Hólmsá HEP

Recommendations for installed capacity based on simulation of energy generation and reservoir level

Ólafur Jónsson

Hólmsá HEP

Recommendations for installed capacity based on simulation of energy generation and reservoir level

Ólafur Jónsson

A 30 ECTS credit units Master´s thesis

Supervisor
Mr. Úlfar Linnet, Landsvirkjun

A Master´s thesis done at
RES | The School for Renewable Energy Science
in affiliation with
University of Iceland &
University of Akureyri

Akureyri, February 2011

Hólmsá HEP

Recommendations for installed capacity based on simulation of energy generation and reservoir level

A 30 ECTS credit units Master´s thesis

RES | The School for Renewable Energy Science

Solborg at Nordurslod

IS600 Akureyri, Iceland

Telephone + 354 464 0100

www.res.is

February, 2011

Akureyri, Iceland

ABSTRACT

This M.Sc. thesis deals with the problem of determining the appropriate installed capacity for a specific hydropower plant development project, based on available hydrological measurements. This is important in order to maximize a return on investment for the project. Investment costs are not covered in this project.

To accomplish a determination, a model was constructed to emulate the inflow and reservoir capability to produce power. The inflow data was analyzed using statistical measures and reservoir routing simulations. This gave indications on the current available flow of water and flow predictions for the future. A hypothetical power intensive customer was defined to control the energy demand in the system. Losses in waterways were worked out for different flow and water surface level in the reservoir.

The model was then used to run iterative simulations for different values of installed capacity to find total revenue per year from sold energy and to record the results. Graphing the results clearly shows a peak were total revenue is maximized and indicates a recommended installed capacity of 58,8 [MW] for the way this scenario was set up.

The results from this project have been verified against numbers at the same project location but done by the National Energy Authority in Iceland. This shows that the difference in total energy capability per year of these two compared results is within ~5% variance.

PREFACE

This thesis is submitted as partial fulfillment of requirements for a Master of Science Degree in renewable energy science at RES | The School of Renewable Energy Science. The degree is awarded in affiliation with the University of Iceland and University of Akureyri.

The thesis is based on studies conducted from February 2010 to February 2011 with emphasis on hydropower development. Mr. Úlfar Linnet from Landsvirkjun; Iceland's main power company, has worked as the thesis advisor. The thesis and model work is based on course studies, lecture notes and other sources of information that have been referenced to the best of my ability.

Purpose

This thesis is focused on determining the recommended installed capacity for a proposed hydropower plant in Southern Iceland. The proposed project location has been studied by Landsvirkjun for several years.

A hydropower project of this scale involves many disciplines of science and requires extensive research. It is impossible to complete a full design of a hydropower plant and everything that comes with it in the timeframe of this project. So many factors fall out of scope in this thesis, and will have to be considered at another time.

Acknowledgment

I wish to take this opportunity and thank my advisor Mr. Úlfar Linnet and also Mr. Helgi Jóhannesson, both at Landsvirkjun, for their assistance. I also thank Mr. Valur Knútsson at Landsvirkjun Akureyri for providing facility for meetings and Mr. Steinar I. Halldórsson at the Icelandic engineering firm *Almenna Verkfræðistofan* for his contribution.

I also want to thank Mr. Jónas Elíasson, hydropower coordinator and all the professors involved in my studies at RES for an excellent program.

I thank Mr. Björn Gunnarsson, Rector of RES; Ms. Ólöf Baldvinsdóttir for proof reading and all the staff members and especially Ms. Sigrún L. Kristjánsdóttir for all the assistance to provide an entertaining yet tough year.

All my classmates from all over the world I thank for outstanding parties and an awesome time together. I hope to stay in touch with all of you in the future.

Finally, I especially want to thank my wife Halla and my three kids; Aldís, Emil and Ívan for all their endless patience and sticking with me through this year. I also thank my parents for sheltering me during my thesis writing.

Ólafur Jónsson, February 2011.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES & GRAPHS

1 INTRODUCTION

Constructing a medium to a large hydropower plant is a process that involves many disciplines of science. It is very important to have the size of the whole system appropriate for the environment it is planned to operate in. Having the system too small means lost energy with water flowing past the turbines. Likewise, having the system to big means higher investment cost and underutilization of equipment which results in lower efficiency, hence revenues are lost.

The problem to be solved in this project is to find a way to determine the appropriate size of a hydropower plant. In more detail the scope of this project is to focus on installed capacity; which is how big the generator should be in [MW] for a specific location.

In conclusion, the use of reservoir and inflow data provided with the project description, created a model of a running hydropower plant. In the model simulations are done with different settings to find out which setup gives the highest total revenues. An example of an energy sales contract between a power company and a big consumer customer is used to be able to determine the economics. The generator recommended installed capacity for this environment is then known from the setup that gives the highest revenues.

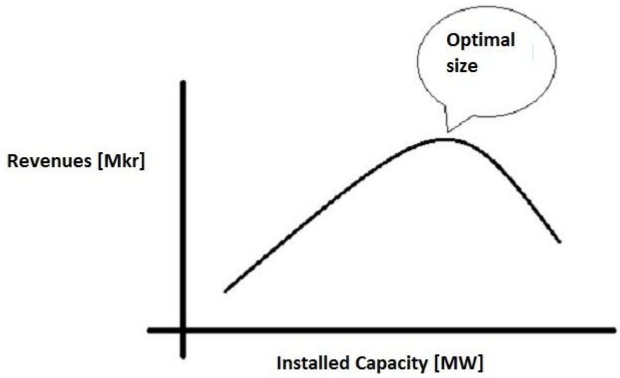


Figure 1.1 How to find optimal installed capacity.

The following chapters will look at the Icelandic hydropower statistics in general and the project site plus layout in more detail. Evaluate the data that is given and which data will need to be worked on. Analyzing the inflow data using statistical measures, this is done to understand its behavior and evaluate future possibilities. Losses in waterways and related methods for this project are then determined and followed by a description of how the example contract used in this project works. A chapter on how the model is set up, what variables can be adjusted and how the calculations are done. In closing, a chapter on the results found from the model simulation with the highest revenues.

2 BACKGROUND

This chapter covers information about hydropower production in Iceland, where current power plants are located and future possibilities. This project proposed location showing the dam, tunnels and the power house. Look at the data given in the project description and the tributaries flowing into the reservoir.

2.1 Hydropower in Iceland

Landsvirkjun (LV) is Iceland’s biggest power company with around 75% market share in the electrical energy market. Most of Landsvirkjun power comes from hydropower and only around 63 [MW] from two geothermal plants. Below is a list of Landsvirkjun hydropower plants with a total installed capacity of 1.798 [MW].

