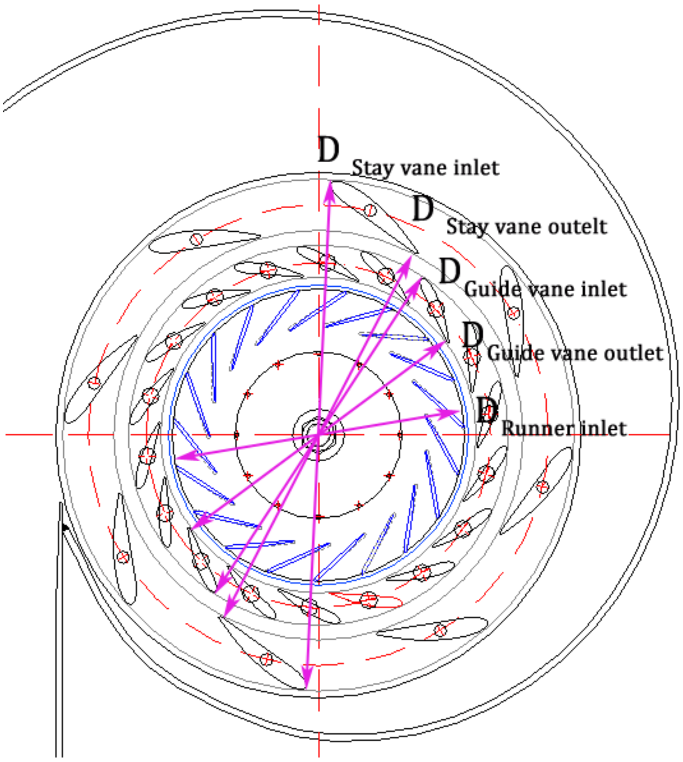


Figure 2.31: The different diameters in the Francis turbine. Figure is taken from lecture notes by Ole Gunnar Dahlhaug, [7].

A free vortex is assumed between the outlet of the guide vanes, and until the inlet of the runner, the velocity out from the guide vanes is given in equation 2.80.

$$c_{\mathrm{u,\,gvo}} = \frac{c_{u1} \cdot D_1}{D_{\mathrm{gvo}}} \quad [\mathrm{m/s}] \tag{2.80}$$

The median absolute velocity out from the guide vanes are given by equation 2.81, where it is assumed that the thickness of the guide vanes are approaching zero.

$$c_{\text{m, gvo}} = \frac{Q}{\pi \cdot B_{\text{gvo}} \cdot D_{\text{gvo}}} \quad [\text{m/s}] \tag{2.81}$$

Where the subscript *gvo* stands for guide vane outlet.

The outlet angle of the guide vane is given in equation 2.82.

$$\beta_{gvo} = \arctan \frac{c_{\text{m, gvo}}}{c_{\text{u,gvo}}} \quad [^\circ] \tag{2.82}$$

The maximum outlet angle is set 150% higher than the calculated outlet angle at design flow. This is found from the lecture notes examples, [7].

The guide vane shaft diameter, that is the diameter from the axis of the guide vanes, is found by the empirical equation 2.83.

$$\frac{D_0}{D_1} = 0,29 \cdot \Omega + 1,07 \tag{2.83}$$

The next step of the design is to choose the number of guide vanes, the length of the guide vanes, and the length of the leading edge of a guide vane. A symmetrical shape is chosen for the guide vane, figure 2.32. The length of the guide vane is chosen based on 20% overlap in closed position.

The preliminary equation for the guide vane length is shown in equation 2.84.

$$L = \frac{D_0 \cdot \pi \cdot 120\%}{\text{Number of guide vanes}} \quad [\text{m}] \tag{2.84}$$

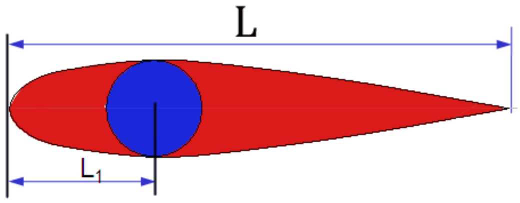


Figure 2.32: Example of a guide vanes, [7].

When the lengths are decided, the inlet angle of the guide vane can be calculated. Now the overlap between each guide vane has to be checked, so that no leakage is possible. An investigation if it the guide vanes will get close to the runner at full opening has to be done. The angles are calculated by trigonometry.

The angles and distances of the guide vane are shown in figure 2.33.

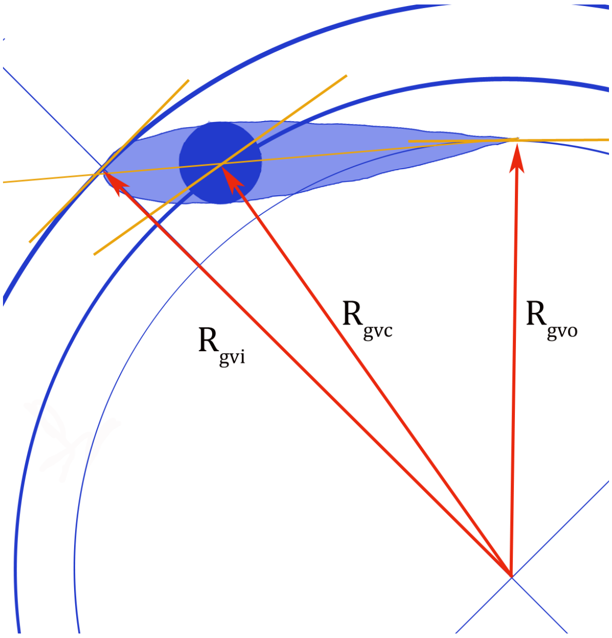


Figure 2.33: The angles and diameters of the guide vane.

2.7.4 The choice between Francis and Pelton

There are several criteria for choosing between a Pelton and a Francis runner. This section will give an overview of the different aspects.

As shown in figure 2.17, the choice between Francis and Pelton can be based on the speed number. But the speed number is changeable, by adjusting the parameters and dimensions.

Head

The first criteria to be evaluated for the choice between Francis and Pelton, is the head available for the power plant. Francis turbines are not to be used for too high heads. It is not an exact answer for where the limit is placed, but an example is shown in figure 2.34. Which shows that the limit is about 700 meters. The reason why Francis is only used for head below 700m is the high pressure that would cause buckling of the covers of the turbine. It is possible to design a Francis turbine that could withstand high pressures, but that would be too expansive to be profitable, [8].

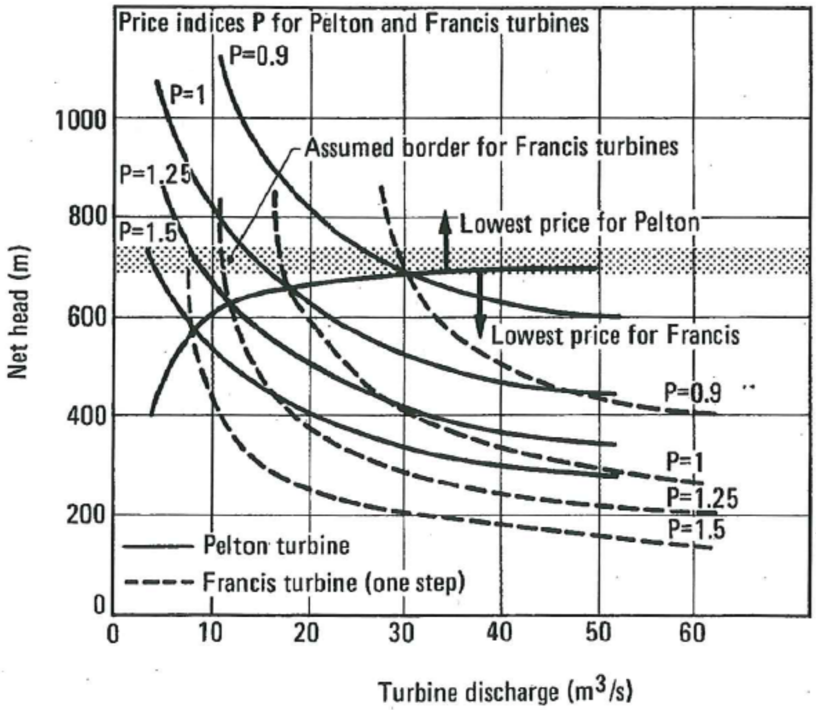


Figure 2.34: The choice between francis and pelton based on the price of the units. From [2].

Efficiency

The efficiency curves of the Francis and Pelton turbine are different. The Francis turbine will reach the highest efficiency, while the Pelton turbine's efficiency will stay high for a larger range of loads. The curves can be seen in figure 2.35.

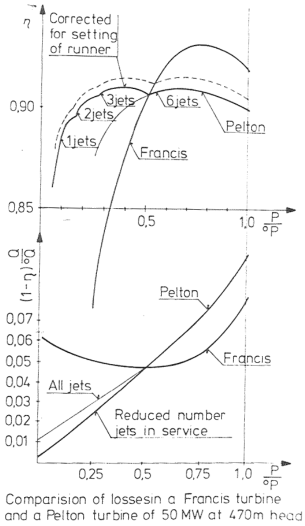


Figure 2.35: The choice between francis and pelton based on the efficiency and losses. From [2].

Price

The price of the two different constructions is another element when making the choice, also shown in figure 2.34. The price of a Francis unit will increase as the height is increasing. The reason for this is mainly the increase in material used in the construction. The higher heights, the more material is used to withstand the pressure. For the Pelton turbine this correlation between height and price is not as prominent. Which makes the price of a Pelton turbine favorable at heights above 700 meters.

Maintenance

The maintenance aspect is important at Kirne, and in Nepal generally. Specially because of the heavy erosion, already described in section 2.3.

Khimit I has an extensive maintenance programme, where each runner has a spare runner for replacement while the other runner is grinded. The cycle repeats itself each year just after the wet season.

The Pelton runner is easily replaced, and the production only has to be stopped for a few hours to remove the wared runner, and to insert a newly grinded runner. At Khimti I the staff has the expertise, to maintain the Pelton runners, and the maintenance can be done at site.

A Francis runner is more difficult to maintain at site. It is also more difficult to to grind a Francis runner in a proper way, and to secure a good result and efficiency.

For the turbine chosen in the end it is important that a maintenance scheme is made for the life time of the turbine. The production stop should be minimized when the maintenance is ongoing.

The advantage of Kirne is that the runners are only to be operated during the monsoon period. Thus the dry season can be used for maintenance and repair of the runners.

2.8 Costs

2.8.1 Pressure shaft

The cost of the pressure shaft is based on the steel price and the amount of steel used in the pipe. The formula for calculating the cost is given in equation 2.85

$$\text{Cost} = m \cdot M = \rho_m \cdot V \cdot M = \rho_m \cdot \pi \cdot D \cdot L \cdot t \cdot M \quad [\text{USD}] \tag{2.85}$$

Where m is the mass of the material, M is the material price, and ρ_m is the density of the material. The thickness of the material is represented by t.

2.8.2 Turbines

The cost of the turbines will be based on the handbook from NVE, the Norwegian Electricity Industrial Asocciation. The results are based on similar experiences in Norway.

Chapter 3

Method

This chapter will present the methods and tools used to reach the results of the thesis. Appendix G shows a summary of how the calculations in the Excel sheet is organized. The Excel sheet is used to calculate the dimensions of the runners, analyze the hydrology, and decide other dimensions.

3.1 Hydrology

The results from the Rausnalu Gauging station over the last 38 years have been collected. The data is averaged and rearranged so that the exceedance of the different flow rates are visualized in the duration curve. The duration curve for the wet season is also produced, since this is the period of interest for Kirne.

The hydrology data are corrected due to the increased catchment area between the gauging station and the intake to Khimti I. The correction uses the catchment areas given in the feasibility study report [11]:

- Rasnalu Gauging station, total 304 km^2, 302 km^2 below 5000 m.a.s.l.
- Intake, Khimti I, total 358 km^2, 356 km^2 below 5000 m.a.s.l.

The result and design of Kirne Power Plant will be dependent on the possible amount of water.

3.2 Sediment handling

The most important question for the sediment handling, is the size of the settling basin, and if there is room for making an enlarged basin or an extra basin at the intake of Khimti I. The size of the basin is directly proportional to the volume flow through the system. As described in section 2.3 the basin has to be designed following certain rules. Today the basin has a capacity of about 10 m^3/s. In the theory section 2.3 and in Appendix B, it is shown that the efficiency of the settling basin is porpotional to the cross sectional size.

In this thesis a suggested new area will be used, and it is assumed that the new sediment handling works satisfactory. The accurate dimensions and design will not be calculated.

3.3 Head losses

The head losses need to be calculated for different purposes.

3.3.1 Head loss in tunnel - tunnel capacity

The head losses encountered in the tunnel of Khimti I are calculated by the Manning's formula 2.4, given in section 2.4. The exact head loss in the tunnel is known at a given volume flow, through the head loss measurement report made by Statkraft Grøner, [14]. Then it is possible to calculate the Manning number.

The length of the tunnel is found from the *As built drawings*, [17], and equal to: 7885 m. The average cross-sectional area of the tunnel is 11,6 m^2. The average area is used through the whole tunnel, and it is not taken into account that the tunnel has summit and valley points along the way.

The tunnel capacity can be based on the head losses in the tunnel. If the total losses are larger than the difference between the intake level, and the lowest down surge limit, it will result in air suction. The corresponding volume flow will give the maximum tunnel capacity.

Increased head loss for Khimti I

Due to the increased head losses in the tunnel, also the head of Khitmi I will be reduced. The power output of Khimti I is supposed to be maintained, and the volume flow to Khimti I has to be increased as shown in equation (3.1).

$$P\text{, original} = \rho \cdot \eta \cdot g \cdot Q \cdot H \quad [\mathrm{MW}] \tag{3.1}$$

$$P\text{, new} = P\text{, original} = \rho \cdot \eta \cdot g \cdot (Q_{\text{original}}+Q_{\text{added}}) \cdot (H_{\text{original}}-\Delta H_{\text{added}}) \quad \text{[MW]}$$

3.3.2 Head loss in pipe

The head losses in the pipes are calculated by formula 2.6 in section 2.4. The friction factor is found from the Moody chart, which is enclosed in Appendix D.

The head losses for the pipes are calculated for a range of volume flows. An economic optimal diameter is used in the calculations. The method for finding the correct diameter is given in section 2.6.6.

3.4 Stability

The stability of Kirne Power Plant is dependent on the surges in the surge shaft.

The surges have to be calculated based on the volume flow, the closing time of the valves, and the friction in the water way. When the surges are calculated the results are compared to the given surge limits. If the surges exceed the limits, the shaft or the other elements in the water way will require changes.

The surges are calculated by the estimation formulas given in the last part of section 2.5. The up-surge is calculated for a sudden load rejection, and the down-surge is calculated for a sudden gate opening. It is assumed that there is an immediate change from full load to zero load, or the opposite.

Increasing the cross section of the surge shaft

When the surges are above the tolerated limit, the surge shaft can be expanded, and thus increasing the volume. In figure 3.1 an illustration of how the problem can be solved, is shown.

If the down-surge is the problem, the closing time of the valves can be prolonged to reduce the down-surge.

3.5 The elements of the power plant

Since it is the mechanical aspect that is most important for this thesis, the civil elements of the power plant will only be roughly calculated to give an

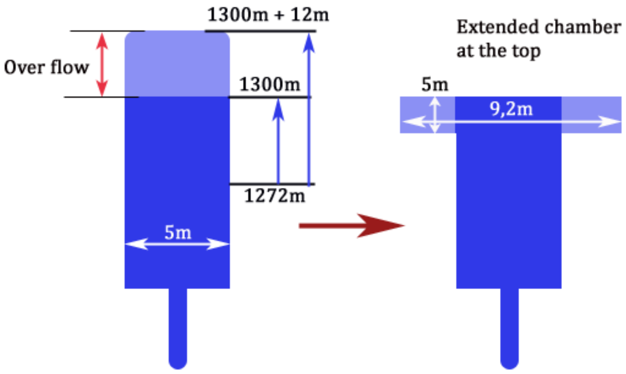


Figure 3.1: Excavation of surge chamber instead of overflow.

overview and understanding. The detailed calculations will be left to the further work.

When altering the elements of the power plant, and especially in the existing water way, it is important to remember that Khimti I is a running plant, and thus as small as possible production losses are desired.

3.5.1 Intake

The intake has to be enlarged to handle the increased volume flows. Only the rough size is calculated, based on a doubling of the volume flow.

3.5.2 Tunnel

Figure 3.2 shows the average cross section of the tunnel. It is assumed that no changes will be made to the cross section. The losses are calculated, and improvements could be made to reduce those, but that is not the field of this thesis.

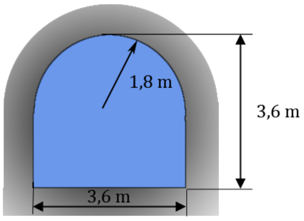


Figure 3.2: The cross section of the tunnel.

Figure 3.3: The new pressure shaft of Kirne Power Plant, as it is planned.

3.5.3 Sand trap

The sand trap will be dealt with in the same way as the tunnel. Changes are required to increase trapping efficiency. The changes will not be calculated here. It is assumed that the sand trap works satisfactory for the design of the rest of the plant.

3.5.4 Surge shaft

The surge shaft should not be altered too much in the lower part. Due to the running of Khimti I simultaneously with the construction of Kirne. If the surge shaft needs to be altered, this should be done by excavation in the upper part.

3.5.5 Pressure shaft

Figure 3.3 shows the new planned external pressure shaft for Kirne.

The optimal diameter of the pressure shaft is calculated in Excel, based on the marginal cost of the installation and the accumulated losses that will occur during the first 20 years of operation. The principle of the method is shown in figure 3.4.

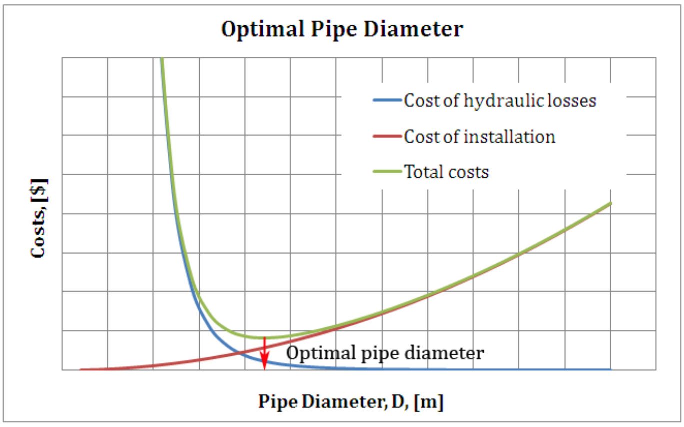


Figure 3.4: The principle of finding the optimal pipe diameter

The optimal pipe diameter is found when equation 3.2 is satisfied.

$$\frac{\mathrm{d}K_{tot}}{\mathrm{d}D} = \frac{\mathrm{d}(K_f + K_t)}{\mathrm{d}D} = 0 \tag{3.2}$$

3.5.6 Power house

The power house will be an outdoor construction, but the construction will not be described her. As for some of the other civil elements, it is assumed that the construction is not a problem, and that the final building will work satisfactory for the purpose. The power house will be dependent on the type of turbine chosen, and number of units.

3.5.7 Draft tube

A draft tube is only neccesary if it is a Francis turbine that is the chosen solution. The size of the draft tube is dependent on the amount of submergence that is necessary in order to avoid cavitation at the outlet. The draft tube will not be investigated here.