Fljótsdalur	690 MW
Búrfell	270 MW
Hrauneyjarfoss	210 MW
Sigalda	150 MW
Blanda	150 MW
Sultartangi	120 MW
Vatnsfell	90 MW
Írafoss	48 MW
Steingrímsstöð	27 MW
Ljósifoss	15 MW
Laxá III	14 MW
Laxá II	9 MW
Laxá I	5 MW

Table 2-1 Landsvirkjun current hydropower plants. (www.lv.is)

The new hydropower plant proposed in this project is expected to be small to medium size, compared to Landsvirkjun’s exciting hydropower plants in the table above. These expectations are based on having around 124 [m] head (H) with an average flow around 50 [m3/s] (Q) using the following rule of thumb for 87% efficiency to find the power (P) close to +50 [MW].

$$P[\mathrm{MW}] = H[\mathrm{m}] * Q[\mathrm{m}^3/\mathrm{s}] * 0,0087[\,] \tag{1}$$

The following figure illustrates where the current power plants are located, which ones are or were under construction and what future possibilities have been looked at.

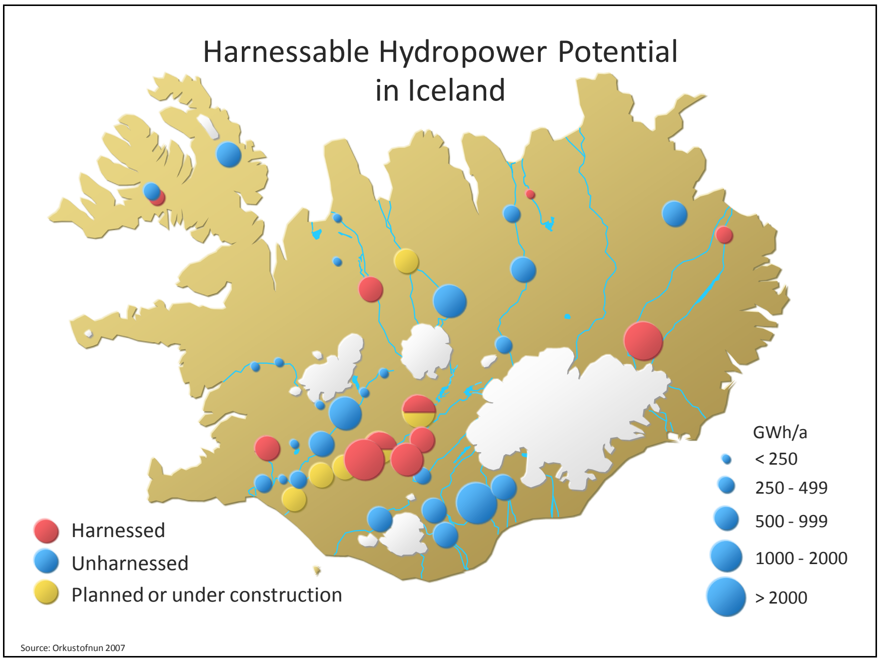
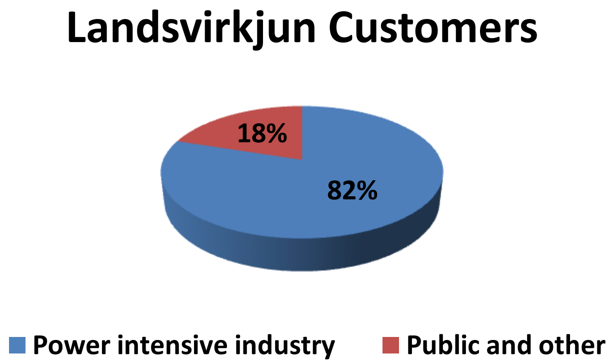


Figure 2.1 Power potential in Iceland 2007. (www.os.is)

Iceland has one of the highest energy per capita consumption in the world (www.wikipedia.com). This fact can be explained by a low population and a few power intensive customers like aluminum smelters. On the following graph it can be seen how the energy is roughly divided between customers.



Graph 2-1 Energy division between Landsvirkjun customers. (www.lv.is)

This graph demonstrates that around 82% of Landsvirkjun energy is delivered to power intensive industry, in fact a few big customers. In total Landsvirkjun generates around 12,5 [TWh] per year (Hörður Árnason, LV). This project is aimed at providing energy to a power intensive industry.

2.2 Project location

This project is planned in the southern part of Iceland close to the glacier Mýrdalsjökull and not too far from the coastline. South Iceland has more precipitation than The North (www.vedur.is). The location can be seen on the figure below marked by a yellow pin. This project is called Hólmsá HEP (hydroelectric power) after the main tributary.

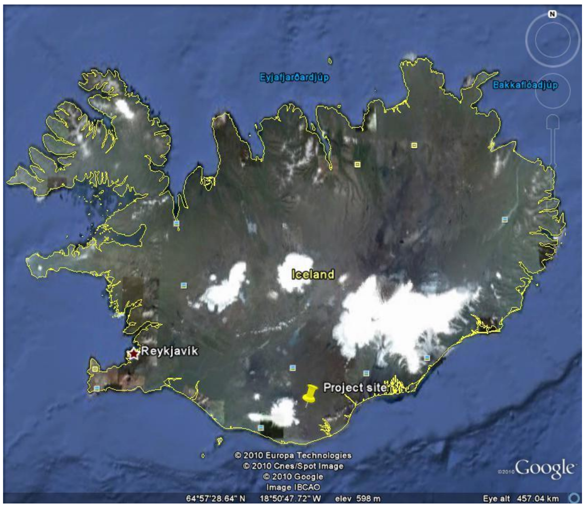


Figure 2.2 Rough project location. (www.googleearth.com)

Below is a more detailed map showing the reservoir and dam which are located close to the mountain Atley, where the headrace tunnel leads to the powerhouse and then the tailrace tunnel leads to the outlet at Flögulón.

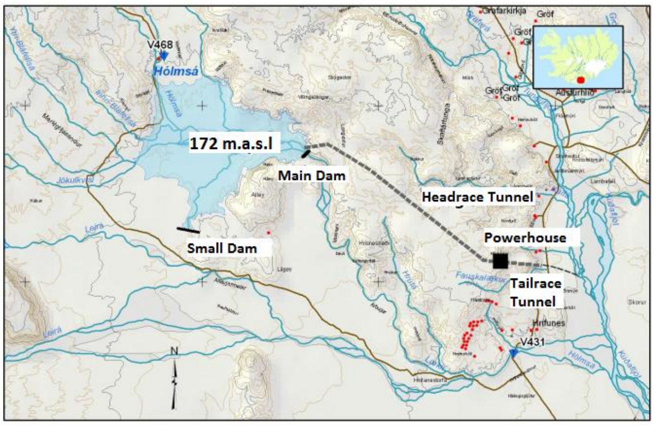


Figure 2.3 Detailed project location. (www.red.is)

On this figure the water flow measurement station V468 (also called V231) is shown, an approximate view on how the reservoir appears while it is full. From the main dam lies a gray dashed line representing the headrace tunnel to the powerhouse and from that a tailrace tunnel followed by a canal. The main tributary Hólmsá is shown along with the additional tributaries; Bláfellsá (both) and Jökulkvísl.

2.3 Data relevant to project

The first chapter lists the data that came with the project description; the next chapter has data from other external sources and explains which data needs to be worked out. The final chapter has a summary of data to be used during the process of solving this project.