3.5.8 Outlet

The planned outlet for Kirne is through an already existing canal, which only has to be excavated deeper and wider. This canal is shown in figure 3.5.

The final capacity of the canal should be the volume flow from Kirne together with possible flooding during the monsoon period.

Figure 3.5: The planned outlet from Kirne, through the existing canal shown.

3.6 Turbines

When deciding the type of turbine to be used in Kirne, several parameters are to be evaluated. First the empirical laws are set up, to eliminate unrealistic possibilities. The speed number is calculated for different volume flows through the turbine. Then it is possible to draw a theoretical line between a Pelton and a Francis turbine. The speed number limit of 0,22, as shown in the theory section 2.7.1, has to be followed here.

When the possibilities for the technical design are set, the other parameters are evaluated. Which turbine is the most suitable to tolerate the sand erosion? The economic gain on the better efficiency of a Francis turbine is evaluated against the turbine prices, and possibilities for maintenance.

3.6.1 Speed number

The speed number is found at different available volume flows, and is the first indicator of which turbine that should be chosen.

In the Excel sheet a selection of volume flows are used, and the speed numbers are calculated based on different rotational frequencies. A graph is then plotted, and shows the border between a Francis and a Pelton turbine.

3.6.2 Pelton turbine

Main dimensions

The main dimensions are first calculated following the designing procedures given in the theory section, section 2.7.2. Based on the theory of Brekke,[2], and lecture notes, [19].

When the first design is finished it is attempted to get the speed number closer to 0,1, to increase the performance. This is mainly done by increasing the diameter ratio of the runner. The ratio can be increased by up to 20%.

Number of nozzles

To decide the number of nozzles experiences and empirical data are important elements. In this work, a list of turbines produced by Rainpower, former GE and Kværner, was used as a reference. The list contained data of 38 Pelton turbines with head ranging from 82 m to 1034 m, and power ranging from 0,8 MW to 280 MW. The data given were the number of nozzles, the arrangement of the turbine, if it is horizontal or vertical axis, the head, the power, and the rotational frequency.

From the list from Rainpower the volume flows of the different turbines were calculated from the general power equation for turbines, equation 2.44. The general efficiency was assumed to be 0,92. When this was done it was possible to plot a scatter combining the reduced volume flow, and the number of nozzles, for each of the 38 turbines. The relation between the two gave a correlation that could be used for deciding the number of nozzles.

In addition to the empirical data, the desired properties of the runner at Kirne has to be taken into account. The efficiency and load range are important in this process.

Efficiency curve

The efficiency curve is estimated from the NVE book, [24], and shown in figure 3.6. When the efficiency graph is used in the model, the maximum volume flow is set to 17 m^3/s, in order to place the BEP at 11 m^3/s. The efficiency curve of the final design might be different from the example curve, but the shape of it is representative.

3.6.3 Francis turbine

Main dimensions

The design of the Francis runner follows the procedures described in the theory section, section 2.7.3. The design is based on some assumed values, which will have effect on the final design. The assumptions are based on experienced runner designers. The effect of altering some of the parameters is shown in the results section, and the design chosen for the possible Francis runner of Kirne is a very traditional design following the rules.

When designing the guide vanes, simplifications are used, since this is done only to get the main dimensions, not the total design of the vanes. When adjusting the thickness of the guide vanes, only the water velocity through the channels will be altered. Since the flow conditions are not considered in this thesis the thickness calculations will not be necessary.

The stay vanes and spiral casing are not calculated in this thesis, but the procedure is shown in Appendix F.

3.6.4 Maintenance

The maintenance is not a quantitative size, and that is also a problem when money should be allocated for the purpose. It is easy to see the costs of maintenance, but more difficult to quantify the gain from good maintenance. The maintenance will be discussed in the discussion section.

3.6.5 Choice of turbine

The choice of turbine is based on the results found, and the qualitative and quantitative evaluations in the end. The decisions will be accounted for in the discussion section.

3.7 Costs estimates

Only the pressure shaft and the turbine is cost estimated, other elements that will add considerable costs to the building of Kirne Power Plant will be:

- Sediment basin
- Tunnel, improvements
- Surge shaft, improvements

- Sand trap, improvements and enlargement
- The power station
- Various equipment for the turbine
- Canal, extra excavation, not the whole canal.
- Generator
- Transformer

The generator and the transformer could be calculated from the hand book, but are not prioritized here.

3.7.1 Pressure shaft

The cost of the pressure shaft can be estimated based on the guidelines of the NVE handbook. And also by estimating the weight of the pressure shaft and then use the steel price to calculate the price of the whole shaft. The steel price of an assembled shaft is between 50 and 70 NOK/kg, which is equal to 7,5 to 10,5 USD/kg, given by Kjell Finnerud and Hans Aunemo at Sweco Norge AS.

Using the NVE handbook the price of the pressure shaft is calculated in three steps. The construction and contractor costs, the mechanical costs and the owners costs. The construction costs are given in figure B.9.1 in the NVE handbook, [24]. In this figure it is possible to read out the cost per meter of pipeline, based on the diameter of the pipe. The diameter is the economic correct diameter. For the contractor costs, 50% can be added for difficult terrain.

The mechanical costs are given in figure M.6.A in the NVE handbook, [24]. In this figure the equations for the prices based on different heads and different diamteres are given. The equation for a pipeline with a head of 660 meters is found by linear regression between the price for 600 meters head and 800 meters head.

The last part of the price is the owners expenses of the construction. The owners expenses includes the planning costs, the financing, the taxes, local transport, advising and other unforeseen costs. In this thesis the owners expenses are assumed to be 25% of the mechanical and constructor costs.

The handbook was published in 2005, and recent experiences tell that 50% should be added in 2009, to acheive a more correct price estimate. [22].

3.7.2 Turbines

The prices of the different turbines are also taken form the NVE book. The curves given here are excluded the transport at site, the civil and electrical installation costs, the taxes and the expenses of the owner. Also for the turbines the recent experiences tell that 50% should be added to get a more realistic cost.

The prices are given as functions of the maximum volume flow, the net head and the rotational frequency. If there are more than one turbine that is ordered, the extra turbines will normally have a price reduction of 10%.

Efficiency curves

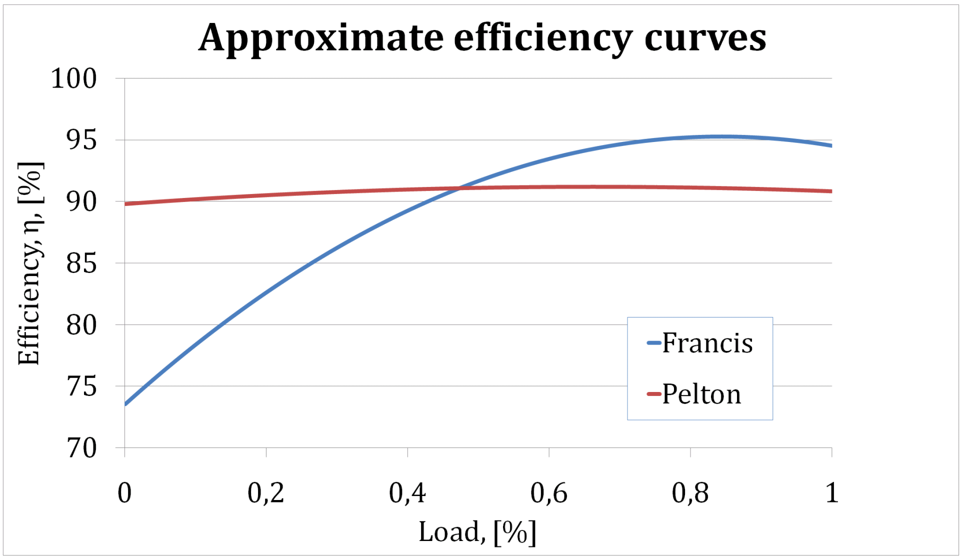


Figure 3.6: Standard efficiencies based on the NVE booklet. [24]

The NVE hand book gives information on general efficiency curves for 5 MW turbines and 100 MW turbines. The resulting turbine at Kirne will be about 50-60 MW, and the average of the NVE curves are used to get a representative graph for the efficiency of this unit. The equation for the two curves are given in equation 3.3 and 3.4.

$$\eta_{\text{ Francis}} = -30,61X^2 + 51,65X + 73 \tag{3.3}$$

$$\eta_{\text{ Pelton}} = -3,20X^2 + 4,24X + 89,78 \tag{3.4}$$

The curves are shown in figure 3.6, and are used in the calculations.

3.8 Assumptions

The assumptions used to reach a conclusion in the thesis are presented here.

Economy

It is assumed that the agreements with NEA and HPL or another owner is organized, and that there are no problems evacuating the power, either to India, or to Nepal. It is however obvious that this is a huge assumption, and that the largest share of the risks in the project are placed here.

Sediment handling

It is assumed that a new sediment basin works satisfactory, and that no extra sediment problems will be induced to Kirne.

General assumptions

The head of Kirne will be equal to a gross head of 672 m minus the head losses. The head of 672 m is equal to the head of Khimti I. In reality the head of Kirne might be a little less, since Kirne is placed upstream Khimti I, but this is not accounted for.

Tunnel

- The tunnel length is set to 7885 m in all the calculations.
- The tunnel length until Adit 4 is set to 7737 m.
- The tunnel roughness is calculated to a Manning number of 41.

Pressure shaft

The length of the pressure shaft is set to 1800 m. This is based on the first report, produced by Sweco and SN Power, a report to the investment committee.

Other assumptions and values chosen when calculating the optimal diameter of the pressure shaft is listed in the following list:

- Calculation factor, I; 8%
- Closing time for the turbine, T_C; 50 s
- Stresses in the material, σ_t; 206 MPa
- Power price, kWh_{price}; $0,08$ USD/kWh
- Volume flow, Q; 11 m/s
- Material Price, M; $7,6$
  $textUSD$/kg
- Time of operation, T; 3360 h
- Pressure rise due to water hammer, Δh_{wh}; $\approx$ 24 m
- Internal pressure in pipe, p; 7 MPa

Power prices

There will be done a rough sensitivity analysis of how the varying power prices will affect the outcome of the project, but the price that will be used otherwise is 5,5 US cent/kWh

Turbine

- Closing time, $T_C = 50$ s
- The designing efficiency used in the runner calculations, $\eta_h = 96\%$.
- Slim runner- and stay vanes in the Francis turbine, thickness approaching zero, and thus neglected.

Chapter 4

Results

4.1 Hydrology

The hydrology data are given by Lars Johansen at Sweco. The duration curve over the year is shown in figure 4.1. While in figure 4.2 the duration curve for only the wet season is shown.

The correlation factor is based on the catchment area at Rasnalu and at the Khimti intake. The equation is shown in equation 4.1.

$$\frac{356\ \text{km}^2}{302\ \text{km}^2} = 1,179 \tag{4.1}$$

The volume flow to the intake of Khimti I can be calculated as shown in equation 4.2.

$$Q_{\text{Khimti I intake}} = 1,179 \cdot Q_R - 0,5\text{m}^3/\text{s} \tag{4.2}$$

As both figure 4.2 and table 4.1 show, near 80% of the days, the flow is exeeding 20 m^3/s, and for near 70% of the days, the flow is exceeding 30 m^3/s. For 60% of the days, the flow is also exceeding 38 m^3/s.

Table 4.1: The percentage exceedance of increasing volume flows available for Kirne Power Plant.

Volume flow, [m^3/s]	*% Exceedance*
5	91,7
10	81,1
15	74,4
20	69,6

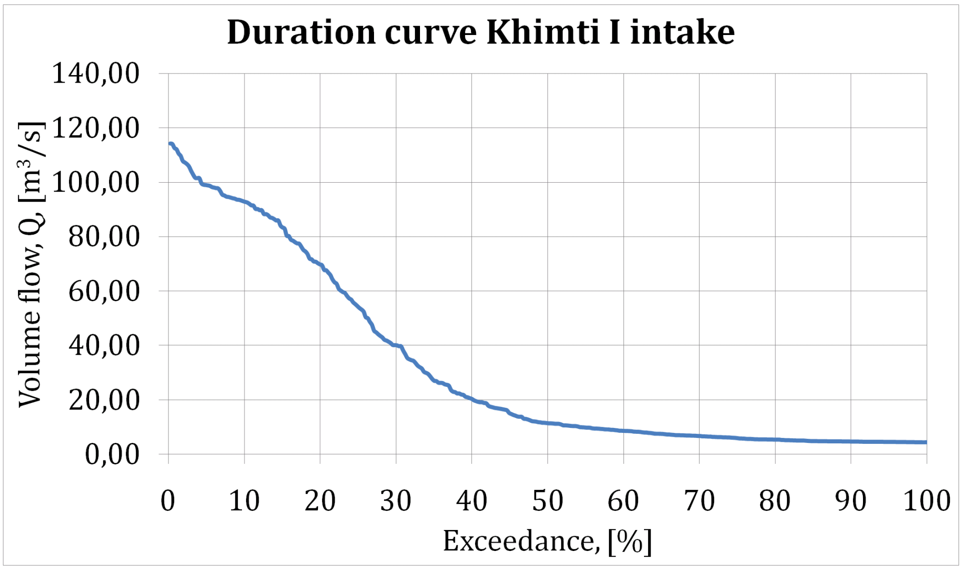


Figure 4.1: Duration curve for Khimti I through the year. Based on a 38 years average.

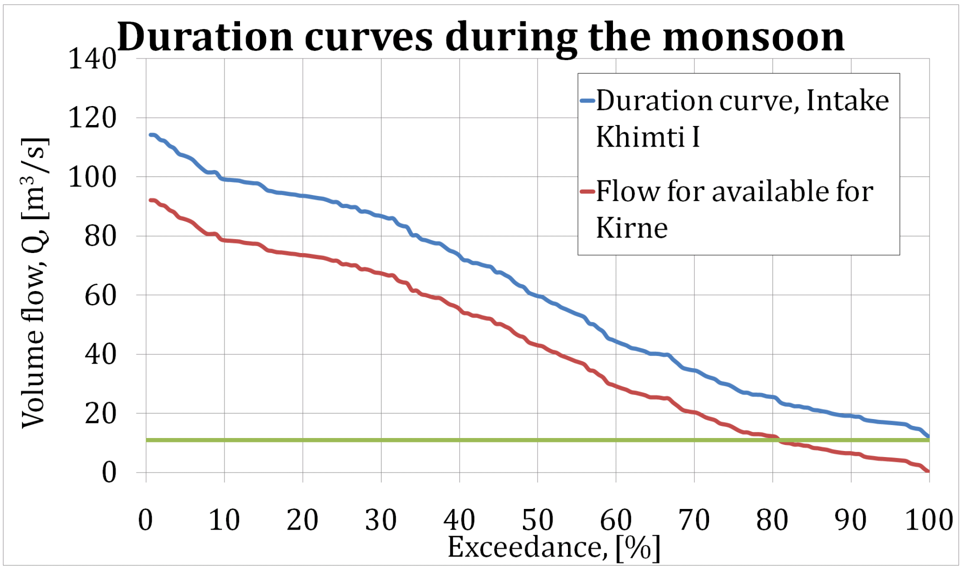


Figure 4.2: The duration curve for the wet season at Khimti I. Both for the whole Khimti I, and the flow available for Kirne Power Plant.

4.2 Sediment handling

4.2.1 Settling basin

The settling basin has to be enlarged proportional to the increase in the volume flow. When the volume flow is increasing from $10,75\ \mathrm{m}^3/\mathrm{s}$ to $22\ \mathrm{m}^3/\mathrm{s}$, the corresponding cross sectional area of the settling basin is shown in equation 4.3.

$$A_{\text{Original basin}} = 21,7\ \mathrm{m} \cdot 6,6\ \mathrm{m} \approx 143\ \mathrm{m}^2 \tag{4.3}$$

The new basin will require the same size as the original one, since it is a doubling of the volume flow. A drawing of the cross sectional area of the original basin is shown in figure 4.3.

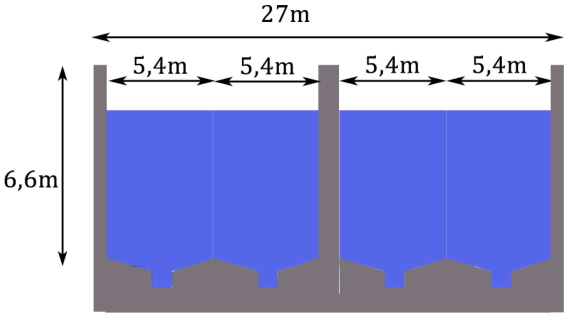


Figure 4.3: The main dimensions of the existing settling basin, a new one of similar size is to be built.

Fall velocity

The fall velocity that will ensure capturing in these basins is shown in equation 4.5, and the transient velocity is found based on the cross section, equation 4.4.

$$v_t = \frac{11\ \mathrm{m}^3/\mathrm{s}}{6,6\ \mathrm{m} \cdot 21,7\ \mathrm{m}} = 0,077\ \mathrm{m/s} \tag{4.4}$$

$$w = \frac{6,6\ \mathrm{m} \cdot 0,077\ \mathrm{m/s}}{90,8\ \mathrm{m}} = 0,0056\ \mathrm{m/s} \tag{4.5}$$

4.3 Head losses

4.3.1 Tunnel

Manning number

The Manning number of the tunnel, is found from the head loss measurement report, [14]. This report states that there is a head loss of $4,21$ m through the tunnel at a volume flow of $10,3\ \mathrm{m}^3/\mathrm{s}$. The corresponding calculation of the Manning number is shown in equation 4.6

$$M = \sqrt{\frac{L \cdot Q^2}{h_f \cdot A^2 \cdot R_h^{4/3}}} = \sqrt{\frac{7885\ \mathrm{m} \cdot 10,3\ \mathrm{m}^3/\mathrm{s}}{4,21\ \mathrm{m} \cdot 11,6\ \mathrm{m}^{2^2} \cdot 0,9^{4/3}}} = 41,22 \tag{4.6}$$

Head loss limit

The limit for the head loss is set by the lowest down surge. Equation 4.7 shows how the limit for the head loss is calculated.

$$h_{f,\ \text{limit in the tunnel}} = \text{Intake level} - \text{Lowest down surge} \tag{4.7}$$

$$h_{f,\ \text{limit in the tunnel}} = 1272\ \mathrm{m} - 1249\ \mathrm{m} = 23\ \mathrm{m}$$

The maximum volume flow in the tunnel will correspond to this head loss limit, 23 m. The graph in figure 4.4 illustrates this, and the principle is illustrated in figure 2.8 in the theory section 2.4.

The volume flow limit due to the head losses in the tunnel is $24\ \mathrm{m}^3/\mathrm{s}$, as can be seen from the graph in figure 4.4. To leave some space for the surges, the volume flow available for Kirne Power plant will be set to $11\ \mathrm{m}^3/\mathrm{s}$, and the same amount for Khimti I. The total volume flow allowed in the tunnel will thus be $22\ \mathrm{m}^3/\mathrm{s}$.

In table 4.2 the corresponding flow limits are shown, if the Manning number is changed.

Increased head loss for Khimti I

Khimti I will experience an increased head loss due to the increased volume flow in the tunnel. In figure 4.5 the gain from Kirne is plotted against the increased losses of Khimti I, over a year.

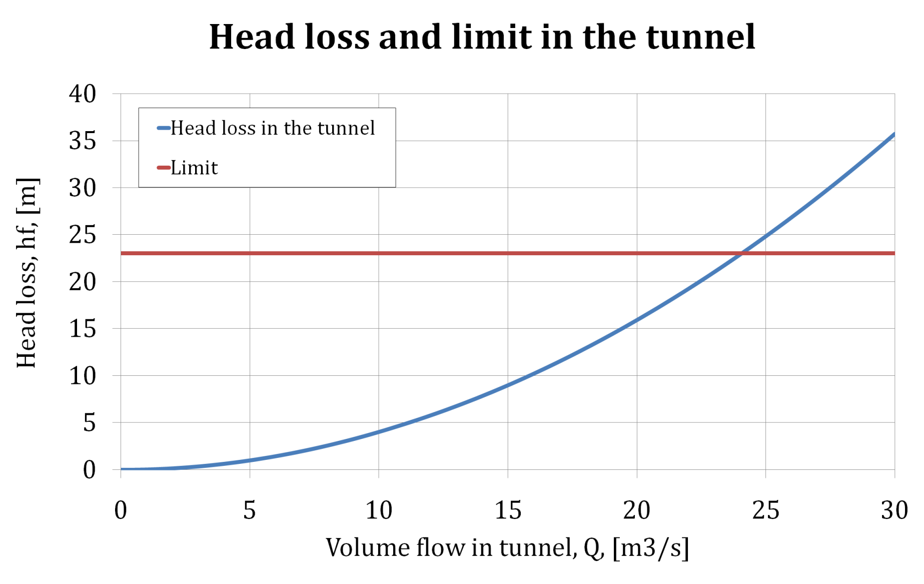


Figure 4.4: The head loss limit for increasing volume flow in the tunnel.

Table 4.2: Flow limits for different Manning numbers

Manning number	*Flow limit*
35	20 m^3/s
41	24 m^3/s
47	28 m^3/s

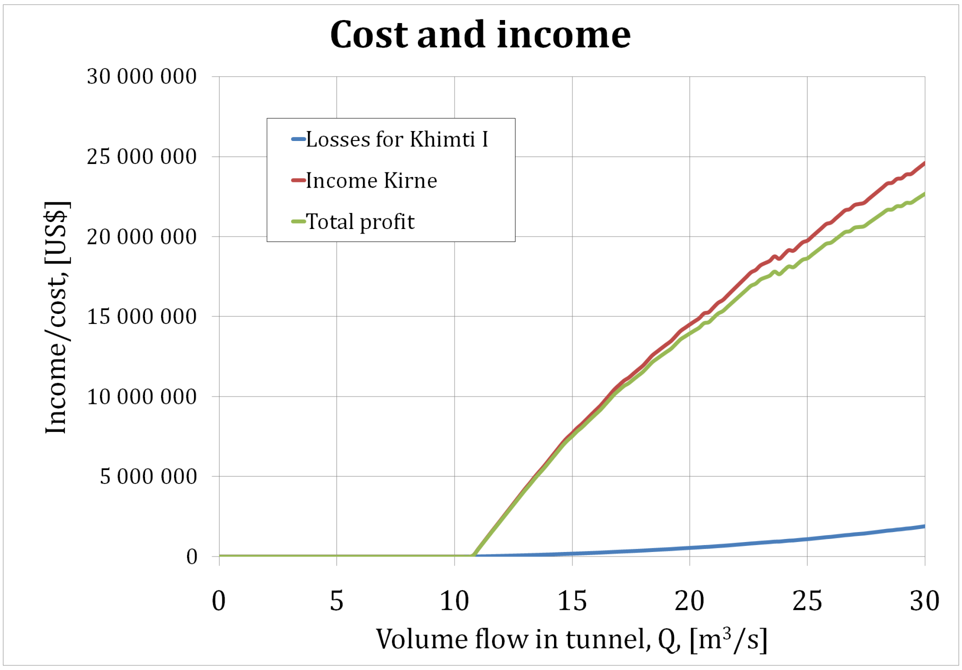


Figure 4.5: The result of the increased head losses for Khimit I, and the gain from building Kirne.

The increased losses of Khimti I will require 0, 25 m^3/s extra volume flow to maintain the power output of Kirne.

4.3.2 Pressure shaft

The head loss in the new pressure shaft with an optimal diameter of 2, 16 m is shown in figure 4.6. At the decided volume flow of 11 m^3/s, the total head loss for the new pipe is 3, 2 m.

4.3.3 Total head loss

The total head losses of the two power plants Khimti I and Kirne, are shown in figure 4.7.

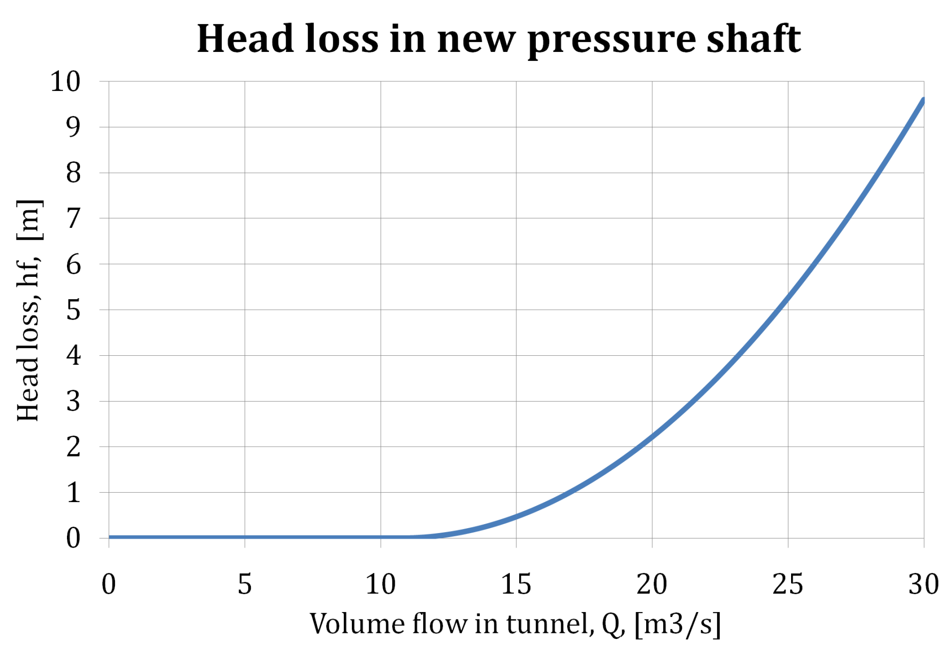


Figure 4.6: The head losses in the new pressure shaft to Kirne Power Plant, at a diameter of 2, 28 m.

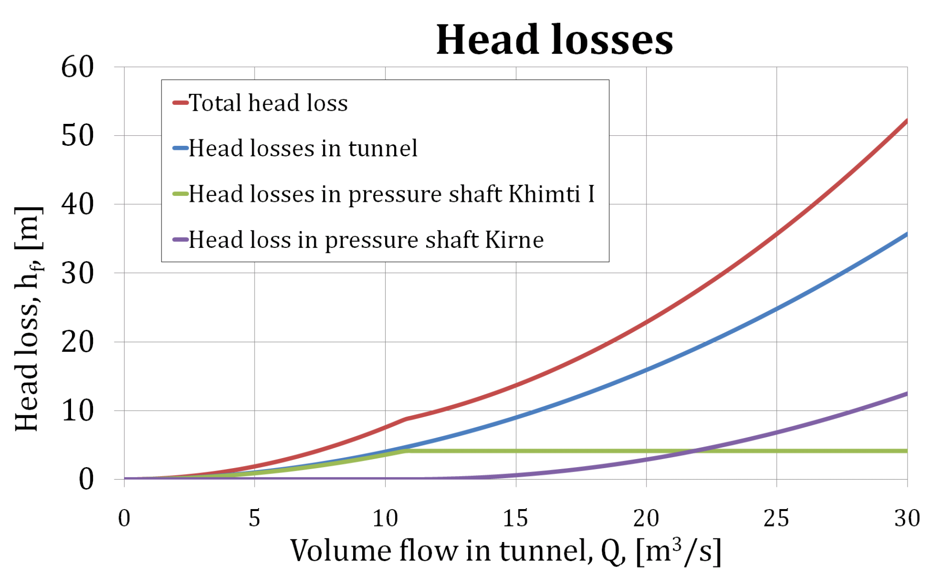


Figure 4.7: The head losses of Kirne and Khimti I.

4.4 Stability

4.4.1 Surge shaft

The original limits for the surges in the surge shaft is an up-surge of maximum 1300 masl, and a down-surge limit of 1249 masl. This leaves a few meter of margin between the top of the surge tank, and the tunnel roof at down-surge. [17].

To calculate the surges, the estimation equations given in the theory section are used, equations 2.22, 2.23 and 2.24. The resulting graph for increasing volume flows is plotted in figure 4.8. Also the limits are shown in this graph. These results are based on the original surge shaft without any changes made to it.

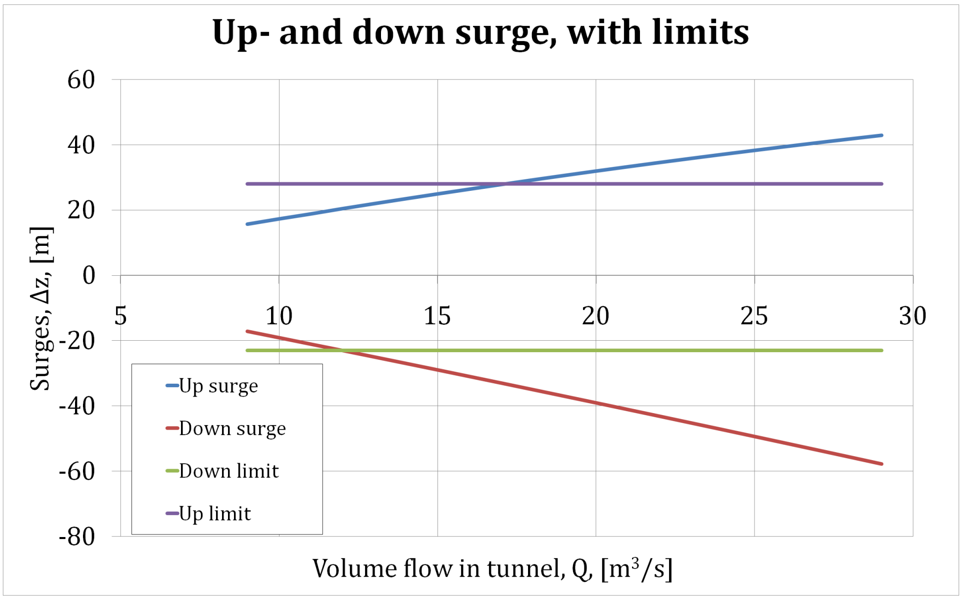


Figure 4.8: The surges as a function of the volume flow, and the predefined surge limits for the surge shaft at Khimti I.

4.4.2 The Thoma cross section

The Thoma cross section is calculated in equation 4.8.

$$A_{th} \approx 0,0085 \cdot \frac{41^2 \cdot 11,6\ \mathrm{m}^{2^{5/3}}}{660\ \mathrm{m}} = 1,29\ \mathrm{m}^2 \tag{4.8}$$

The smallest cross section in the existing surge shaft is:

$$A_s = \pi \cdot \frac{1050 \text{ mm}^2}{2} = 0,87 \text{ m}^2$$

Which means that the smallest cross section used today is too small to ensure stable u-tube oscillation in the tunnel. The problem will be discussed in the discussion chapter.

4.5 The elements of the power plant

4.5.1 Intake

The changes to the intake are calculated in the sediment section 4.2.

4.5.2 Tunnel

No changes are calculated for the tunnel in this thesis.

4.5.3 Sandtrap

The sand trap is also assumed to work satisfactory, no changes are calculated for the trap.

4.5.4 Surge shaft

The surge shaft has to be adjusted to tolerate the extra surges that are calculated in the stability section, 4.4. The surges corresponding to the different volume flows are shown in the graph in figure 4.8.

Table 4.3: The surges above the surge limit, and the corresponding water volume.

Volume flow, Q, [m^3/s]	12	14	16	18	20	22	24
Up surge, Δz, [m]	20,5	23,5	26,5	29,3	32,0	34,6	37,1
Down surge, -Δz, [m]	23	27	31	35	39	43,1	47,3
Surge above limit, [m]				1,3	4,0	6,6	9,1
Corresponding volume, [m^3]				25,23	78,7	130,2	179,5

At the flow limit of 22 m^3/s the up-surge is $34,6$ m. That is $6,2$ m above the surge limit, which gives the up-surge volume shown in equation 4.9.

$$\text{Volume} = \text{Extra up surge} \cdot \text{Cross section of shaft} = 6,6\ \text{m} \cdot 19,6\ \text{m}^2 = 130\ \text{m}^3 \tag{4.9}$$

This gives that at least 129 m^3 has to be excavated at the top of the surge shaft, so that the surges can expand freely at a sudden load rejection. If a safety factor of 1,3 is included, the excavated volume will increase:

$$\text{Total volume} = 1,3 \cdot 130\ \text{m}^3 = 169\ \text{m}^3$$

The down surge can be adjusted by introducing a prolonged opening of the valves and turbines.

4.5.5 Pressure shaft

Optimal pipe diameter

The optimal pipe diameter is presented in the diagram in figure 4.9. The calculation is shown in equation 4.14. The constants used in equation 4.14 is C_2, 4.10, and C_1, 4.11

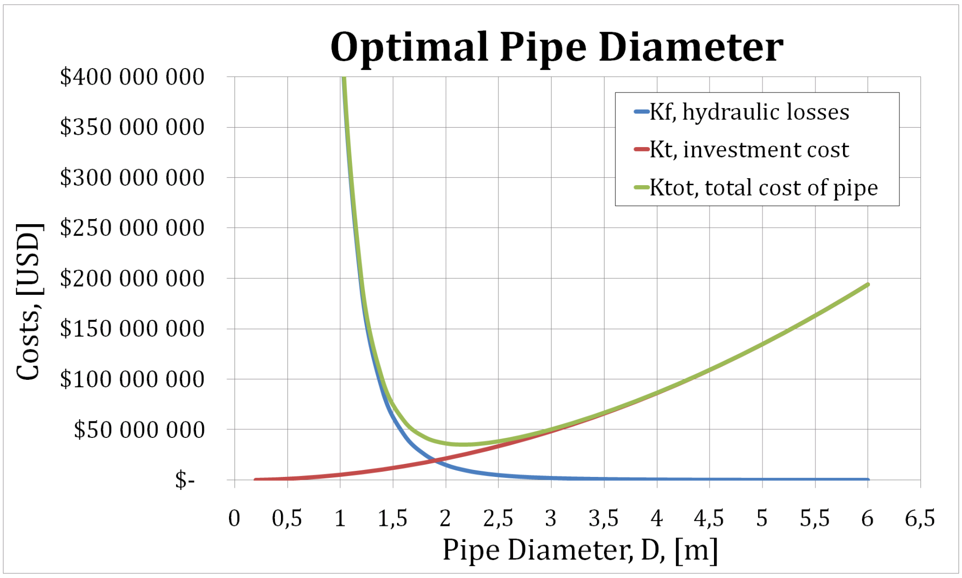


Figure 4.9: The economic optimal pipe diameter is found where the total costs are at the lowest. Based on a volume flow of 10 m^3/s

$$C_2 = \frac{1000\ \text{kg/m}^3 \cdot (11\ \text{m}^3/\text{s})^3 \cdot 0,0107 \cdot 1800\ \text{m}}{4 \cdot \pi^2} = 649344 \tag{4.10}$$

$$C_1 = \frac{2 \cdot 7830 \text{ kg/m}^3 \cdot \pi \cdot 6,7 \text{ MPa} \cdot 1800 \text{ m}}{206 \text{ MPa}} = 2880194 \qquad (4.11)$$

The pressure rise from the water hammer is found from equation 4.12.

$$\Delta h_{wh} = \frac{(\frac{11\text{m}^3/\text{s}}{3{,}57\text{m}^2}) \cdot 2 \cdot 1800\text{m}}{9,8\text{m/s}^2 \cdot 50\text{s}} = 23,5\text{m} \qquad (4.12)$$

Internal pressure in the pipe, equation 4.13.

$$p = 1000 \text{ kg/m}^3 \cdot 9,8 \text{ m/s}^2 \cdot (650 \text{ m} + 22,6 \text{ m}) = 6,6 \text{ MPa} \qquad (4.13)$$

$$d = \sqrt[7]{\frac{5}{2} \cdot \sum_{i=1}^{20} \frac{649344 \cdot 135 \text{ days} \cdot 24 \text{ h} \cdot 0,055 \text{ USD/kWh}}{7,6 \text{ USD/kg} \cdot 2880194 \cdot (1+8\%)^i} \cdot \frac{1}{2}} = 2,16 \text{ m} \qquad (4.14)$$

The result of equation 4.14 can also be read from the diagram in figure 4.9. Figure 4.10 shows how the optimal diameter of the new pressure shaft will vary with the volume flow.

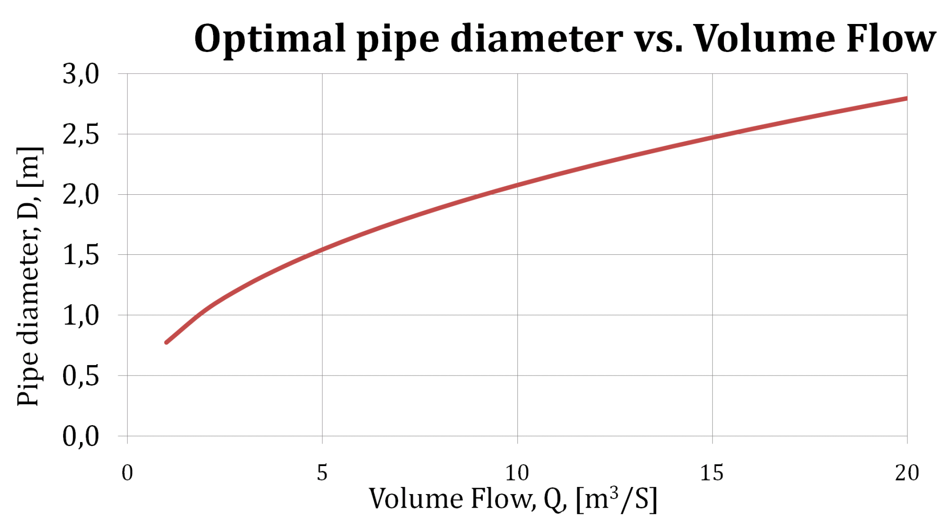


Figure 4.10: The optimal pipe diameter versus the volume flow in the pipe.

Pipe thickness

The pipe thickness is a function of the volume flow, and the diameter of the pipe.

The thickness of the pipe is calculated in equation 4.15

$$t = \frac{6,7\ \text{MPa} \cdot (\frac{2,28\ \text{m}}{2}) \cdot 1,2}{206\ \text{MPa}} = 0,042\ \text{m} \tag{4.15}$$

4.5.6 Power house and draft tube

This thesis has not focused on the design of the power house and the draft tube.

4.6 Turbine

The type of turbine has to be decided based on assumptions and evaluations, the final decision is discussed in the next chapter.

4.6.1 Speed number

Figure 4.11, and table 4.4, show the speed number calculation. The red horizontal line gives the border between a Francis and a Pelton turbine, and as shown, both alternatives are possible for Kirne Power Plant.

Table 4.4: The border between Pelton and Francis, speed number equal to 0,22.

Volume flow, Q, [m^3/s*]*	*Rotational speed, n, [rpm]*
5	1140
8	901
10	806
11	768
12	736
15	658
20	570

4.6.2 Design of a Pelton turbine

Designing the Pelton turbine follows the criteria stated in the theory section, section 2.7.2.