2.3.1 Data from project description

The original project description comes from Mr. Helgi Jóhannesson, a project manager at Landsvirkjun. Landsvirkjun is Iceland's main power company and state owned. Apart from the daily operation and maintenance Landsvirkjun is also involved in the investigation and design of new hydropower plants. Another employee of Landsvirkjun; Mr. Úlfar Linnet, is this project's advisor and contact person within the company.

A few hydrological measurements stations operate in the project area. Station V468 in Hólmsá (used to be V231) has been in operation since 1984, flow series is available from September 1984 to August 2008. In the project description it is stated that the flow series from 1988/89 to 2007/08 should be used, i.e. daily average values for 19 years. The summer of 1988 was dry compared to other years. The inflow data is in [m^3/s] with an accuracy of one decimal digit, see Appendix G.

The Flow from other tributaries, other than Hólmsá, is evaluated by looking at measurement station V577. This station is located downstream of the proposed dam site and has only been in operation from September 2009. Based on these recent measurements it was first suggested in the project description to multiply the flow series by a yearly constant 1,6. Then more accurate monthly constants were provided, see chapter 2.3.2.

In the project description, the leakage from the reservoir under the dam was given as constant 0,5 [m^3/s]. A more accurate formula was provided later on which calculated the leakage based on the height of the water in the reservoir, see chapter 2.3.2.

According to the project description, the crest elevation of the spillway cannot be higher than 172 [m.asl.] due to environmental reasons. This also means that the surface level of the water in the reservoir will not be able to go higher than 172 [m.asl.]. Hence, this limits the maximum volume of the reservoir and the system's ability to store water/energy.

2.3.2 Data from external sources

Flow

As mentioned above a more accurate estimation of the other tributaries contribution were provided in a report by the engineering firm Almenna Verkfræðistofan (AV); done for Landsvirkjun (LV) and Rarik Energy Development (RED) in September 2010. The flow values from the V468 series should be multiplied by a constant that varies month by month. The following table shows this relationship between V577 and V468.

Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
2,3	2,0	1,7	1,7	1,6	1,4	1,6	1,7	1,9	2,4	3,5	3,5

Table 2-2 Values for monthly flow constants. (Steinar I. Halldórsson, AV)

This recent measurement station V577 needs to be monitored for the next years and then it can be verified if this table of constants is accurate enough to describe to total inflow to the proposed reservoir at the Atley site.

Leakage

Landsvirkjun provided information about the leakage from the reservoir under the dam. The leakage should be linear in the range 0,5 [m^3/s] for minimum reservoir level of 155 [m.asl.] and up to 1 [m^3/s] for full reservoir at 172 [m.asl.]. Using linear interpolation function in Excel the following table for leakage was derived. Reservoir evaporation is not covered in this project.

Elev.	**[m.asl]**	155	156	157	158	159	160	161	162	163
Q_L	**[m^3/s]**	0,50	0,53	0,56	0,59	0,62	0,65	0,68	0,71	0,74
Elev.	**[m.asl]**	164	165	166	167	168	169	170	171	172
Q_L	**[m^3/s]**	0,76	0,79	0,82	0,85	0,88	0,91	0,94	0,97	1,00

Table 2-3 Leakage under the dam for different elevations.

Efficiency

The generator and transformer efficiencies are given as constants, 98% and 99% respectively, but the turbine efficiency is a function of load. The following figure provided by Landsvirkjun is used to determine turbine efficiency.

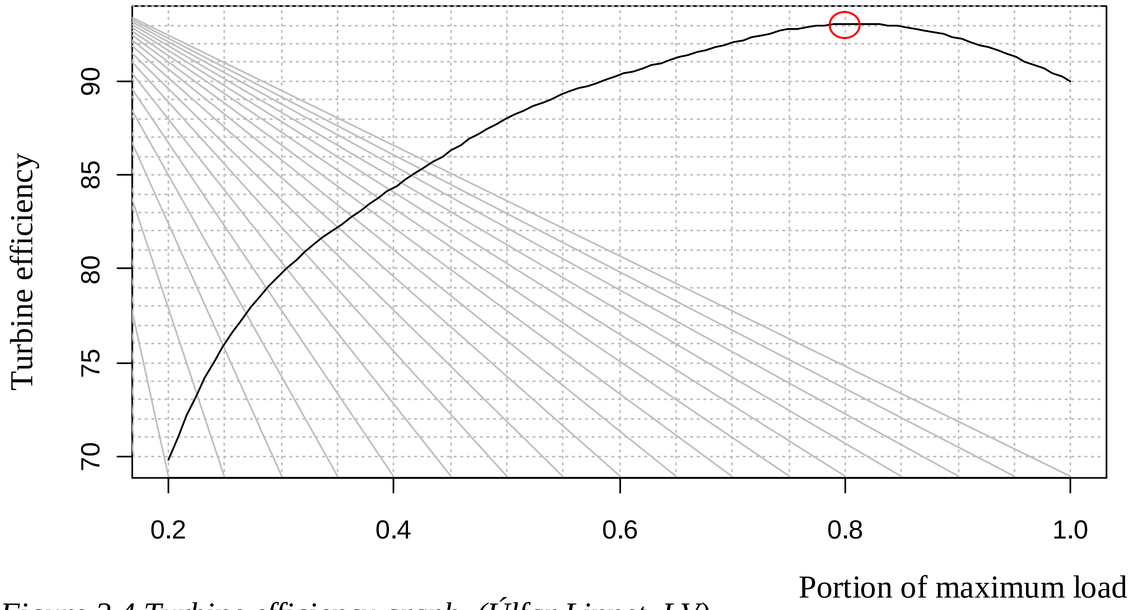


Figure 2.4 Turbine efficiency graph. (Úlfar Linnet, LV)

As can be seen on the figure above, maximum turbine efficiency of 93% is achieved by running at 80% of maximum installed capacity. Again a linear interpolation function in Excel was used to derive the values for the turbine efficiency table, see Appendix A.

Reservoir elevation & volume

For the relationship between reservoir elevation and usable storage volume, a graph and a formula was obtained from AV. The formula seen below was used in Excel to create a table with values for volume at different elevation ranging from 155 - 172 [m.asl.] S is volume in [Gl] and x is elevation in [m.asl.]. Table can be seen in Appendix B.

$$S[\mathrm{Gl}] = 0{,}19882x^2 - 59{,}028x + 4372{,}6895 \qquad (2)$$

(Steinar I. Halldórsson, AV)