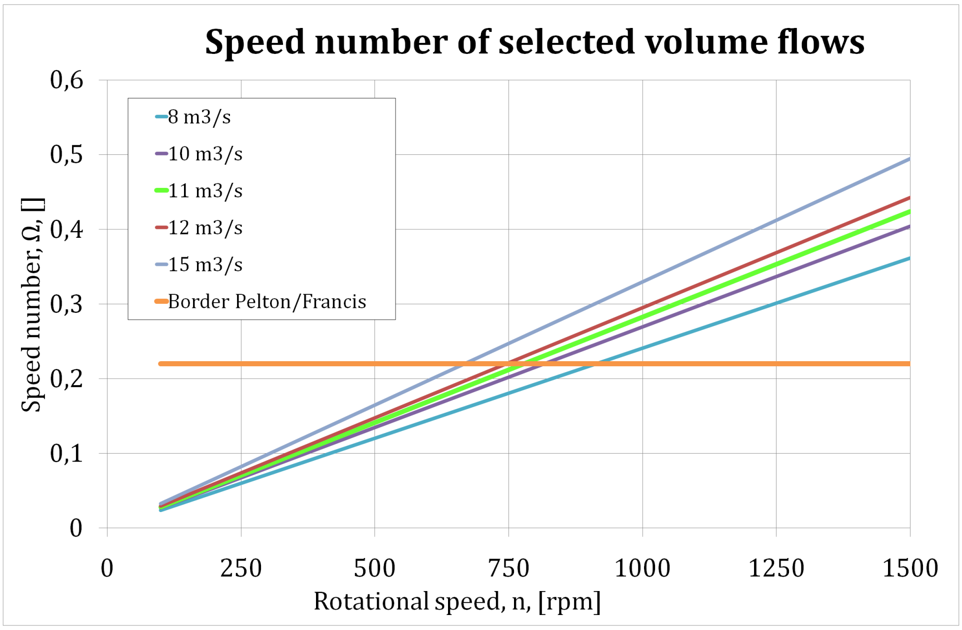


Figure 4.11: Speednumber as a function of rotational speed and volume flow.

First the dimensions of one unit utilizing 11m^3/s will be calculated. In section 4.6.3 the dimensions of two smaller units will be calculated.

Number of nozzles

The results found from the data given by Bjarne Børresen in Rainpower, [4], are presented in the following graphs.

The correlation between number of nozzles, Z, and the reduced volume flow at BEP, $\underline{Q}^*$ is shown in figure 4.12 for all the units. The result for vertical axis only is shown in figure 4.13

If a trend line is added to the graph, the equation will be equation 4.16. The R^2 value of the trend line is equal to 0,3844.

$$y = -72,711x^2 + 33,881x + 1,671 \tag{4.16}$$

If one Pelton turbine is chosen, the number of nozzles will be equal to five. If two units are chosen, they will have three nozzles each. The arguments are given in the discussion chapter, section 5.6.2.

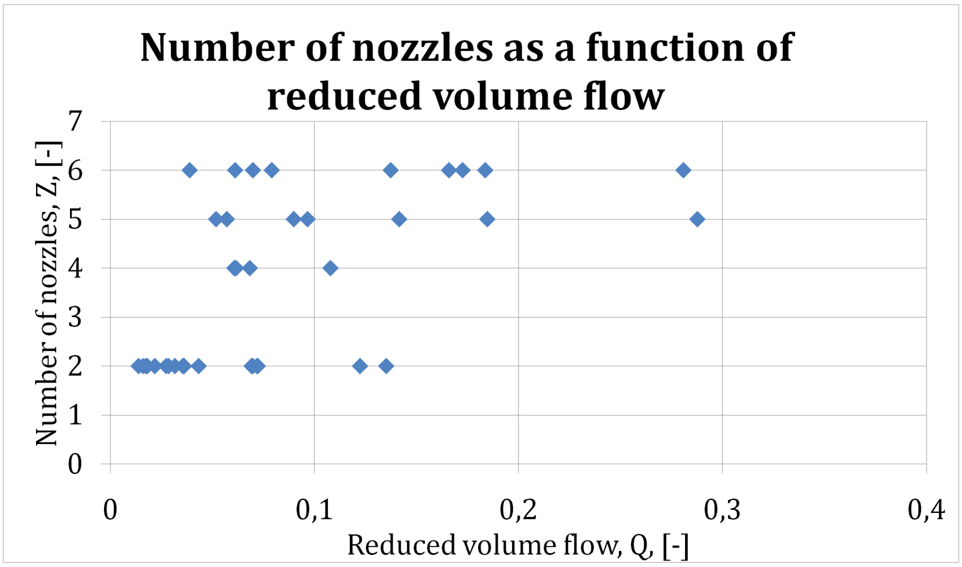


Figure 4.12: The number of nozzles in a Pelton turbine, versus the reduced volume flow at BEP, [4]

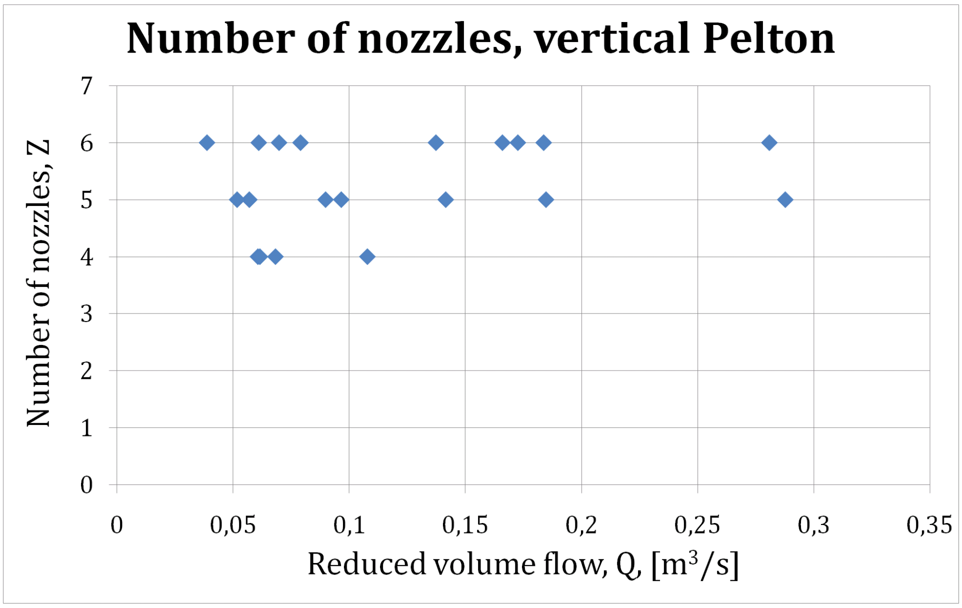


Figure 4.13: The scatter for the vertical axis Pelton turbines, [4].

Main dimensions

The basis of the Pelton design is the Euler equation;

$$\eta_h \approx 0,96 = 2(\underline{u}_1 \cdot \underline{c}_{1u} - \underline{u}_2 \cdot \underline{u}_{2u}) \tag{4.17}$$

The volume flow used in the calculations is the flow given in section 4.3, 11 $\mathrm{m^3/s}$.

The total net head available is shown in equation 4.18.

$$H_n = H_{\mathrm{gr}} - H_f = 672\ \mathrm{m} - 23,4\ \mathrm{m} = 648,6\ \mathrm{m} \tag{4.18}$$

Where $23,6$ m is the head loss in the water way for Kirne when a total flow of 22 $\mathrm{m^3/s}$ is flowing in the tunnel.

The hydraulic efficiency of the Pelton turbine is assumed to be 96% in the designing process, and the reduced median speed is set equal to one. The circumferential speed, $\underline{u}_1$ is then equal to 0,48.

The absolute peripheral velocity of the water jet becomes, equation 4.19.

$$c_{u1} = \sqrt{2 \cdot 9,8\ \mathrm{m/s^2} \cdot\ 648,6\mathrm{m}} = 112,8\ \mathrm{m/s} \tag{4.19}$$

The jet diameter becomes, equation 4.20.

$$d_j = \sqrt{\frac{4 \cdot 11\ \mathrm{m^3/s}}{5 \cdot \pi \cdot 112,6\ \mathrm{m/s}}} = 0,16\ \mathrm{m} \tag{4.20}$$

The ideal diameter ratio based on the rule of thumbs, is interpolated in equation 4.21:

$$\frac{15-10}{1300\mathrm{m} - 500\mathrm{m}} = \frac{15-x}{1300\mathrm{m} - 650\mathrm{m}} \rightarrow D = 10,94 d_j \tag{4.21}$$

The next parameter to be decided is the preliminary diameter of the runner, equation 4.22, based on the rules of thumbs given in section 2.7.2.

$$D_{\mathrm{preliminary}} = 10,94 \cdot 0,157\ \mathrm{m} = 1,72\ \mathrm{m} \tag{4.22}$$

The circumferential velocity, u_1 is decided in equation 4.23, based on the Euler equation.

$$u_1 = 0,48 \cdot \sqrt{2 \cdot 9,8 \text{ m/s}^2 \cdot 648,6 \text{ m}} = 54,1 \text{ m/s} \tag{4.23}$$

The preliminary rotational frequency, n, is decided in equation 4.24.

$$n = \frac{54,14 \text{ m/s} \cdot 60 \text{ s}}{\pi \cdot 1,72 \text{ m}} = 599,77 \text{ rpm} \tag{4.24}$$

The number of pole pairs is given in equation 4.25.

$$P = \frac{50\ Hz \cdot 60 \text{ s}}{599,77 \text{ rpm}} = 5 \tag{4.25}$$

The first design hit a whole pole number, hence correction calculations were not necessary.

The number of buckets is chosen to be 22.

Speed number close to 10

Discussions with Ole Gunnar Dahlhaug have shown that a Pelton turbine has a better performance and design if the speed number is close to 0,1. Some changes of the design given has to be introduced. The result shown in table 4.5 is adjusted.

The jet diameter/diameter ratio, D/d_j, can be altered. The effect of adjusting the ratio, while the other parameters are kept, is shown in table 4.5.

Table 4.5: The effect of adjusting the diameter ratio for the Pelton runner.

$\frac{D}{d_j}$	*10,94*	*12*	*13*	*14*	*15*
Ω	0,17	0,17	0,14	0,14	0,12
n, [*rpm*]	600	600	500	500	428,6
D, [m]	1,72	1,72	2,07	2,07	2,41
Number of pole pairs, Z	5	5	6	6	7

The chosen solution is the runner with a speed number of 0,14, and a diameter ratio of 13. This ratio does not exceed the suggested maximum increase of 20%, given in *Pumps and turbines*, [2].

Production Pelton

The maximum efficiency of the Pelton runner presented in section 3.7 under efficiency curves, is 91,2%. When this efficiency is used, the power of the Pelton turbine is presented in equation 4.26, and equal to 63, 8 MW.

$$P = 0,912 \cdot 9,8 \text{ m/s}^2 \cdot 1000 \text{ kg/m}^3 \cdot 650 \text{ m} \cdot 11 \text{ m}^3\text{/s} = 63,8 \text{ MW} \qquad (4.26)$$

This gives a total production over the year of 235, 5 GWh at 11 m^3/s, which is equal to an income of 13 MUSD. The efficiency curve with the accumulated production is shown in figure 4.14. In the figure, the curve is fitted so that the BEP will coincide with the design flow of 11m^3/s.

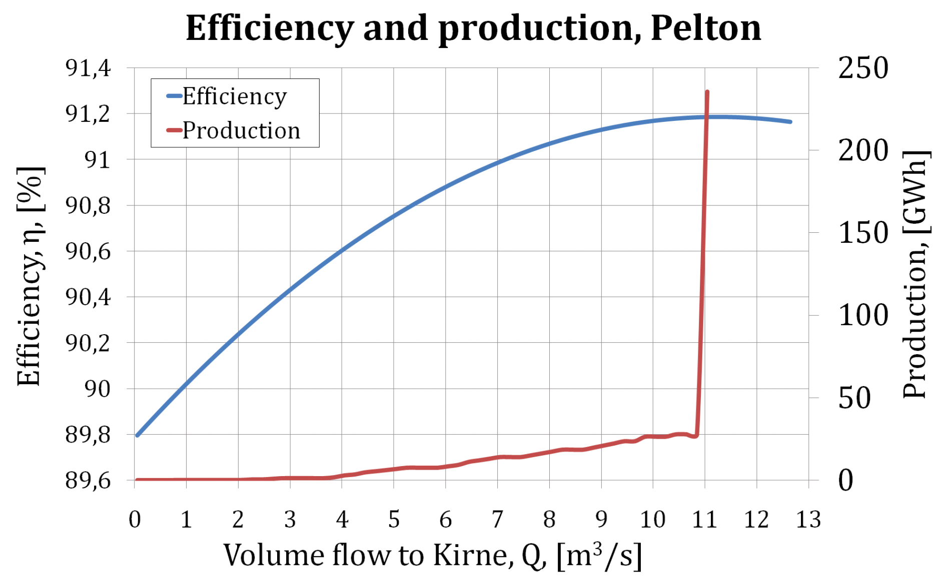


Figure 4.14: The accumulated production in GWh and the efficiency curve for a Pelton turbine at Kirne Power Plant.

4.6.3 Two Pelton units

The results if two units of 5, 5 MW each are installed in in Kirne are shown in figure 4.15. The total production through a wet season will increase from 236 GWh to 244 GWh, and the accumulated gain from the difference of one unit will give 4,5 million USD. The turbines considered here are of the same design as the previous shown turbines. The dimensions of the smaller turbines are calculated in the same way as for the solution with one turbine. The results are given in table 4.6.

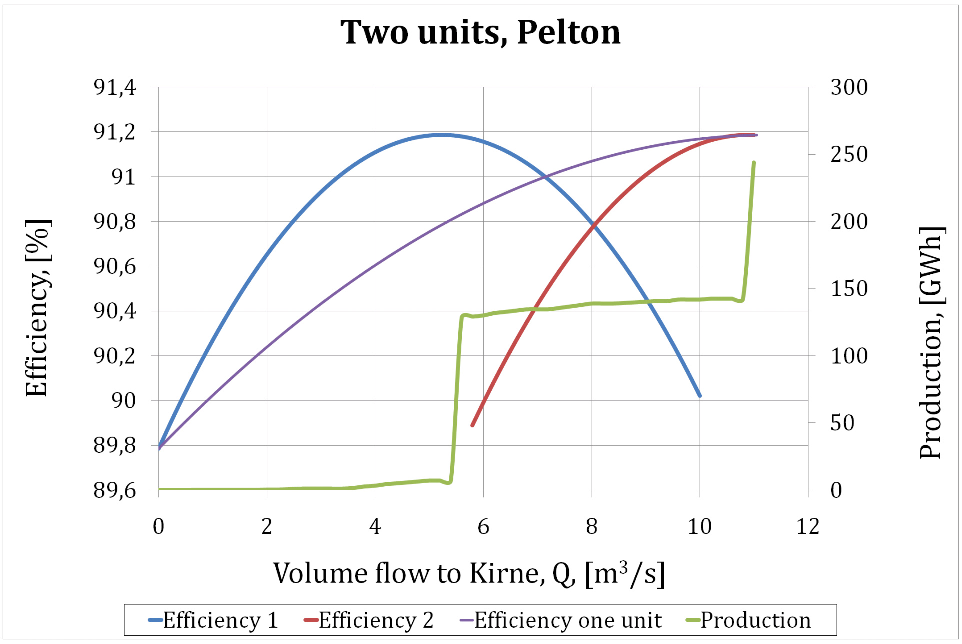


Figure 4.15: The efficiency curves for two Pelton units, and the total production.

Table 4.6: The main dimensions for a Pelton turbine of $5,5\mathrm{m}^3/\mathrm{s}$.

Dimension	*Symbol*	*Value*
Number of nozzles	Z	3
Number of pole pairs	Z	5
Rotational speed	n	600 rpm
Runner diameter	D	$1,7$m
Diameter ratio	D/d_j	12
Bucket widht	B	$0,47$ m
Number of buckets	z	22
Power	P	32 MW
Speed number	Ω	$0,12$

The values for a Pelton turbine that is adjusted to a speed number closer to 0,1 is shown in table 4.7.

Table 4.7: The main dimensions for a Pelton turbine of $5,5 \mathrm{m}^3/\mathrm{s}$ that is adjusted to a speed number of 0,1.

Dimension	*Symbol*	*Value*
Number of nozzles	Z	3
Number of pole pairs	Z	6
Rotational speed	n	500 rpm
Runner diameter	D	$2,07$ m
Diameter ratio	D/d_j	$14,4$
Bucket widht	B	$0,47$ m
Number of buckets	z	22
Power	P	32 MW
Speed number	Ω	$0,10$

4.6.4 Design of a Francis turbine

The design of a Francis turbine is taken from the theory section 2.7.3.

Francis runner

The size of the Francis runner as a function of the outlet angle, β_2, and the chosen peripheral velocity, U_2, is given in the graph in figure 4.16.

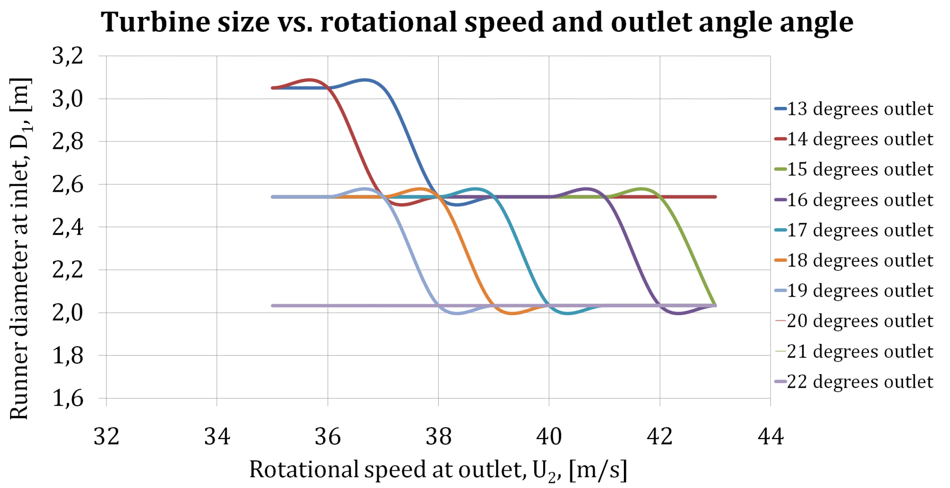


Figure 4.16: The size of a Francis turbine at different chosen peripheral speeds, U_2 and outlet angles, β_2.

The main dimensions of the Francis runner are given in table 4.8, where the chosen and assumed values are stated in the beginning of the table. The calculations can be found in the enclosed Excel sheet.

Table 4.8: The main dimensions of the Francis turbine

Parameter	*Symbol*	*Value*
Assumed/chosen values		
Outlet angle	β_2	16°
Peripheral speed at outlet	U_2	40m/s
Hydraulic efficiency	η_h	96%
Degree of reaction	R	$0,5$
Number of runner vanes	Z	21
Calculated values		
Net pressure suction head	$NPSH$	$15,55$ m
Absolute median velocity at outlet	c_{m2}	$12,11$ m/s
Rotational frequency	n	750 rpm
Number of pole pairs	Z	4
Corrected peripheral speed at outlet	U_2	$42,23$ m
Diameter at outlet	D_2	$1,08$ m
Peripheral velocity at inlet	U_1	$79,88$ m/s
Diameter at inlet	D_1	$2,03$ m
Inlet height	B_1	$0,156$ m
Inlet absolute peripheral velocity	c_{u1}	$76,55$ m/s
Inlet absolute median velocity	c_{m1}	$11,01$ m/s
Inlet angle	β_1	$73,18$ °
Speed number	Ω	$0,22$

Guide vanes

In table 4.9 the calculated results for the guide vanes of the Francis turbine are shown.

Stay vanes and spiral casing

The stay vanes and spiral casing is not calculated in this thesis.

Production Francis turbine

The maximum efficiency of the Francis is found to be 93,5%. The power of the Francis turbine is given in equation 4.27.

Table 4.9: The calculated results for the guide vanes of a Francis turbine.

Parameter	*Symbol*	*Value*
Assumed/chosen values		
Number of guide vanes	Z	24
Calculated values		
Diameter at outlet	D_{gvo}	2, 13 m
Median velocity at outlet	$c_{\mathrm{m,\ gvo}}$	10, 42 m/s
Peripheral velocity at outlet	$c_{\mathrm{u,\ gvo}}$	72, 9 m/s
Outlet angle	α_{out}	8, 14 °
Maximum outlet angle	$\alpha_{\mathrm{max,\ out}}$	12, 2 °
Height at outlet	B_{gvo}	0, 16 m
Diameter of guide vane shaft	D_{gvs}	2, 3 m
Length of guide vane	L_{gv}	0, 36m
Length from trailing edge to shaft	$L_{g}vs$	0, 22 m
Recalculated diameter to shaft	D_{gvs}	2, 17 m
Diameter to inlet	D_{gvi}	2, 19 m
Shaft angle	α_{gvs}	12, 6 °
Inlet angle	α_{gvi}	14, 81 °
Median velocity at shaft	$c_{\mathrm{m,\ gvs}}$	10, 27 m/s
Peripheral velocity at shaft	$c_{\mathrm{u,\ gvs}}$	71, 88 m/s
Median velocity at inlet	$c_{\mathrm{m,\ gvi}}$	10, 17 m/s
Peripheral velocity at inlet	$c_{\mathrm{u,\ gvi}}$	71, 20 m/s
Outlet diameter at max guide vane opening	D_{gvo}	2, 11 m

$$P_{\text{Francis}} = 95,3\% \cdot 9,8 \text{ m}^2/\text{s} \cdot 1000 \text{ kg/m}^3 \cdot 650 \text{ m} \cdot 11 \text{ m}^3/\text{s} = 67 \text{ MW} \quad (4.27)$$

In figure 4.17 the accumulated production of a Francis turbine is shown, and at which efficiency the electricity is produced.

The accumulated production for a Francis turbine at Kirne is equal 253 GWh, which which will give an income of 13,9 MUSD.

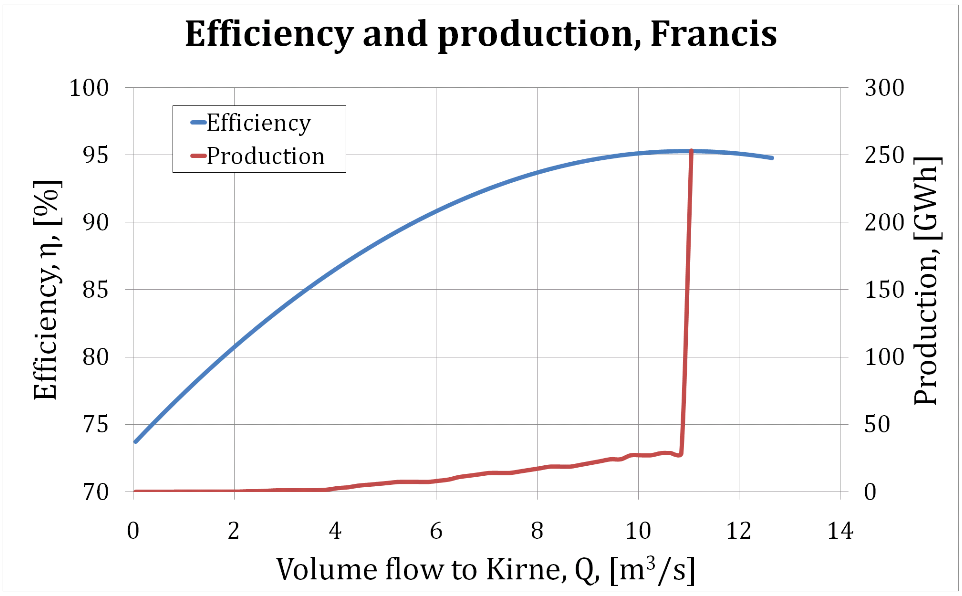


Figure 4.17: The efficiency and accumulated production for a Francis turbine at Kirne.

Number of units

When the production of the Francis turbine is split into two smaller Francis units, as for the Pelton units, the production becomes 254 GWh. Which is only one GWh more than the initial production of one unit. The efficiency and production of the two Francis turbines are shown in figure 4.18. The main dimensions for two smaller units are not calculated, since the difference is this small.

4.6.5 Choice of turbine

One of the factors deciding if the chosen turbine is a Francis or a Pelton is the production and the economy. Figure 4.19 shows the difference in produced

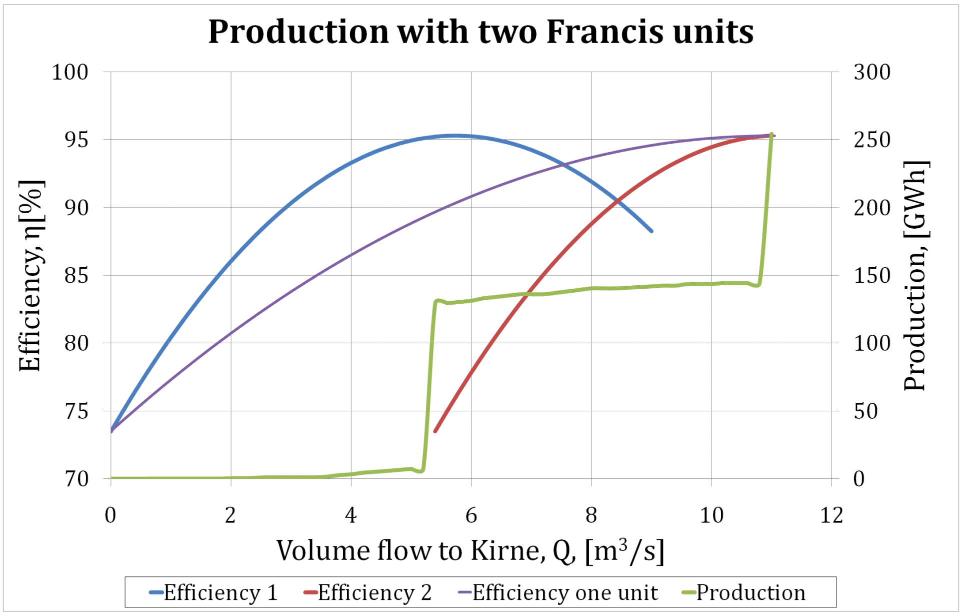


Figure 4.18: The efficiency and production of two Francis units.

GWh through the year for a Francis and a Pelton turbine, at different volume flows.

When the interest rate is set to 8% and the maximum difference is accumulated for 20 years, the result is shown in equation 4.28.

$$\text{Accumulated} = \sum_{i=1}^{n} \frac{\text{Difference}}{(1+I)^i} = \sum_{i=1}^{20} \frac{980000\ \text{USD}}{(1+8\%)^i} = \mathbf{9{,}7\ MUSD} \tag{4.28}$$

Other aspects are discussed in the next chapter.

4.6.6 Maintenance

There are no calculations done for the maintenance aspect, so the maintenance will be evaluated and accounted for in the discussion chapter.

4.7 Costs

This section will show the price estimates for the pressure shaft and the turbines. The other elements will not be calculated in this thesis.

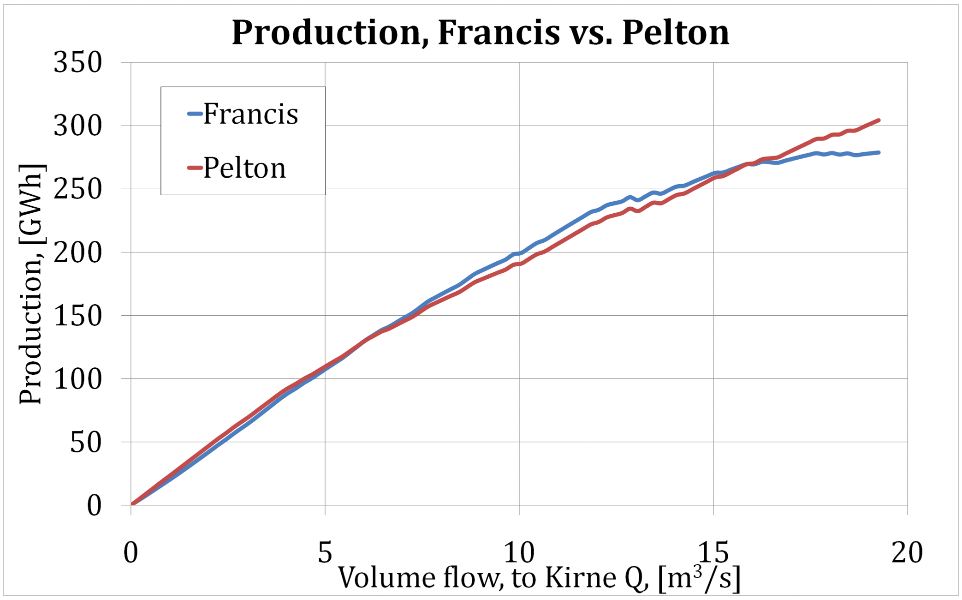


Figure 4.19: The difference in production of a Francis and a Pelton turbine

4.7.1 Pressure shaft

Based on steel price

The cost of the pressure shaft is based on the cost of the material of the steel pipe. Given in equation 2.85, the calculation is shown in equation 4.29.

$$7830\ \mathrm{kg/m^3} \cdot \pi \cdot 2,16\ \mathrm{m} \cdot 1800\ \mathrm{m} \cdot 0,042\ \mathrm{m} \cdot 7,6\ \mathrm{USD//kg} \approx \mathbf{30{,}2\ MUSD} \tag{4.29}$$

Based on the NVE handbook

The construction costs, equation 4.30 gives the price in thousand NOK per meter of pipe.

$$\text{Total cost} = 4,1D + 6,3 \tag{4.30}$$

Included 50% added for difficult terrain, this gives:

$$\text{Total cost} = \frac{(4,1 \cdot 2,16\ \mathrm{m} + 6,3) \cdot 1800\ \mathrm{m} \cdot 1000\ \mathrm{NOK}}{6,6\ \mathrm{NOK/USD}} \cdot 150\% = 6,2\ \mathrm{MUSD}$$

The mechanical costs are given in equation 4.31 and equation 4.32:

$$\text{Price(800 m)} = 0,0079 \cdot D^{1,1052} \tag{4.31}$$

$$\text{Price(600 m)} = 0,0028 \cdot D^{1,2349} \tag{4.32}$$

The price for a pipe with a head of 660 m will thus be, 4.33:

$$\text{Price(660 m)} = 0,00237 \cdot D^{1,1052} + 0,00196 \cdot D^{1,2349} \tag{4.33}$$

$$\text{P(660 m)} = \frac{1}{6,6\text{NOK/USD}} \cdot 0,00237 \cdot 2160\ \text{mm}^{1,1052}$$

$$+0,00196 \cdot 2160\ \text{mm}^{1,2349} \cdot 1800\ \text{m} \cdot 1000\ \text{NOK} = 10,2\ \text{MUSD}$$

50% has to be added to these prices:

$$150\% \cdot (6,2 + 10,2)\ \text{MUSD} = \textbf{24,6 MUSD}$$

The owners costs have to be estimated, and there are no rules for these guesses.

4.7.2 Turbine

Calculated and found from the curves and formulas of NVE, [24].

Cost of the Pelton turbine

When finding the costs of the turbine, it is based on the main dimensions calculated.

The price for a Pelton turbine of a rotational frequency of 600 rpm and 63 MW, will be given by an interpolation between the price of 600 m and 800 m, each given in Fig.M.1.A in [24]. Equation 4.34 shows the result.

$$\text{Price, Pelton 650m} = 1394,625 \cdot Q^{-0,5171} + 363,025 \cdot Q^{-0,5218} \tag{4.34}$$

$$\text{Price, Pelton 650 m} = 1394,625 \cdot 11\ \mathrm{m^3/s}^{-0,5171} + 363,025 \cdot 11\ \mathrm{m^3/s}^{-0,5218}$$

$$= 507,40\ \mathrm{NOK/kWh}$$

The total price for a Pelton unit will thus be as given in equation 4.35.

$$\text{Total price, Pelton} = \frac{507,40\ \mathrm{NOK/kWh}}{6,5\mathrm{USD/NOK}} \cdot 63800\,\mathrm{kW} \cdot 150\% = \mathbf{7{,}47\ MUSD} \tag{4.35}$$

Cost of two Pelton units

The same equation as for the single unit is valid for the two Pelton units, only the volume flow is altered, equation 4.36.

$$\text{Price small Pelton} = 1394,625 \cdot 5,5^{-0,5171} + 363,025 \cdot 5,5^{-0,5218} \tag{4.36}$$

$$= 726,73\ \mathrm{NOK/kWh}$$

$$\text{Total Price} = 1,9 \cdot \frac{26,73\ \mathrm{NOK/kWh}}{6,5\ \mathrm{USD/NOK}} \cdot 32000\ \mathrm{kWh} \cdot 150\% = 10\ \mathrm{MUSD}$$

The second unit has a price reduction of 10%, that is the reason of the factor of 1,9 in equation 4.36.

Francis cost

The price equation for a Francis turbine is given in figure Fig. M.1.B in the NVE book, [24], and recited in equation 4.37

$$\text{Price}_{\text{Francis, 650m}} = 682,34 \cdot Q^{-0,3044} \tag{4.37}$$

$$\text{Price}_{\text{Francis, 650m}} = 682,34 \cdot 11^{-0,3044} = 329\ \mathrm{NOK/kWh}$$

The total price of a Francis unit is given in equation 4.38.

$$\text{Total Price}_{\text{Francis}} = \frac{329\ \text{NOK/kWh}}{6,5\ \text{USD/NOK}} \cdot 66200\ \text{kW} \cdot 150\% = \mathbf{5{,}0\ MUSD} \tag{4.38}$$

Chapter 5

Discussion

5.1 Hydrology

In the results section, section 4.1, figure 4.2, shows the available hydrology in the Khimti River during the monsoon period. As shown, there is a lot of water available through the whole period.

Even though the average duration curve is a smooth curve, the daily variation can be large from year to year. This is illustrated with an example in figure 5.1, where the yearly fluctuations of 25. of August through the 38 years are shown. In this example the maximum flow is 160 m^3/s, and the minimum flow is below 40 m^3/s. It is important to take the uncertainties into account, when evaluating the hydrology and production at Kirne. The duration curve is still the best available tool to use during the production planning.

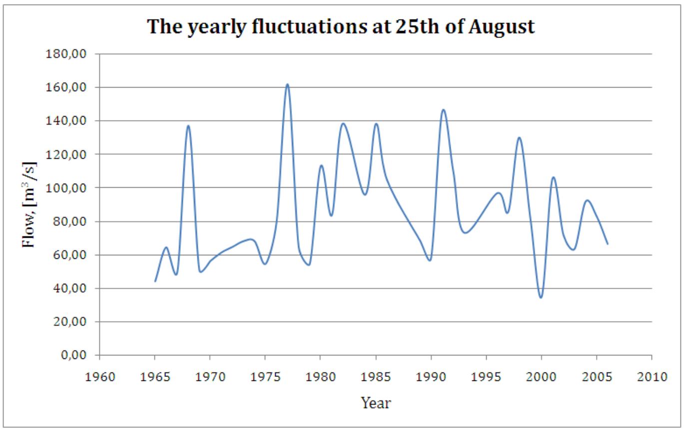


Figure 5.1: The fluctuations from year to year at 25. August, (randomly chosen).

In the calculations an average flow of 11 m^3/s will be used to Khimti I, this is $0,25$ m^3/s more than the design flow. The increase is to cover up for the extra head losses, that were caused by Kirne, through the tunnel.

As calculated in the results section 4.3, the limiting flow for the whole system of Kirne and Khitmi I is 24 m^3/s. In order to have some margin for the surges, the limit used in this thesis will be 22 m^3/s. Which leaves 11 m^3/s for each of the power plants. In figure 5.2 the limits are shown together with the corresponding duration curve. The minimum release flow of $0,5$ m^3/s is also included in this diagram.

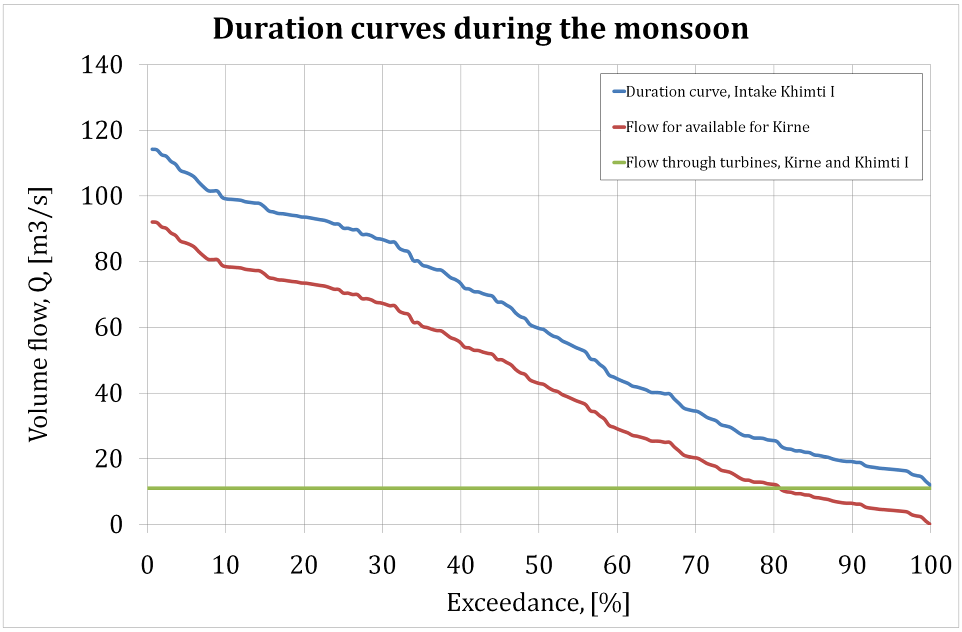


Figure 5.2: The volume flow limits shown in the duration curve.

The chart in figure 5.2 shows that Kirne can be run at full load about 80 % of the monsoon periods, and at lower load during the rest of the period. Still a huge amount of water is lost during the season. There is thus foundation for further hydro power devellopments in the Khimti valley, given that a new tunnel is built. Roughly calculated from the figure, the lost production is equal to, equation 5.1.

$$\Delta P = \frac{(115-22)\ \mathrm{m}^3/\mathrm{s}\cdot 0,8}{2}\cdot 168\ \text{days}\cdot 24\ \mathrm{h}\cdot H_{\text{net}}\cdot g\cdot \rho\cdot \eta = 1720 + \mathrm{GWh} \tag{5.1}$$

Not all of this enegy is economic feasible. The topmost part of the duration curve is extreme, and thus very loaded with sediments, and has difficult flow conditions.