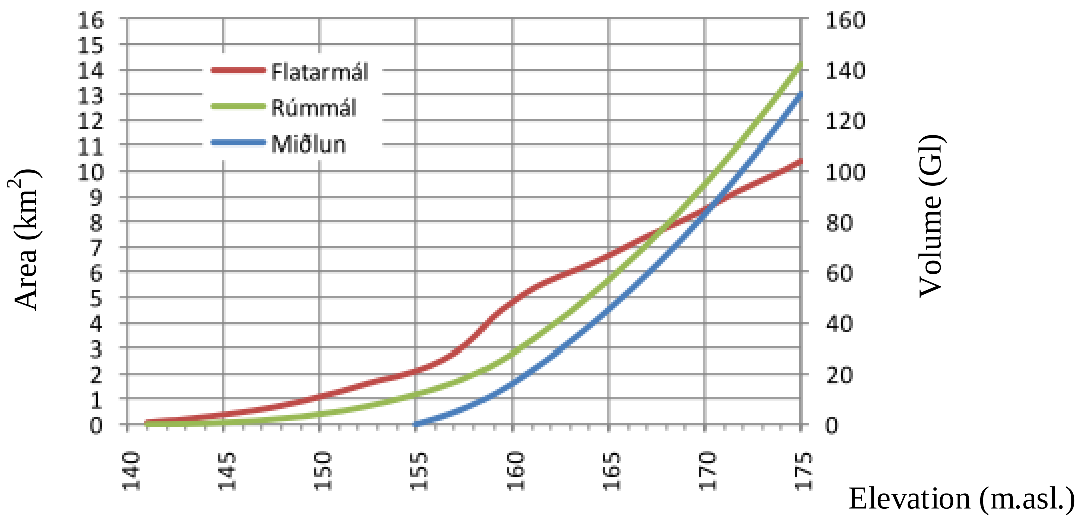


Figure 2.5 Reservoir elevation and volume. (Steinar I. Halldórsson, AV)

The figure above shows reservoir data and displays the relationship between area (red line), total volume (green line) and usable storage (blue line). From the figure above and with the previously stated maximum elevation of 172 [m.asl.] it can be seen that the volume lies is in the range of 0 – 100 [Gl].

Head loss

Head losses in waterways are given by Landsvirkjun as an average constant of 7,5 [m]. This value is used in this project when other values are not available. The formula seen bellow was also given by AV to calculate head loss, this formula was given for flow of 60 [m^3/s].

$$H_L[\mathrm{m}] = 0{,}00314 * q^{1{,}9991}[\mathrm{m}^3/\mathrm{s}] \qquad (3)$$

(Steinar I. Halldórsson, AV)

In this formula H_L is head loss in [m] and q is the flow in [m^3/s]. In chapter 4, head losses for this project are shown and then compared to this formula by AV for verification.

Energy price

For the purpose of economical evaluation the price of energy is needed. Example prices are given as 2,5 [kr/KWh] for energy sold and as 4,7 [kr/KWh] for energy bought (Úlfar Linnet, LV). As seen, the process of buying energy instead of generating it, with the purpose of selling the energy has a net loss of 2,2 [kr/KWh].

Turbine

The suggested turbine type for this project is a Francis (Steinar I. Halldórsson, AV). Francis turbines are the most common turbines today and operate in the range from ten meters to several hundred meters, see figure below. The Francis turbine is a reaction-impulse turbine, i.e. works on change in pressure and kinetic energy.

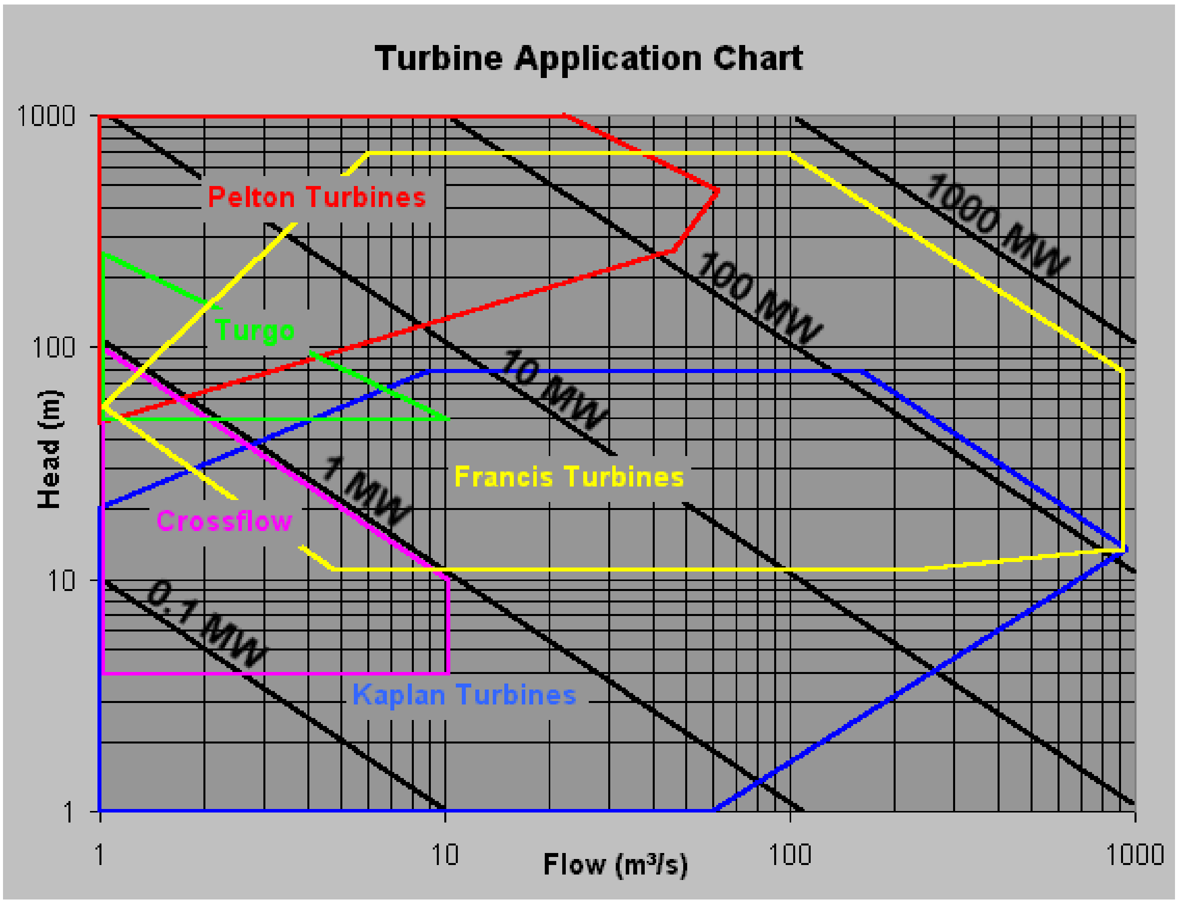


Figure 2.6 Turbine application chart (Elías Elíasson, LV)

It can be seen on the figure above that Francis turbines are well suited for this proposed project with an estimated net head around 100-120 [m] and flow in the range 40-60 [m^3/s]

2.3.3 Data summary

Here is a summary table of data that was used in the project. More detailed information on some of these values is found in the relevant chapters of this report.