It is also important to be aware of that the hydrology can vary more than hundred percent from year to year. Through the 38 years of measuring, the average volume flow over the monsoon has an average maximum of 106 m^3/s and a minimum average of 32 m^3/s. In Appendix H, figure H.1, a chart of the individual duration curves is given. The figure shows that in the years with least flow, the flow of Khimti I and Kirne is exceeded for about 60% of the monsoon, and the average is 80%. Which gives that the production can be 31% less at BEP, than what is used for estimation through this thesis.

5.2 Sediment handling

5.2.1 Settling basin

A working sediment basin with a satisfactory efficiency is necessary for operation of Kirne and Khimti I. It is assumed that there is room enough for building a new basin at one of the riversides, and that the new basin is big enough to handle the sediments in the river.

Another solution for the settling basin, is the possible new power plant, Khimti II, upstream of Khimti I. If a sediment basin is built in connection with this plant, it is not necessy to enlarge the Khimti I basin. The largest portion of the sand will be taken out at Khimti II, and the existing settling basin at Khimti I will be able to handle the rest of the sediment load. This will create an acceptable solution for the sediment removal for all three power plants. If Khimti II will be built, this is the best and most cost-effective solution. Before Khimti II is built, some temporary solutions have to be made.

Fall velocity

The minimum fall velocity, w, in order for the sediments to be trapped is only one fourth of what is stated as a minimum requirement in the theory chapter. This fact will increase the amount of sediments trapped. The sediments at Khimti only needs one fourth of the fall velocity stated in the theory section, to be captured.

Even so, there is quite a lot of sediments that manage to cross the basin and enter the turbines. Solutions for the turbines are discussed in the next section.

5.2.2 Sediments in the turbine

So far, sepcial turbine design for sediment loaded water has not been considered. This thesis will not do any calculations for such special design, but there exist solutions for silt friendly runners. Such designs will reduce the needs for maintenance. A company in Trondheim, called DynaVec, has specialized on designing runners for heavy sediment loaded environments. Solutions for both Francis and Pelton runners exist, and might be a good possibility for Kirne power plant. Figure 5.3 shows one solution for a Pelton runner, where the buckets are changeable. Also a Francis runner with changable vanes is in production, and also in operation in the Peruvian power plant, Chaua, where the results are very good so far. [1].

Figure 5.3: Silt friendly design of a Pelton runner, by DynaVec, [1].

5.3 Head losses

5.3.1 Tunnel

Manning number

The head loss is dependent on the Manning number used in the tunnels. Figure 5.4 shows how the head loss will vary according to the Manning number. As seen in the figure, there will be uncertainties connected to the head loss calculations. For a volume flow of $30\text{m}^3/\text{s}$ the variation between the Manning number of 35 and 47 will be about 20m. This is a large variation, and the uncertainty has to be incorporated into the conclusions. The actual unceraintу is probably not as large as shown in figure 5.4. The Manning number of 41 is calculated from the head loss measurement report, [14], and thus it is the accurate registered value at the start-up of the plant. The tunnel conditions might have been altered during the years, but not more than a few percent change from the original Manning number.

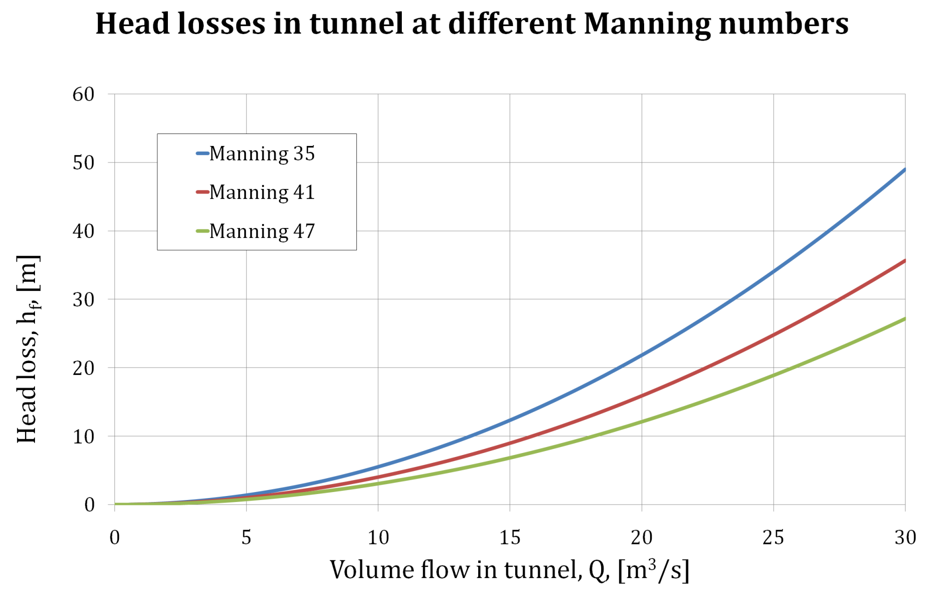


Figure 5.4: The head loss as a function of Manning number

Limiting flow

The limiting volume flow in the tunnel is based on the head losses. If the head losses are larger than the tolerated down surge in the surge shaft, air will be sucked into the tunnel.

The limit is at 24 m^3/s, and will be the stable water level in the surge shaft during operation. The limit used in the caclulations will be 22 m^3/s, this is so that the stable level will be a few meter above the critical level, which leaves some room for down-surge below the stable level.

Increased losses in Khimti I

The increased volume flow in the tunnel will affect the production of Khimti I. The output of Khimti I has to be maintained due to the obligations to NEA. To maintain the same mega watt output from Khimti I, with the new head loss conditions, $0,25\ \mathrm{m^3/s}$ extra has to be added to the plant as shown in equation 3.1.

In figure 4.5 the losses of Khimti I are shown compared to the value of Kirne. The value of the losses will nearly vanish in the extreme gain.

5.3.2 Pressure shaft

The head loss in the pressure shaft can be decided based on the calculated diameter of the shaft. The diameter is an optimalization of lost production and cost of a shaft with less head loss. The optimal pipe diameter is discussed in section 5.5.4, and the results form the optimalization is used in the head loss calculations. Lower head losses could be achieved by a larger diameter, but the price would be too high, to give a better result.

5.4 Stability

5.4.1 Surges

In figure 4.8, in section 4.4, the results of a rough calculation for the surges are shown. From the figure it can be seen that if nothing is done to the surge shaft or the regulation of the turbines, the maximum volume flow in the tunnel will be about $16\ \mathrm{m^3/s}$ for the down-surge, and $19\ \mathrm{m^3/s}$ for the up-surge. This is valid as long as the assumptions used are valid; zero closing and opening time of the valves and turbines.

A lot of the changes can be made to the system to tolerate more water in the tunnel. The shaft can be extended to handle a higher upgurge, the changes are discussed in section 5.5.3. For the downsurge the opening time of the valves and turbines can be prolonged until the down surges are below the limit.

5.4.2 Thoma cross section

At the inlet to the surge shaft, a restriction orifice is installed. The purpose of this orifice is to damp the surges. The calculations of the Thoma cross section, to ensure stable U-tube ocssilations, shows that the existing area might be too small at the Khimti I surge shaft.

The cross section is not directly related to the volume flow, and is thus too small for the volume flow used today as well. No problems concerning the orifice has been reported so far, but to be on the safe side, when Kirne is installed, the orifice should be expanded to the calculated necessary cross section. The branch in the tunnel has a larger area, and the smallest area of the lower part of the surge shaft is about 2 m^2, thus the problem is solved if the orifice is removed, or enlarged

The conclusion is that the surges can be made stable up to the volume flow limit of 22 m^3/s without problems.

5.5 The elements of the power plant

If all the elements of Kirne power plant should be calculated and dimensioned, the thesis would be too comprehensive. Thus some of the elements are only described, and the changes not calculated. This is reflected in the discussion of the elements.

One important element is that the Khimti I plant should be in operation during the construction period of Kirne. It should be attempted to keep the down time as short as possible for Khimti I. Which gives that revisions for the water way is difficult work.

5.5.1 Intake

The intake is already mentioned under the sediment section, 5.2. There are quite alot of changes that have to be made to the intake in order to double the volume flow through it. The diversion weir has to be elevated proportionally, and the settling basin has to be enlarged. Also the trash racks and gates have to be extended to be able to operate functionally when the flow rate is increased. It is assumed that all these changes are possible to make, and that the result will be satisfactory.

It is important that the volume flow into the settling basin is uniform, stable, and evenly distributed on the different sections of the basin. It is difficlt, if not impossible calculations that are required here. A model test is the best tool to ensure a well functioning design. [16].

5.5.2 Tunnel

The tunnel at Khimti I and Kirne is a long tunnel, where difficulties were encountered during the construction. There are several summit and valley points along the tunnel, but this is not taken into consideration when designing the new plant. No changes are planned for the tunnel in this work, but it should be considered to reinforce some parts of the tunnel, due to withstand the increased volume flow, and to avoid rockfall in the tunnel. No large revisions of the tunnel can be carried out, because that would result in long down time for the Khimti I plant, which is not desirable.

5.5.3 Surge shaft

The surge shaft is briefly discussed in the section about surges, section 5.4.1. In the results in table 4.3, the different volumes that have to be excavated if no flooding shall occur in the surge shaft are shown. For the decided volume flow of 22 m^3/s, an excavation of 168 m^3 is necessary. The best solution is probably to do the excavation at the top of the surge shaft, to minimize the disturbance of the operation in Khimti I. A possible solution for the layout is shown in figure 5.5.

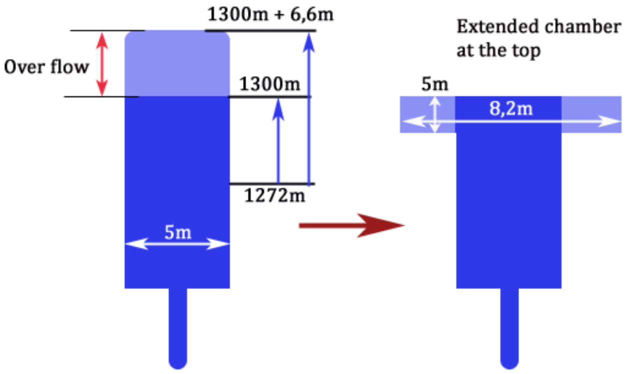


Figure 5.5: A possible solution for the excavation at the top of the surge shaft.

5.5.4 The pressure shaft

The optimal diameter of the pressure shaft was found from the marginal total cost calculation. This ensures that the most economic profitable diameter is chosen. When the diameter is decided, other parameters, such as the weight and assembly, can be included, to come to a conclusion. If the optimal dimension concerning costs and gain are not compatible with the procedure of assembling the whole shaft, a new solution has to be formed. It is important that the dimensions are realistic. Here it is assumed that the economic correct pipe diameter is also a pipe dimension that is possible to assemble.

The pipe will be an huge and heavy construction, and might cause problems during the installation.

The optimal pipe diamter is based on assumptions, and might change over time. As examples, the diameter is dependent on the power price and interest rate used. A higher power price will allow a larger diameter, and a higher interest rate will give a smaller diameter.

5.5.5 Power house

The design of the power house is not prioritized in this thesis. It is however important that the power house is optimized concerning size and cost, to get the best result. The power house of Kirne will be an outdoor arrangement, and the construction will be easier and cheaper if a Pelton turbine is chosen before a Francis turbine, due to the draft tube. This is a parameter that should be taken into consideration when evaluating the costs of the two alternative turbines.

5.6 Turbine

The initial values for the design of both the Francis and Pelton turbine is equal. The head and volume flow are given. Thus it is the design that will give the best overall result, based on maintenance, income and efficiency, that will be the chosen turbine in the end. This evaluation will be based on assumptions and rules of thumbs.

5.6.1 Speed number

As stated in the theory section, the border between when to use a Pelton turbine and when to use a Francis turbine, is at a speed number of 0,22. It might not be the most important parameter when choosing turbine, but the result of the speed number calculations gives a hint of what to expect from the further calculations. The speed number can be used to eliminate one of the turbines, if it is out of the reach. For Kirne none of the tubine types are eliminated based on the speed number. With adjustments both the Pelton and Francis turbine can be used.

In figure 4.11, the speed number of a range of flows and rotational frequencies is shown. If a turbine with rotational frequency of about 750rpm is chosen, the resulting turbine type will be on the border between Francis and Pelton, thus other parameters than the speed number will decide the type of turbine to be used. Below 750rpm, a Pelton turbine should be considered, and above 750rpm, a Francis.

5.6.2 Pelton turbine

As calculated in the results section, a solution with Pelton turbine can be utilized by one or two units. Both solutions will be discussed in this section. Only the runner will be discussed, and the number of nozzles. The layout and placing of the nozzles are not discussed and rather left for the further work if the Pelton turbine is chosen for Kirne.

Number of nozzles

When starting to design the Pelton turbine, the number of nozzles should be decided. No clear guidelines are given for this choice. Results from Rainpower's turbines were collected, and no correlation was found from these results, as shown in figure 4.12 in section 4.6.2. The lack of correlations gives that the number of nozzles has to be chosen based on other arguments than volume flows and mathematical correlations.

The efficiency curve of a Pelton turbine is dependent on the number of nozzles, as shown in figure 2.22. For Kirne a fairly flat curve is desired, so that the whole monsoon period could be utilized in the best possible way, through one or more turbines.

When the number of nozzles is lowered, the size of the runner increases. It is desireable to keep the dimensions down, in order to ease the transport to site. On the other hand, the turbine should not get too small, as this will cause a smaller bucket radius, and thus increase the water velocity in the buckets, and also the amount of sand erosion.

If one Pelton runner is chosen, the efficiency curve of 4-5 nozzles would cover the most of the monsoon period. And based on the evaluation above, a Pelton turbine with 5 nozzles would be suitable for Kirne. The diameter of one runner with varying number of nozzles is shown in figure 5.6

If two Pelton units are chosen instead of one, the picture will change. The runners can be of approxemately the same size as one runner, but the number of nozzles can be lowered to three. In this way the erosion in the buckets will be reduced, and more of the monsoon period can be utilized at a higher efficiency. The gain of the change from one to two units is $8,6$ GWh. The efficiency will also stay high for a larger range than the efficeincy curve of a a turbine with more nozzles.

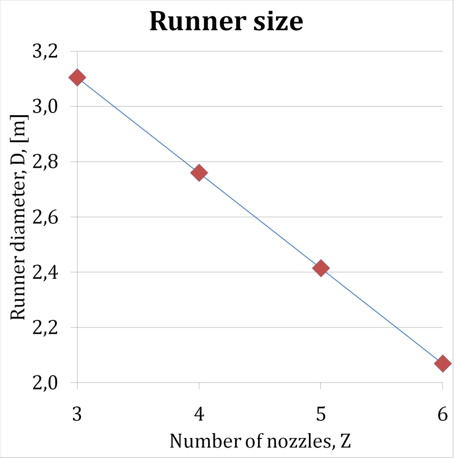


Figure 5.6: The runner diameter of a Pelton runner at Kirne as a function of number of nozzles

Main dimensions of Pelton runner

The calculating procedure for the main dimensions is stated in the theory section 2.7.2. The net head is decided based on the head loss for 22 m^3/s in the tunnel and 11 m^3/s to Kirne, this head is used through all the calculations. Sensitivity analysis is done for some of the parameters, while others are based on only one assumption.

First the design of one Pelton unit utilizing the whole volume flow is evaluated. As discussed with Ole Gunnar Dahlhaug, [8], the Pelton turbine has a better performance as the speed number gets closer to 0,1. After the general design, the diameter ratio is altered from 10,94 to 13, to get the speed number closer to 0,1. The speed number is by this operation reduced from 0,17 to 0,14. The change is still within the limit of 20% which is stated in *Pumps and turbines* by Brekke, [2]. The resulting diameter increase is 35 cm, and the rotational speed will be lowered from 600 rpm to 500 rpm. The change might also improve the risk of pitting at the backside of the bucksets, as the angle between the absolute velocity and the bucket gap will decrease.

For two smaller units of $5,5$ MW each, the same designing procedure is followed. The starting point is the traditional design, and when the diameter ratio is increased, a speed number of 0,1 is reach. Thus the design of the smaller turbines is better than the design of one turbine for the whole flow. The size of the two smaller units will be the same as one big unit, but the power will only be the half of it. The benefit is the reduced erosion in the buckets, and the better utilization of the water available.

Other changes can be done to the design of the Pelton runner as well, but is not calculated or discussed in this thesis. The new design from DynaVec, [1], can be considered for the Pelton runner. Other possibilities is to deviate more from the traditional designing procedure, to get a better performance and flow condition in the buckets, but experience and more advanced computing tools than available for this thesis will then be necessary.

Production Pelton

The calculated power of one Pelton turbine is $63,8$ MW and gives a total production during the monsoon of 235 GWh, based on the average duration curve. The power of the turbine can be calculated fairly accurate, and is based on the maximum efficiency of the efficiency curve from NVE, [24]. The efficiency curve is fitted to the duration curve, so that the flow of 11 m^3/s will coincide with the BEP. When calculating the production, it is important to remember the variations in the duration curve. The deviation between the average and the actual flow, below 22 m^3/s throught the year can be up to 31%. This will lead to a maximum deviation of 31% also for the production.

For two units, the power will be 32 MW each and the total production through a monsoon period will be 244 GWh in an average year, and with a possibility of 31% less production in a bad year. As easily seen, the production of two units is higher than the production from one unit. The reason for this is that the first unit can be run at full load for 91% of the monsoon period, and the other one for 81% of the monsoon period. This gives a longer interval of production at BEP, than for one unit. Illustrated in fiugre 4.15.

5.6.3 Francis turbine

The Francis turbine is an alternative for Kirne, even though the existing Khimti I has five Pelton units. The dimensions of the Francis turbine are only calculated and discussed for the runner. The stay vanes and spiral casing are left for the further work, if the Francis turbine is the chosen solution for Kirne.

Main dimensions of Francis runner

For the Francis runner the procedure of design is taken from lecture notes and a report, [7] and [13]. Rules of thumbs are used in the design of the Francis runner, and recalculated later in the design process to reach the best result. Designing a turbine runner is not an exact science, and the design methods of the main manufacturers are secret. Thus the design of this runner is based on the common assumptions, and will not be the accurate runner, but a hint of the sizes of a final runner, if a Francis runner should be chosen.

The main dimensions found will depend on the starting point for the design, and which assumptions that forms the basis of the design. Figure 4.16 shows how the runner size is dependent on the outlet angle and the rotational speed at the outlet, which both are parameters that are decided based on assumption. The chart in figure 4.16 shows that the size of the runner can vary between $2,07$ m and $3,1$ m, dependent of the initial choice. The choices for the possible Francis of Kirne gives a small runner of $2,07$ m.

Guide vanes

The guide vanes are calculated with as many simplifications as possible, and thus will only be a estimate of the size and dimensions. Among the assumptions are the one that the guide vanes are incredibly thin, and the thickness is approaching zero. This assumption will make the construction smaller than if the guide vanes were shaped as real air foils. Thus the calculated size of the guide vane diameter is smaller than that of a real turbine.

Production Francis

The same considerations that are made for the production of a Pelton turbine are valid for a Francis turbine. The calculated production can vary up to 31% from the given value, as the hydrology varies from year to year. The shape of the efficiency curve of the Francis turbine has a distinct top, and will produce at a high efficiency at BEP, but the curve will decrease more sharply, and thus not produce very good outside the design area at the top of the efficiency curve. This is also the reason why two Francis turbines will not show a gain in produced power, as the Pelton units, with the flatter curve will.