H_R	Reservoir maximum elevation	172 m.asl.
H_R	Reservoir minimum elevation	155 m.asl.
H_T	Turbine center elevation	51 m.asl.
H_L	Average head losses in waterways	7,5 m
V_{max}	Reservoir usable volume	100 Gl
L_H	Headrace tunnel length	6.600 m
L_T	Tailrace tunnel length	1.050 m
	Turbine type	Francis
η_{tu}	Turbine efficiency (maximum value)	93%
η_{ge}	Generator efficiency	98%
η_{tr}	Transformer efficiency	99%
g	Gravitational acceleration (Iceland)	9,82 m/s^2
ρ	Density of water	1.000 kg/m^3
Q_A	Average discharge (from RED)	50 m^3/s
H_A	Average head (from RED)	124 m
$ks_{(st)}$	Roughness factor for steel	0,3 mm
$ks_{(sh)}$	Roughness factor for shotcrete	150 mm
S_{min}	Minimum slope for water to flow	0,2%
T_A	Average water temperature	4°C
ν	Kinematic viscosity of water at 4°C	$1{,}566 \cdot 10^{-6}$
Q_L	Leakage trough dam	0,5 – 1.0 m^3/s
D_1	Diameter of headrace- and tailrace tunnels	6,5 m
D_2	Diameter of pressure pipe	3,5 m
L_P	Length of pressure pipe (calculated)	85,75 m
	Price of energy sold to power intensive industry	2,5 kr/KWh
	Price of energy bought	4,7 kr/KWh

Table 2-4 Summary table of data values.

3 INFLOW DATA ANALYSIS

This chapter will go over inflow series data analyses. Having a decent amount of data is good to get more accurate results from statistical analysis. Over 20 years of inflow data with daily measurements are available for the proposed project location. This data set will be used to get an idea about how the inflow is behaving and what could be expected in the future.

3.1 Describing the data set

The inflow data set provided with the project (LV) contains daily flow measurements from September 21, 1984 and up to August 31, 2008; a total of 8746 days and around 24 years. This amount of data is close to being 50% or more of the average “deprecation time” of a power plant (Úlfar Linnet, LV). Therefore this will give a good idea of how a power plant could have been run for the first half of its time up until today. The project description states that only a partial data set for the years from 1988/89 to 2007/08 should be used to estimate the energy capability of the system. So data analyses were done on the full data set and also the partial version.

3.2 Data statistics

This section covers data analyses results from both the full data set and the partial data set.

3.2.1 The full data set

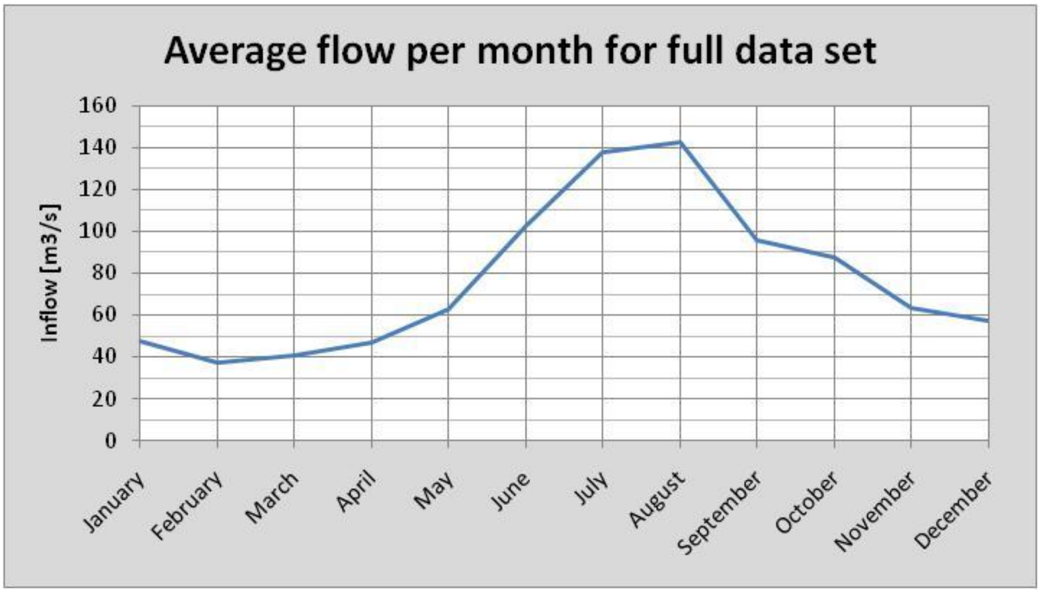
In the table below the main results from several statistical tests are shown, numbers are flow in [m^3/s]. As seen in the table the difference between minimum and maximum is substantial (max. ~ 24 * min.), see graph in Appendix E. Flood analysis is not covered in this project. The standard deviation is also high (~60% of avg.), which is not optimal for hydro power plants. A more stable inflow would be more optimal and possible lead to a smaller reservoir. Having such large fluctuations in inflow increases the need for a bigger reservoir to handle those fluctuations and make better use of the water. Without a big enough reservoirs one must accept the fact that more water will be lost by flowing over the spillway.

Avg.	77,1
Std.dev	46,1
Mode	40,8
Median	64,6
Min	24,5
Max	602,0

Table 3-1 Statistical results from full data set analysis.

A statistics analysis which was done in Excel shows that just over 82% of the flow is within the standard deviation limits, i.e. the average flow of 77,1 [m^3/s] +/- the standard deviation 46,1 [m^3/s].

The average monthly flow within a year shows that the fluctuations are still quite big or around 100 [m^3/s]. Seen on the graph below;



Graph 3-1 Average monthly flow within a year.

The average flow is at a minimum around 40 [m^3/s] in February and March and at a maximum around 140 [m3/s] in July and August. A flow distribution graph was done which clearly shows that the data set is sparsely distributed and does not follow normal distribution. Flow distribution and more graphs for the full data set are in Appendix E.

3.2.2 The partial data set

The full data set has been cut down to 19 years according to project description or from 1989 to 2007 with both years included. This partial data set contains average daily flow measurements for 6939 days. In the table below the main results from several statistical tests are shown, numbers are flow in [m^3/s].

Avg.	79,9
Std.dev	47,2
Mode	40,8
Median	68,2
Min	25,4
Max	602,0

Table 3-2 Statistical results from partial data set analysis.

Most of the results from the partial data set are similar to the full data set. The data is still very sparsely distributed with a similar difference between minimum and maximum inflow. The monthly average flow through the year is similar; ranges from around 40 [m^3/s] up to around 140 [m^3/s]. The frequency flow distribution graph shows similar results as for the full data set. A flow duration graph along with graphs showing the main results from statistical analysis are found in Appendix F. One important difference to notice is in the graphs for the yearly averages, this is covered in next section.

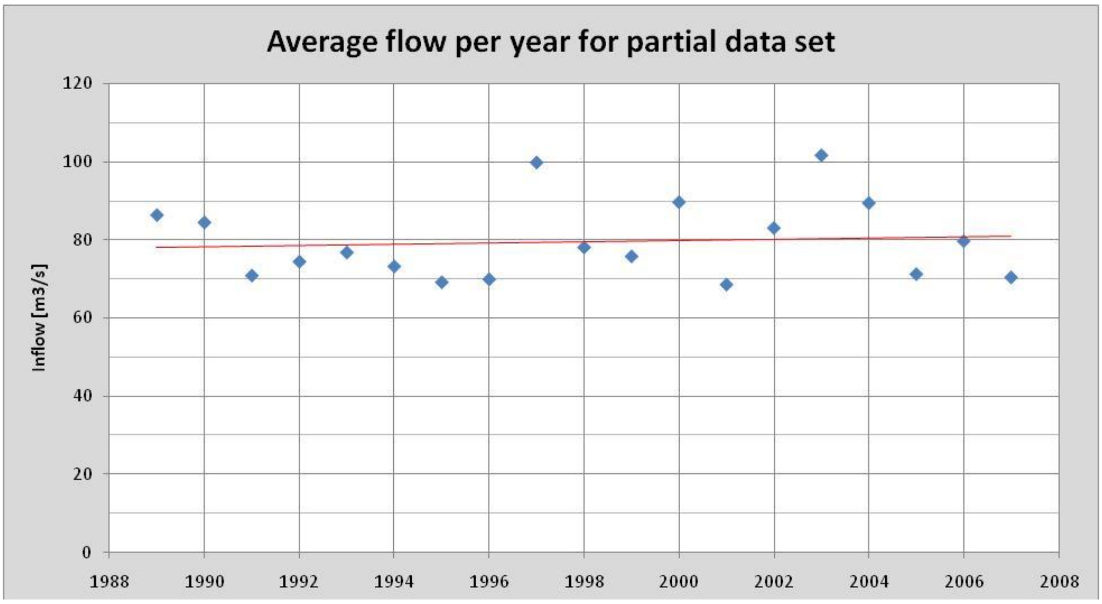
To summarize the inflow data analysis, the partial data set inflow can be described as around 80 [m^3/s] on an average yearly base. The inflow also has high seasonal fluctuations within the year, around 100 [m^3/s], these fluctuations are mainly caused by snowmelt as part of the reservoir tributaries is from glacial water. This partial data set will be used in the remainder of this project to evaluate the optimal installed capacity of the system.

3.3 Future predictions

With this amount of data it is possible to get a good idea of how this water system has behaved and how it is likely to behave now. But to try to predict how the water system will behave in the coming year is also interesting. Because if the installed capacity is only determined on the current and past data the power plant might be too small in 10-20 years and would only be able to utilize a smaller portion of the water flowing through. Power plants can have an economical life time of 40-60+ years (Úlfar Linnet, LV) with proper maintenance, which could mean a lot of lost energy with the installed capacity being underestimated.

Looking at the average flow per year graph in Appendix E for the full data set, it can be seen that the linear trend line indicates a substantial increase in flow. The increase is close to going from around 66 [m^3/s] in 1984 up to 86 [m3/s] in 2008, which would mean an increase in flow of around just over 0,80 [m3/s] in every year.

Looking at the same kind of graph but for the partial data set see graph 3-2 on next page, it can be seen that the trend line has a significantly less slope. Going from something like around 78 [m^3/s] up to around 81 [m3/s] in 2007, which means an increase of around 0,15 [m3/s] in a year.



Graph 3-2 Increase in average flow per year.

So care must also be taken in not overestimating the future increase in flow and designing the power plant installed capacity too big. Having the installed capacity too big will cause the power plant to run on low efficiency. Looking at the milder increase in the case of the partial data might still mean a substantial increase. With a lifetime of 50 years that would mean a total increase in flow of around 7,5 [m3/s].

But it is noted that for the sake of this project, that an increase in the range of the two above mentioned values can be expected in the coming years. That will be taken into account when determining the final design installed capacity.

4 WATERWAY LOSSES

Losses in the waterways are an important factor in a hydropower plant development such as what is proposed in this project, see Appendixes C and D. Losses in waterways can be divided into two subcategories; singular losses and frictional losses. Singular losses occur in places of the waterways like bends, expansions, contractions, inlets, trash-racks and more. Whereas frictional losses are caused by friction between the water and the waterway, like on the pipe walls inside a pressure pipe.

All above mentioned losses are in units of [m] and are subtracted from the gross head of the system. Therefore, in a fixed amount of water, the higher the losses are the less power the system is able to output.

As mentioned in chapter 2.3.2 both an average head loss of 7,5 [m] and a formula for head loss at the flow of 60 [m^3/s] is given. Since head losses depend on velocity [m/s] of water and velocity is depended on flow [m^3/s], head losses are therefore bound to change with flow. The model can take as input different values for power, see chapter 6.2.2, and within the same system that leads to different values for flow in the model. For this reason it was decided to calculate head losses for different flows and insert them in a table to use in the model. The remainder of this chapter covers these results, more detailed calculations are found in the model. When constants are in some range and the details to determine what value to select are not known, the approach in this project is to assume the middle value.

4.1 Supporting calculations

Supporting calculations are needed in order to complete the waterway loss calculations will be demonstrated in this chapter. As mentioned above a cross section diagram and a location map are found in Appendix C and D.

Intake elevation

A phenomenon called "free surface vortexes" can form on the surface of the reservoir above the intake to the headrace tunnel. This phenomenon is formed when the depth of the intake; compared to the flow into it, is too shallow. See formula below for minimum depth;

$$\frac{S}{D} > K * \frac{V}{(g * D)^{0,5}} \tag{4}$$

(Gordon, J.L.)

In the above formula:

- S: is the minimum intake depth in [m]
- D: is the headrace tunnel diameter in [m]
- K: is a constant in the range 1,7 – 2,2. The middle value is used 1,95.
- g: gravitational acceleration, see table 2-4.
- V: is the water velocity in [m/s]. With reservoir simulations in Excel flow is found to be 37,9 [m^3/s] (starting point for flow) and with area, velocity is found.

$$V\,[\mathrm{m/s}] = \frac{Q[m^3/s]}{A[m^2]} \tag{5}$$

There are two values for the different diameters in this system; the 6,5 [m] for head- and tailrace tunnel, and the 3,5 [m] for the pressure pipe. Using the above mentioned starting point value for flow 37,9 [m^3/s] and the two different areas (diameters) in the formula above for velocity. That gives two velocities called V_1 and V_2. V_1 is 1,142 [m/s] for the diameter (D_1) of 6,5 [m] and V_2 3,939 [m/s] for the diameter (D_2) of 3,5 [m]. The V_2 and D_2 values are used for head loss calculations in pressure pipe.

Next using the above mentioned formula to determine minimal depth the value for depth is found to be around 5 [m]. So with the minimum reservoir water elevation at 155 [m.asl.] the intake can be located at 150 [m.asl.] to avoid free surface vortexes. The location of the intake does not affect the head of the system since that is determined by the reservoir water elevation at any given moment. The intake location was needed for determining the length of the pressure pipe.

Coming back to the intake elevation when the results are known suggests that for an average flow through turbine of 46,2 [m^3/s] the minimum depth is ~5,5 [m]. That means the intake can be located at 149,5 [m.asl.] to avoid free surface vortexes. This also leads to a decrease in pressure pipe length and hence also decreases pressure pipe head loss.