5.6.4 Maintenance

There is no problem finding time for the maintenance of the runners at Kirne. This is due to the operation only during the monsoon period. Which leaves six and a half month for maintenance and repair. This fact gives that only one set of runners is necessary. Every new monsoon period can start with freshly grinded and repaired runners.

When it comes to the difference between the Francis and Pelton runners, the Pelton runner is more easily maintained than the Francis runner. The design of the Pelton runner makes every spot of the runner more accessible. This makes the grinding and welding process much easier. In the Francis runner, it is more difficult to reach the spots in the channel between the vanes. But it is still possible to grind and welt both type of turbines. The erosion at the Francis turbine will be mostly at the inlet and the outlet, where it is possible to grind, [10]. In figure 5.7 the grinded outlet of a Francis runner is shown, from the power plant Cahua in Peru.

Figure 5.7: The grinded outlet of a Francis runner at Cahua in Peru.

As seen with the Pelton runners used at Khimti I, the grinding is done every year, while the welding is only done in a eight-nine years intervals. The grinding of a Pelton runner is not a very costly process, and can be done at site. The welding process is much more costly, and the runner has to be sent away for the operation.

Another point of interest for the maintenance is that the staff at Khimti I has experience with the Pelton runners, and how they are maintained in the best possible way. Thus the staff would be most comfortable with the Pelton solution.

5.7 Power price

The power price will together with the turbine type decide the income of Kirne. In figure 5.8, the possible variation in the price is shown, together with the corresponding income of the price.

In the calculations a careful estimate of 5, 5 UScent/kWh is used. This is the estimate given by the Nepalese office, and is the expected price given if the power is to be purchased by NEA. At peaking hours the price can be higher, but this is not incorporated into the calculations here. It is also possible that the power could be sold to Inida at a higher rate, but there are no agreements for this yet.

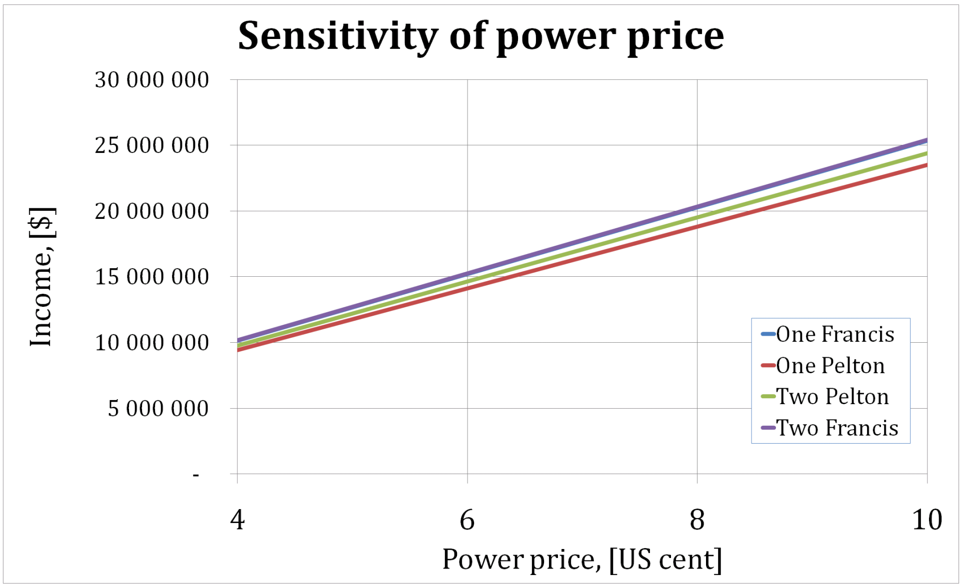


Figure 5.8: The income variation as a function of the power price.

5.8 Costs

It is very difficult to give exact estimates of the cost of the different elements in the power plant. There can be large variations in the prices of raw materials from year to year. Also the fact that hydro power plants are not in mass production, and that individual solutions are required for nearly all plants, makes it difficult to estimate the costs for a new plant. The estimates given in the cost section in the results chapter, 4.7, have many uncertainties and can only be used as rough estimates.

Since it is decided that Kirne is going to be built, this thesis has not focused on the economy regarding the build/not build issue. It is rather an optimizing of the mechanical elements that is done, and then calculating the cost of these elements.

The main costs of the Kirne Power Plant will be the changes made at the intake, and the new pressure shaft along the hillside of Kirne. The turbines and other changes are minor posts on the budget compared to these two.

5.8.1 Intake and water way

The costs for the changes that needs to be done at the intake and in the water way, are not computed or evaluated in this thesis.

5.8.2 Pressure shaft

The pressure shaft cost is estimated based on a rule of thumb for the cost per kilogram of installed pipe. Experience from Norway and abroad tell that the prices of this will not vary to much from different parts of the world. The price of 50NOK/kg is used in the calculations in this report. It is difficult to estimate the exact price per kilogram, and it is suggested that the price used in this thesis might be a bit too low. After the financial crisis in the autumn 2008/winter 2009, it is difficult to estimate the future steel prices, and steel market, this uncertainty has to be considered.

The cost of the pressure shaft is calculated based on the steel price, and based on the guide lines of NVE in their cost estimate. The difference between the two methods show a difference of 5,7 MUSD, but that is before the owner's costs are included in the NVE model. Including these costs, the total price is assumed to come out quite equal, at about 34 MUSD.

5.8.3 Turbine

The price of the turbines is estimated based on the NVE estimates. The results show that a Francis turbine of this size is cheaper than the Pelton turbine. And that the two Pelton turbines are the most expansive solution. The price of the turbines is on the other hand one of the smalles costs of Kirne, and hence other elements than the costs should be emphasised when the final choice is made.

5.8.4 Power house

The power house will be a more expensive construction if a Francis turbine is chosen, as the draft tube needs more place and excavation than a Pelton turbine power house.

5.9 Type of turbine

When the type of turbine is to be decided, several elements have to be evaluated. The technical aspects and the economic aspects should be optimized together, and the best solution in total should be chosen.

The production difference between one Peloton unit and one Francis unit, over the first 20 years will yield more than nine million US dollars in the favour of a Francis turbine, but this is given that both turbines have the same lasting ablility. Since the Francis runner will be more sensitive to erosion, this is not directly comparable.

If two Pelton runners are installed, there will be a gain of $4,5$MUSD over a 20 years period, compared to one Pelton unit. This is due to the wider range of high efficiency.

The conclusiong based on only the produced electricity from the turbines, is that two Francis turbines are marginally better than one Francis turbine. The two Pelton turbines are in the middle of one Francis turbine, and one Pelton turbine.

The cost of investing in the turbines gives also a favour of the Francis turbine, of $2,5$ MUSD. Which leaves a total favour for the Francis turbine of 12 MUSD. Thus the economic aspects show that a Francis turbine will be a good choice for Kirne. That is before the maintenance costs are considered. It is difficult to put an exact price on the maintenance, but if a Francis runner has to be sent away from site to be maintained, which is likely, and a Pelton runner can be maintained at site, the difference in the investment will be eaten up in a few years time.

The efficiency curves shown are only for the new runners. After a while, the curves will be degraded. Which curve that is degraded the most, is a difficult question.

Chapter 6

Conclusion

Kirne power plant will utilize a volume flow of 11 m^3/s. For more than 80% of the year this flow is exceeded. A new sediment basin should be built, of the same size as the existing basin, in order to handle the increased amount of sediments following the increased volume flow. Alternatively a new sediment basin could be built in connection with Khimti II upstream Khimti I.

The surge shaft should be enlarged by an extra volume of 170 m^3 at the top, to handle the extra up-surge caused by the increased volume flow in the tunnel. The down-surges will be regulated by slow opening procedures of the turbines and valves.

The pressure shaft of Kirne will have an economic optimal diameter of 2, 16 m, and will be about 1800 m long.

The recommended turbine choice is one or two Pelton units. Two runners will produce 8, 5 MW more than one unit, but the costs of the turbines and the surrounding parts will increase. Thus the two solutions will end at the approximate same result, but this is not investigated in detail. The Pelton solutions will produce about 240 GWh, which will give an income of 13 MUSD. The production can be up to 30% less in a dry year.

The runners of the two possible solutions will have the same diameters, but if it is only one unit, there will be five nozzles, and 3 nozzles if there are two units. The speed number of the 5, 5 MW runners, will be 0,1 while the 11 MW runner will be 0,14.

The Francis turbine is cheaper to buy, and produces more power, but is more expansive and difficult to maintain, since this is an important aspect of Kirne, the Pelton turbine is therefore chosen.

The construction of Kirne Power Plant should avoid disturbing the operation of Khimti I to the greatest possible extent.

Chapter 7

Further work

The design of Kirne Power Plant is not finished with this thesis. There are a lot of calculations, simulations and model tests that have to be done before the final design is reached, and the construction can start. Some of the main points for the further work are mentioned here.

The intake of Khimti I has to be altered, and the design of this should be done in cooperation with model tests of the head works, at hydro lab in Kathmandu. This is the same place as the model tests for the original intake at Khimti I was done, [16].

The excavation for the surge shaft should be investigated, and a simulation of the possible surges should be done.

The placing and construction of the pressure shaft should be planned and redesigned when the final length of the shaft is found. The way of mounting the pressure shaft, and safety during this, should be emphasized.

More simulations should be done for the runners before the final design and number of units are decided. Production simulations should be done in order to optimize the production and size of the runners at Kirne.

The surrounding parts of the Pelton runner/runners have to be calculated and fitted into the design. The power house should be optimized concerning size, and placement, to reduce the risk of being ruined by floods.

All the elements of the power plant should also go through a detailed cost-estimate.

In the end, all the not-technical agreements should be organized and sorted out. This might be the most difficult part of the Kirne Project.

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Appendix A

Mineral content in Nepali rivers

This table is taken from lecture notes in the course given at the Waterpower Laboratory the autumn 2008. [7]

Minerals	*Khimti River [%]*	*Khimti Adit 4 [%]*	*Jhimruk Turbine [%]*	*Hardness Moh's scale*	*Special characteristics of the minerals*
Quartz	$62 - 64$	$61 - 63$	72	7	Hard mineral, resist weathering
Feldspar	$3 - 5$	$3 - 5$	7	6	Gets weathered, white color
Muscovite	$8 - 9$	$6 - 7$	4	$2.0 - 2.5$	Light color soft flaky mineral
Biotite	$15 - 16$	$18 - 20$	3	$2.5 - 3.0$	Dark color soft flaky mineral
Chlorite	< 1	< 1	5	$2.0 - 2.5$	Soft flaky mineral, green
Phlogopite			9		
Sillimanite	< 0.5	< 0.25		$6.0 - 7.0$	Colorless, transparent, elongated needle and blade like mineral
Magnetite	< 0.5	$0.5 - 1$		$3.5 - 5.0$	Shining dark grey, magnetic
Hematite/ limonite	< 1	< 0.5		$5.0 - 5.5$	Earthy reddish brown iron oxide
Ilmenite	Traces	< 0.5		$5.5 - 6.5$	Shining black/ silver grey
Garnet	< 1	$1 - 2$		$6.5 - 7.5$	Light pink color
Tourmaline	0.5	< 1		$7.0 - 7.5$	Fragments of black, green, pink
Other minor	< 4	< 4			Very fine dust particles, clay and other minerals

Table A.1: Table showing the mineral content of Khimti I, Khimti Adit 4 and Jhimruk

Appendix B

Settling basin

This appendix is a continuation of the section on section 2.3 on sediment handling in the Theory chapter. The efficiency of a settling basin can be found from the Camps diagram in figure B.1, together with the following equations:

$$\frac{w}{U_*} \tag{B.1}$$

Where U_* is the shear velocity. U_* can be found from equation B.3

$$\frac{wA_s}{Q} \tag{B.2}$$

$$U_* = \sqrt{gR_hS_e} \tag{B.3}$$

Where R_h is the hydraulic radius and S_e is the energy gradient, which can be found in equation B.4.

$$S_e = \left(\frac{Q}{MAR_h^{2/3}}\right)2 \tag{B.4}$$

Where M is the Manning number and A is the area.

The final efficiency can be expressed as in equation B.5

$$\eta = 1 - e^{-\left(\frac{wA_s}{Q}\right)} \tag{B.5}$$

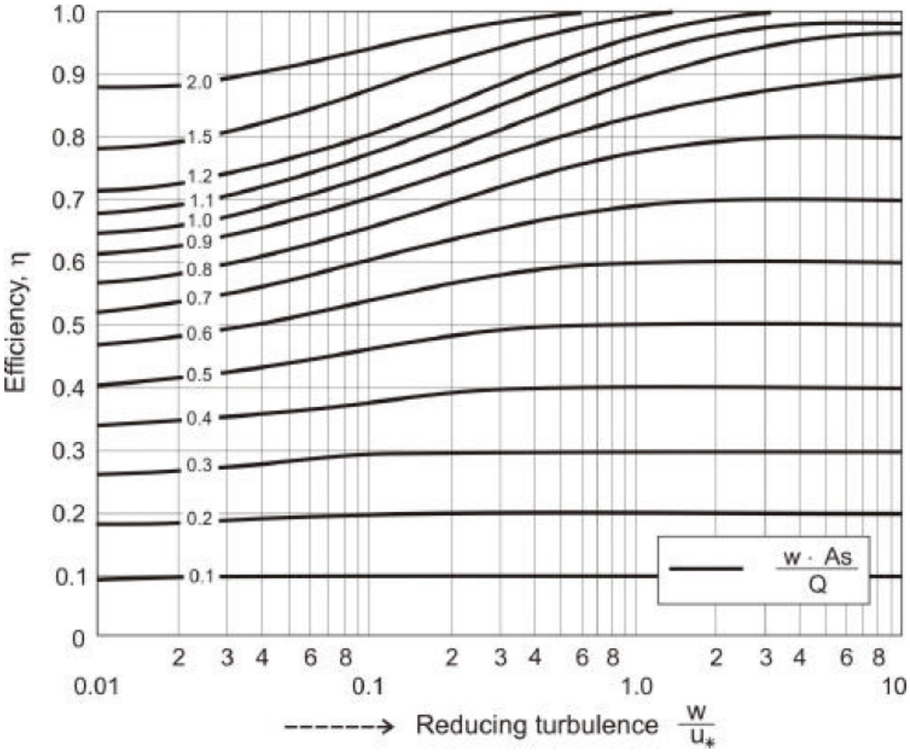

Figure B.1: Camps diagram for trap efficiency including the effect of turbulence on the fall velocity, from [6]

Appendix C

Nepal trips

During my work with Khimti I and Kirne Power Plant I have had two site visits in Nepal.

Figure C.1: Small children at the Khimti School.

Figure C.2: One of the runners at Khimti, ready for maintenance.

Figure C.3: Inside the machine house in Khimti I.

Figure C.4: The electrical grid in Kathmandu.

Appendix D

The Moody diagram

The Moody diagram, from which the friction factor used for calculating the head loss is found. The pressure shafts for Kirne and Khimti I are quite similar, and hence only one friction factor is used.

$$\text{Relative roughness} = \frac{\epsilon}{d} = \frac{0,046\text{mm}}{2000\text{mm}} = 2,3 \cdot 10^{-5} \tag{D.1}$$

Reynolds number:

$$Re = \frac{V \cdot d}{\nu} = \frac{\frac{11\text{m}^3/\text{s}}{3{,}14\text{m}^2} \cdot 2\text{m}}{1,003 \cdot 10^{-6}} \approx 7 \cdot 10^6 \tag{D.2}$$

Figure D.1 shows how the friction factor is found for the new and the old pressure shaft.

[9]

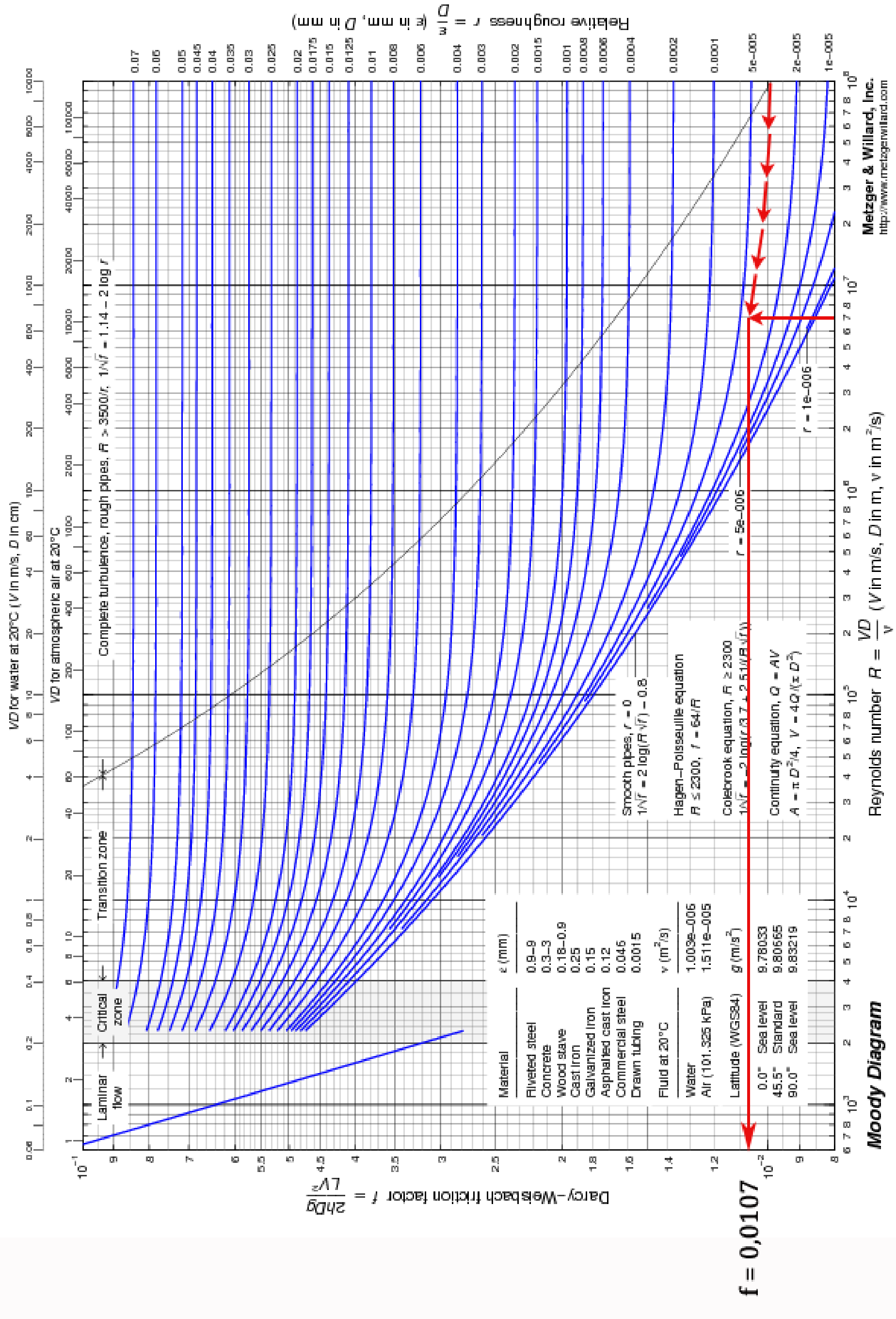

Figure D.1: The Moody diagram

Appendix E

Pipes

There are different materials that can be used for the pipes in hydro power plants. The following tables (E.1 and E.2), will list the physical data of some of them.