Pressure pipe length

To find out the approximate length of the pressure pipe, one must know the elevation of the point where the headrace tunnel ends. The headrace tunnel intake is at 150 [m.asl.] and it is 6.600 [m] long and with a minimum slope of 0,2%, see table 2-4. To find slope in degrees the following formula is used:

$$angle = \tan^{-1}\left(\frac{0,2\%}{100}\right) \tag{6}$$

The angle is found to be 0,115°. Now using this angle to find the headrace tunnel change in height, basic trigonometry is used and the result is 13,25 [m]. By subtracting this change in height [m] and the turbine center elevation [m.asl.] from the intake elevation [m.asl.] the length of the pressure pipe is found to be around 85,75 [m].

4.2 Values for losses in waterways

This chapter is about how the losses in waterways were calculated, what formulae were used and what assumptions were made. The results of the supporting calculations demonstrated above in chapter 4.1 are used here below. The chapter is divided into two sub chapters, the first covering singular losses and the second one going over frictional losses.

4.2.1 Singular losses

Below is how the singular losses are worked out, they are shown in the same order as they appear starting from the reservoir. Calculations are done in an Excel model, formula nr. 7 used for head loss. Seen below;

$$H_L[m] = K[\,]*\frac{V^2[m/s]}{2*g[m/s^2]} \tag{7}$$

(Darcy, H.)

Trash-rack

A trash-rack is a metal frame with bars to prevent trash and other objects from flowing into the intake. H_L = 0,0193 [m].

Intake

This is where water flows into headrace tunnel inlet. H_L = 0,0027 [m].

90° bend

This is the bend from the headrace tunnel to the pressure pipe. H_L = 0,0166 [m].

Contraction

A contraction occurs when going from the diameter of the headrace tunnel and down to the diameter of the pressure pipe. H_L = 0,0498 [m].

90°bend

This is the bend going from the pressure pipe to the turbine inlet. H_L = 0,1975 [m].

Expansion

An expansion occurs when going from the turbine and to the diameter of the tailrace tunnel. H_L = 0,1422 [m].

Singular losses total sum

As seen above singular losses are only a small fraction of head in this project and the total sum of the losses is H_L = 0,4281 [m].

4.2.2 Frictional losses

This chapter covers the frictional losses, shown in the order as they appear, starting from the reservoir. The frictional losses are divided into three subparts.

Headrace tunnel

First the Reynolds (Re) number is calculated, and it is found to be Re = 4.740.102 [unit less]. (Re) is used to evaluate the flow, if Re > 3.000, the flow is turbulent (Kristín M. Hákonardóttir, Verkís). The formula nr.8 for (Re) can be seen on next page;

$$Re[] = \frac{V[m/s] * D[m]}{\nu[m^2/s]} \tag{8}$$

(Reynolds, O.)

Next friction factor (f) has to be determined, which is done using the So-called Swamme-Jain approximation, which is from the original Colebrook-White formula nr.9.

$$f[] = \frac{0,25}{\left[\log_{10}\left(\frac{ks[m]}{3,7 * D[m]} + \frac{5,75}{Re[]^{0,9}}\right)\right]^2} \tag{9}$$

(Swamee, P.K., Jain, A.K)

Since the flow is turbulent and the Reynolds number >> 10.000. The red part of the above formula can be removed and the formula used without it, i.e. the Swamme-Jain. Doing this will led to a friction factor of, f = 0,0514.

Now this friction factor can be used in the well known Darcy-Weisback formula, which is used to determine head losses in closed conduits. See formula below;

$$H_L[m] = f[] * \frac{L[m]}{D[m]} * \frac{V[m/s]^2}{2 * g[m/s^2]} \tag{10}$$

(Darcy, H., Weisbach, J.)

Head loss in the headrace tunnel is now found by using the above variables and applying the above formula. This leads to a head loss of H_L = 3,4656 [m].

Pressure pipe

The same formulae are used, as for the headrace tunnel above, but with variables for the pressure pipe. A head loss of H_L = 0,2245 [m] is found.

Tailrace tunnel

Again same formulae with appropriate variables give a head loss of H_L = 0,5514 [m].

Frictional losses total sum

This is clearly the important factor in the overall head loss of the system. The sum of the above frictional loss gave a total value of H_L = 4,2415 [m].

4.3 Total losses in waterways

Taking the results from chapters 4.2.1 and 4.2.2 the total head loss in the system waterways works out to be around 4,7 [m]. The above calculations in chapter 4 were done in Excel using a flow value of 37,9 [m^3/s]. The purpose of this was to allow the author to replace the above mentioned value for flow with several different values to create a table of head losses for different flows. Seen below;

Q	**H_L**	**Q**	**H_L**
[m3/s]	***[m]***	***[m3/s]***	***[m]***
5	0,100	*65*	13,707
10	0,343	*70*	15,894
15	0,748	*75*	18,242
20	1,315	*80*	20,753
25	2,044	*85*	23,426
30	2,935	*90*	26,261
35	3,988	*95*	29,257
40	5,203	*100*	32,416
45	6,580	*105*	35,737
50	8,118	*110*	39,219
55	9,819	*115*	42,864
60	11,682	*120*	46,670

Table 4-1 Head losses for different flow.

Now the formula in chapter 2.3.2, for head loss provided by AV for a flow of 60 [m^3/s] can be used for verification with the table above. The outcome of the formula by inserting 60 [m^3/s] into it is seen below and gives a value of H_L = 11,26 [m] compared to the value from the table for 60 [m^3/s] which is H_L = 11,68 [m]. Using either of these is considered a better approach in the project rather than using a constant average value of 7,5 [m]. See table 2-4;

$$11,26 = 0,00314 * 60^{1,9991}$$

(Steinar I. Halldórsson, AV)

5 ENERGY CONTRACT

This chapter discusses how a made up energy contract is used to be able to determine some optimal design installed capacity. To find the optimal size a value must be put on the energy and a buyer defined. For this reason an energy sales contract between the power plant owner and a power intensive industry consumer was defined. Then the installed capacity is designed to meet the needs of this consumer in the most economical way possible.

5.1 Infinite energy market

If there was an infinite market for energy without restrictions, it would mean that all energy generated in the power plant could be sold. A similar situation could occur if this proposed hydropower plant was studied as a part of a larger power grid, allowing power plants to cooperate with demand. Hence all energy generated could be sold to a grid.

This is not the case in this project, the proposed hydropower plant is studied as a standalone unit and the market is defined along with restrictions, see chapter 5.3. With an unstable inflow, like in the case of this project, it can mean an unstable energy generation, which in real life is difficult to find a consumer with the exact same needs.

5.2 Types of energy markets

The energy market can be divided into two main types; regular users and intensive users. Next two chapters go over the specifications of these two types and their differences.

5.2.1 Regular energy users

Regular users are; normal households, office buildings, small industry, commercial buildings and similar. What characterizes this type of users is that their energy consumption has daily fluctuations i.e. they use energy during the day and not much during the night. Weekends can be different from weekdays and the time of year also plays a big role in those fluctuations, hence on a yearly basis these users have a lower load factor. Each individual customer also buys energy in rather small amounts.