Table E.1: Physical properties of the pipe materials

Material	*Maximum diameter [m]*	*Maximum pressure [m]*	*Max stresses [MPa]*
Steel, St 37			150
Steel, St 42			190
Steel, St 52			206
PE	1̃,0	160	5
GUP	2,4 (Max. p=160m)	320 (Max. D=1,4m)	
Wood	5̃	80	
Concrete	5̃	4̃00	

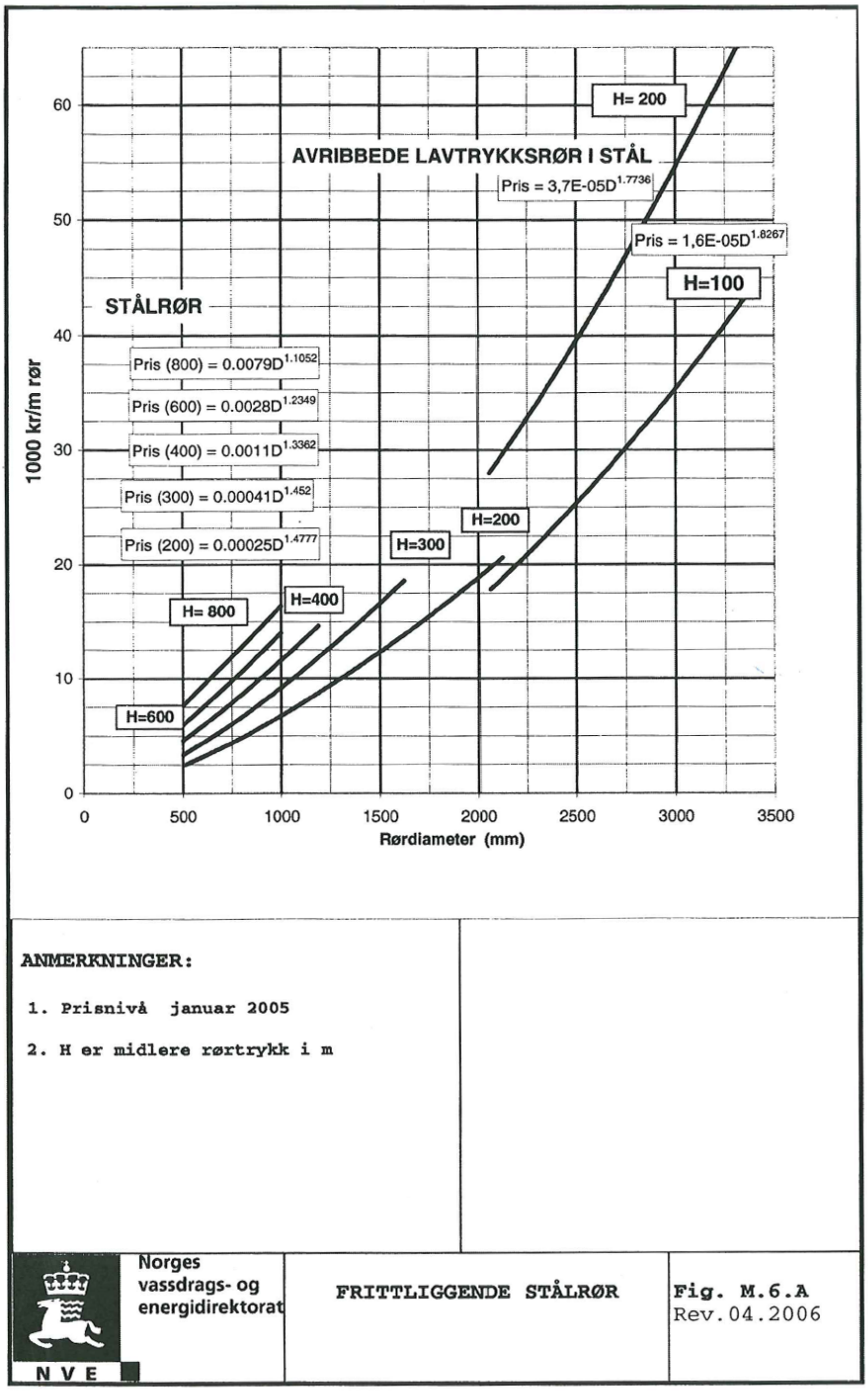

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Fig. M.6.A
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Figure E.1: The NVE price chart for steel pipes

Table E.2: Physical properties of the materials

Material	*Quality*	*Density* [kg/m^3]	*Modulus of elasticity* [MPa]	*Yield limit* [MPa]	*Tensile strength* [MPa]	*Coefficient of thermal expansion* [$m/^oCm \cdot 10^{-6}$]
Steel	St. 37	7830	206	235	363 - 441	12
Steel	St, 52	7830	206	353	510 - 608	12
Stainless steel	NS 14 310-02		205	440	590 - 780	
PE		920	100-300		7 - 19	
GUP						
Wood		300 - 800	4 - 11		28 - 70	5
Concrete		2350	20 - 40		15 - 70	10

Appendix F

Design of Francis stay vanes

When the guide vanes are finished, it is the stay vanes that are to be designed. The only purpose of the stay vanes is to keep the spiral casing together. Thus the aim when designing them, is that they should influence the flow as little as possible. The dimensioning criteria for the stay vanes is the stresses that have to be handeled.

The design of the stay vanes start with the outlet angle. Calculated in the same way as the guide vanes, with a free vortex flow between the stay vane and the guide vane, equation F.1.

$$c_{u,gvi} \cdot D_{gvi} = c_{u,sto} \cdot D_{sto} \tag{F.1}$$

Where the subscript *sto* stands for stay vane outlet.

The equation for the median velocity is given in equation F.2.

$$c_{m,sto} = \frac{Q}{\pi \cdot D_{sto} \cdot B_0} \tag{F.2}$$

When the stay vanes are to be dimensioned, the first step is to calculate the dimensioning pressure from the head and the water hammer, equation F.3.

$$p_{\text{max}} = p_{\text{inlet}} + p_{\text{water hammer}} \tag{F.3}$$

The size of the spiral casing will decide the force that has to be taken up by the vanes. First the diameters of the spiral casing is assumed, and the area is calculated, equation F.4.

$$A_{Casing} = \frac{1}{4} \cdot \pi \cdot D_{\text{outer}}^2 - \frac{1}{4} \cdot \pi \cdot D_{inner}^2 \tag{F.4}$$

When this is done, the force that has to be taken up by the stay vanes can be calculated, equation F.5.

$$F_{\text{max}} = p_{\text{max}} \cdot A_{\text{casing}} \tag{F.5}$$

A maximum stress level in the stay vanes, σ_{material}, is normally set to 100MPa. The thickness, $t_{\text{stay vane}}$, and the number of stay vanes, n, are chosen. Now the necessary cross section and lenght of the stay vanes can be calculated, equation F.6. The inlet angle of the vane is decided based on a free vortex assumption through the stay vanes.

$$L = \frac{F_{\text{max}}}{\sigma_{\text{material}} \cdot t_{\text{stay vane}}} \cdot \frac{1}{n} \tag{F.6}$$

In the end the diameter of the stay vanes can be calculated. Since a guessed area of the spiral casing is used in the beginning of this calculation, the procedure has to be repeated until the result is converging to a value.

Appendix G

Excel calculation sheets

This chapter is meant as an explanation to the Excel sheets made for the calculations in this thesis. The Excel sheet is enclosed in an electronic version of the thesis.

G.1 Objectives

The first sheet in the work book is describing what the calculations should obtain.

G.2 In-Data

The In-Data sheet contains the constant values of different parameters. All in-data should be plotted here, and the calculation sheet will take the values from here.

G.3 Hydrology sheet

- The hydrology for all nearly all the days from 1968 and up to now is collected.
- The average for each day of the year is found.
- A curve is made so that the flow over the year is represented graphically.
- The average is sorted, so that a duration curve over the year is obtained

- The days of the monsoon is selected - from 1. June, until 15. of November.
- The duration curve is made for the monsoon and the whole year.
- The flow available for Kirne is found by subtracting the minimum release in the Khimti River, and by subtracting the flow required for Khimti I.

G.4 Results

The result sheet collects the results from the other calculation sheets.

G.5 Charts

In the Charts sheet, all the graphs and charts from the calculations are presented under the corresponding headings.

G.6 Head loss

The head loss sheet calculates the head losses in the different parts of the power plant.

- The volume flow is the flow in the tunnel. Hence the volume flow available for Kirne is the total flow subtracted the flow for Khimti I.
- The duration curve is calculated from the hydrology sheet, where it is converted to the flows selected for the calculations.
- The head loss in the tunnel is calculated by the manning formula, and for all the water flowing in the tunnel. The loss is only calculated until Adit 4, and for the whole tunnel.
- The next row is giving the head loss in the tunnel for the existing Khimti I and the design flow there. That is so that the increased head losses connected to Kirne PP can be accounted for. Which is done in the next row.
- The flow available for Kirne Power Plant is calculated by subtracting the flow for Khimti I.
- Head loss in pressure shaft is calculated by the Reynolds number and the Chezy formula.

- Total head loss is found by simply adding the tunnel head loss and the pressure shaft head loss.
- Efficiency curves are made based on the standard curves given by NVE. The curves used in this sheet is a middle value of 5 MW turbines and 100 MW turbines. This gives an approximate curve which can be used for initial calculations.
- The cost of the headloss is calculated by the production formula, where the duration curve, power price, head losses and efficiency is combined.
- In the last rows the effect of adjusting the Manning number is shown.

G.7 Production

The production sheet calculates the production at different volume flows, of the different turbines.

- The efficiency curves is adjusted so that the maximum efficiency coincides with the design flow of the turbine.
- The production is calculated for one Pelton, two smaller Peltons, one Francis and two smaller Francis.
- The produced power is calculated with the number of days at maximum flow, and then for the flows below maximum flow is multiplied with number of days. The accumulated flow is given.

G.8 Stability

The stability of the power plant is calculated in this sheet. The estimation formulas given in [18] are used for the calculations. The surge limits are also given, and then plotted.

G.9 Optimal pipe diameter

The optimal pipe diameter is calculated based on the formulas given by Torbjørn Nielsen in the lecture notes, [19].

The investment cost, K_t is calculated for the different diameters, and the cost of the hydraulic losses, K_f is calculated for the different diameters, and then accumulated for the 20 first years of operation, hence the net present value of the losses are calculated. Based on this the curves are produced.

The optimal diameter is also calculated directly from the formula, given in equation (2.38).

G.10 Speed number

In this sheet, the speed number at different rotational frequencies and volume flows are calculated. The resulting chart gives a picture of when to use a Francis and when to use a Pelton.

G.11 Main dimensions Pelton runner

In the sheet for calculating the main dimensions of a Pelton runner, the formulas presented in Pumps and turbines, [2], are used.

The dimension of one Pelton runner of the whole volume flow, and two smaller runners of half the volume flow each are calculated.

G.12 Main dimensions Francis turbine

In this sheet the formulas used are taken from [2],[7],[13]. The result is presented only for one runner utilizing the whole flow.

G.13 Construction costs

Here the costs calculated of the steel pipe and the runners are presented.

G.14 Efficiency

In this sheet the approximate efficiency curves are calculated and shown with the equations.

G.15 Duration individual

This is a copy of the hydrology sheet, just that the focus this time was to produce a chart showing each of the 38 year's individual duration curve.

Appendix H

Duration curves

The duration curves for each of the 38 induvidual years are presented in the graph in figure H.1. Including the limiting flow of $22\text{m}^3/\text{s}$.

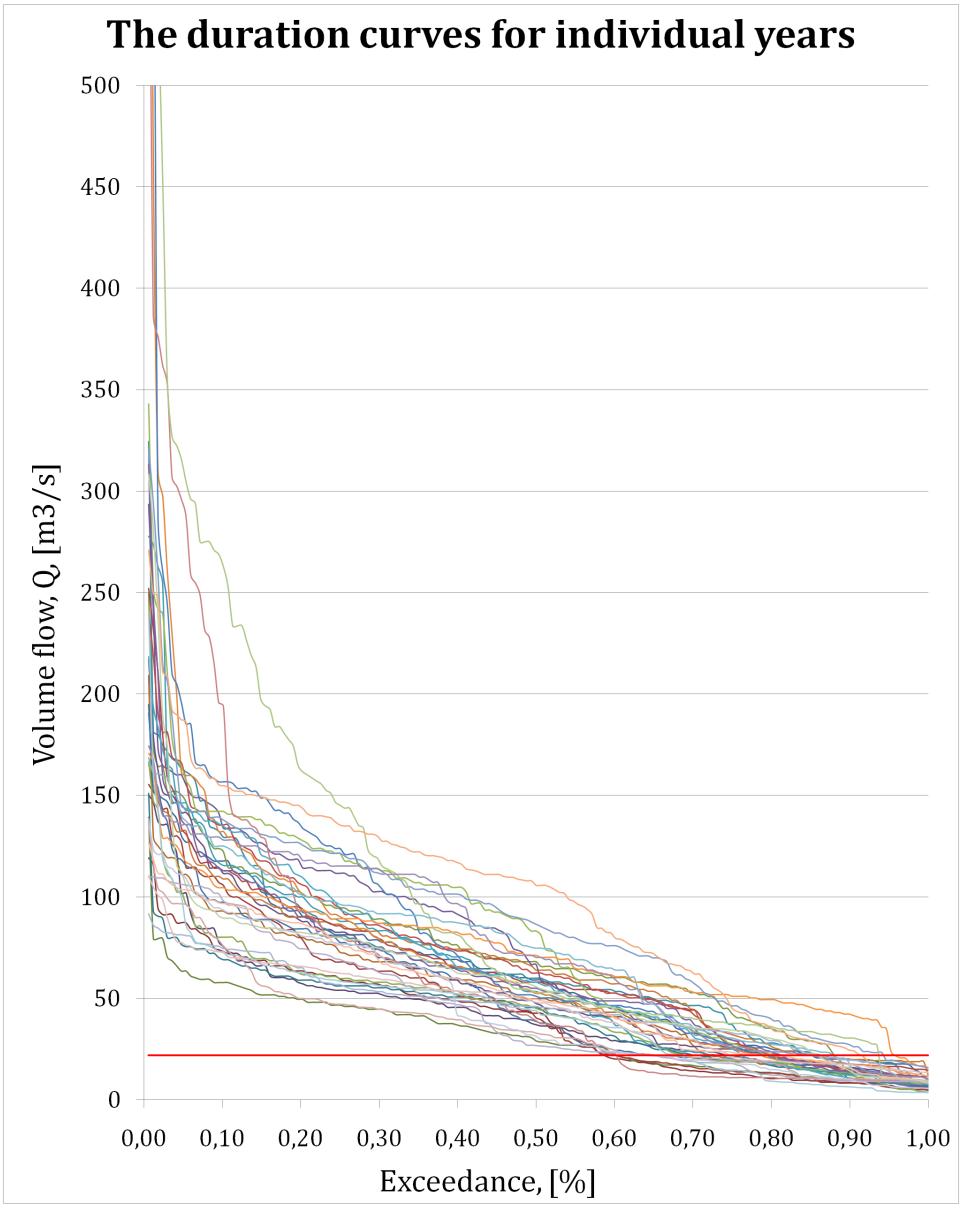

Figure H.1: The duration curve for the individual years.

Appendix I

Brainstorming Kirne Power Plant

During my site visit to Khimti I and the proposed Kirne Power Plant, I attended a meeting where there was a brainstorming around the different aspects of Kirne Power Plant. This chapter will summarize the content of the brainstorming.

I.1 People attending the brainstorming

- Viggo Mossing
- Kjell Heggelund
- Thomas Schönblom
- Rajib
- Bisht
- Nadia Sood
- Lisa Huun Thomsen
- Yngve Trædal
- Bernard
- Tom Solberg
- Ingebjørn
- Subas

- Boban
- ++

I.2 The brainstorming

- Question about the necessity of a peaking period of three hours when selling power to India. It is important that the requriements are stated clearly. As long as Kirne is only used during the wet season there will always be a three hour peaking capasity in the river flow. The conclusion was that it would not be very difficult. *Ask Lisa or Yngve about this, they will know the requirements. I will however dimension it with no peaking capasity.*
- There has to be done an evaluation if it is profitable to sell the power in Nepal. This might be a possebility if the grid to India is not ready when the construction of Kirne is finished.
- There are also several other aspects that have to be evaluated and conclued on before an power sales agreement could be set up. My thesis will asume that the agreements for selling the power are finished and that there is no problems connected to the evacuation of the power. The price of the power will be assumed based on the existing PPA at Khimti with NEA, and a bit less. It is the break even tarif that will be the important number for my thesis. The profit can then be easily calculated from this.
- There will **not** be built a new tunnel.
- Khimti I will not be stopped for a longer time for expanding the existing tunnel.
- A discussion on how much the flow it is possible to get through the tunnel. A few arguments that I did not get, for example that it would not be any more sediments when the volume flow is increased..
- It was suggested that an extra surge shaft could be built parallell with the existing. Or expanding the existing shaft (but I think that this option would be more expansive, and less convenient)
- Have to investigate the Licence for Kirne Power Plant. Is there any restrictions concerning the size of the new power plant. *Talk to Viggo about this.*
- ESIA- Environmental Social Impact Assessment, must be carried out, will not be a part of my thesis.

- The locals have a lot of demands, but not all of them will be fulfilled, for example an access road to adit 4. Too steep and unstable ground. But there has to be an alternative to get the material to the top of adit 4, a ropeway could be a good alternative. (The locals have already started the construction of the road)
- A full tunnelinspection was last done in 2001. There are leakages from the tunnel. A discussion if there is a settlement that uses one of the leakages as their water supply. Then it can be difficult to seal the leakage.
- Will the increased volume flow increase or decrease the leakage in the tunnel. Most probably decrease. The level at the intake will also be increased, important to take this into account.
- There will be done a headloss measurement in May 2009.
- There is a possebility to have a new settling basin at the other side of the river, and then lead the water through an aquaduct over the river.
- **Surge shaft**, load rejektion in the surge shaft is a difficult and complex question.
- Any altering of the surge shaft will result in long down times.
- The closing time of the turbine and valves could be adjusted to a longer time.
- Some shut downs can not be planned, and the shaft has to be dimensioned due to this as well.
- A parallell surge shaft is an alternative, but then one has to be aware of the possebility of u-tube oscillations.
- Down surge is critical.
- **Type and number of units**
- There has to be a valve at the top of the penstock, butterfly valve.
- Investigate the contract energy. HPL is to fulfil this at all times.
- PPA, NEA has the right to purchase excess energy at all times if they want to. So far in the history of Khimti I, they have not used the possebility.
- More sediments with more volume flow. Also more head/volume flow has to be added to compensate for the extra headlosses.
- What is the price of a new settling basin, and is the price so that it would be profitable to invest in more turbines, and rather change them more often, and use only the old settling basin?

- The staff at Khimti knows the pelton turbines, this is an advantage over francis turbines.
- Remember that the turbines has to be transported to the site, this was the limitation and reason why five pelton units were chosen at Khimti I.
- 55 tonnes, road access.
- Might supply power to NEA in other ways during the construction period.
- Outage during the wet season, and transport during the dry season. It is impossible to use the roads for transport during the wet season. NEA might aslo demand that the outage should be in the wet season (?).
- **Watersharing, very important**
- Maintenance schedule Khimti I and Kirne Powre Plant
- Is subsurface power house an alternative? GLOF risk..
- **Legal and financial issues**
- Power tariff, Indian market
- Must decide on the strategy
- A market study is done for Tamakoshi, Sandip has the report
- Free energy to NEA
- Survey License
- Is there a possebility that NEA could be paied out?