For a standalone hydropower plant this would mean running on high load during the day and then on very low load during the night. In such a case, reservoirs are a benefit to store the water flowing during the night to be used during the day.

5.2.2 Intensive energy users

Intensive users, on the other hand, buy large amounts of energy on a constant basis. Therefore, they tend to have a higher load factor. Examples of intensive users are big industries that run around the clock; like aluminum smelters and are consuming energy all the time. For a system with a rather stable inflow such a customer makes it less important to have a big reservoir.

On the other hand a system with an unstable inflow, like in this project, a big reservoir is an advantage. Preferably the reservoir should be big enough to handle seasonal fluctuations within a year, which unfortunately is not the case for this project’s proposed location as is.

5.3 The Project's energy contract

Now let's look at how this project's energy sales contract is set up. In this project the power plant will provide energy to a single power intensive customer. Based on economic value, this contract will define the optimal installed capacity. See the contract specification below, the power values are just to give an example:

- **100% Total contract** – 40 [MW].
- **90% Must always be delivered** – 36 [MW].
- **10% Are to be delivered on average over 80% of the time** – 4 [MW].

If the power plant is not able to generate the needed energy the owner of the power plant must buy the energy from a grid elsewhere. The owner must buy the energy for a higher price 4,7 [kr/KWh] and deliver it to the customer for the same normal price 2,5 [kr/KWh] as before, see prices in chapter 2.3.2. So there is a net loss of delivering this energy to the customer, but the contract has to be fulfilled. This makes it important to know just how much you can get from the system without going to high. Because the higher the contract can be the more the income can be.

6 MODEL

To solve this project an Excel model of the known system is constructed. The basic idea is to simulate the behavior of a reservoir and a power plant using an inflow series. In short, the model takes as input variables from the project description and other related variables. The inflow series is inserted into the model. Then the model runs by adjusting few control variables and the user monitors output variables and graphs for outcome.

The remainder of this chapter covers the model in more details and fully explains how it works step by step. Screenshots to support the following model explanations are found in Appendix G. It can be seen on the Excel number sequence from the screenshots that they are from the same sheet.

6.1 Input and check variables

Below is an example screenshot from the Excel model showing the basic input variables. During simulation runs these variables are not changed by the model operator.

M	N	O	P	Q
Basic input variables				
100	[Gl]	*Maximum reservoir volume*		
0	[Gl]	*Minimum reservoir volume*		
95	[Gl]	*Initial reservoir volume*		
172	[m.a.s.l]	*Reservoir maximum height*		
155	[m.a.s.l]	*Reservoir minimum height*		
51	[m.a.s.l]	*Turbine center height*		
7,5	[m]	*Average head losses, start value*		
1000	[kg/m^3]	*ρ - Density of water*		
9,82	[m/s^2]	*g - Gravitational acceleration*		
0,98		*Generator efficiency*		
0,99		*Transformer efficiency*		
0,93		*Turbine efficiency*		
0,90		*η - Efficiency combined*		
4,274	[Gl/day]	*Minimum flow for primary power*		
0,475	[Gl/day]	*Minimum flow for secondary power*		
0,000	[Gl/day]	*Minimum flow for spillway power*		

Figure 6.1 Basic input variables.

Changes in variables during normal simulation only affects four of the above variables, the others are constant. One of them is the combined efficiency that is depended on three sub efficiencies and one of them, the turbine efficiency is related to load as can be seen in Appendix A. The other three are the flow variables on the bottom of the figure. The primary and secondary are depended on the requested power and use reservoir minimum elevation to give the minimum amount of water to generate the requested power. The spillway works in a similar way but uses reservoir maximum elevation. All three also depend on varying turbine efficiency.

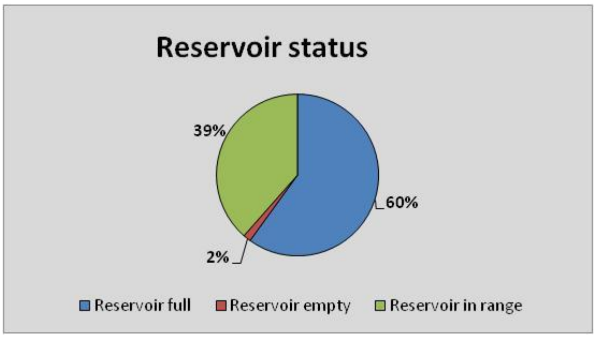
Below is a screenshot from the Excel model showing a set of check variables. These variables are used to support other features in the model and for the operator to monitor the behavior of the reservoir.

S	T	U	V	W	X	Y
	Check variables to monitor					
	155	[m.a.s.l]	*Actual lowest level*			
	6939	[Days]	*Total flow serie (partial set)*			
60%	4161	[Days]	*Reservoir full*			
2%	106	**[Days]**	***Reservoir empty***			
39%	2672	[Days]	*Reservoir in range*			
	2778	[Days]	*No spillway water*			

Figure 6.2 Check variables.

On the figure above it can be seen that the reservoir goes at some point in time, in that simulation run, down to its absolute minimum elevation of 155 [m.asl.]. This can also mean that the reservoir is empty for this time point as can be on the variable showing 106 days. The total number of days in the flow series used in the simulation is shown as 6939.

From this set of variables a graph, see below, is produced showing the behavior of the reservoir elevation in this simulation run.



Graph 6-1 Reservoir status.

As noted on the simulation example graph above the reservoir is full for about 60% of the time, which can lead to water flowing over the spillway which again means lost energy. This fraction of spillway water could indicate high fluctuations in inflow and/or the reservoir being too small.

6.2 Simulation and control variables

This chapter is divided up into two parts, the first going over how the model simulation works and the second one covering the main control variables used during simulation. The simulation is done in discrete time steps of one day, same time step as the inflow data.

6.2.1 Model structure

A screenshot of the model structure is found in Appendix G, showing rows 50 – 73 from Excel. Alphabetical characters in the following description refer to the column names in the Excel model, i.e. (A) means "column A" in the Excel model.

River data

(A) Is the number sequence of the days in the inflow series.
(B) Is the partial inflow data [m^3/s] given with the project description.
(C) Is the same inflow converted to another unit, [Gl/day].

Reservoir volume

(D) The volume of the reservoir in [Gl] before day starts. The first cell is the "Initial volume" variable from the basic input variables, see figure 6.1. The second cell, for day #2, is the value from column (Q) the volume after the day ends, from the previous day, day #1 and so on.

Reservoir

(E) Shows the elevation of the reservoir. A function in Excel is used to map the appropriate elevation depending on the volume in (D). See chapter 2.3.2 and Appendix B.

Leakage

(F) Is the leakage under the dam in [m^3/s]. The leakage is found using a function in Excel to map the elevation (E) with the appropriate leakage from a table, See table 2.3 in chapter 2.3.2.
(G) Converts the leakage to another unit [Gl/day].

Head data

(H) Shows the head lost in waterways. The first cell, day #1, uses the average head loss value given from the project data from AV, since the flow is not known beforehand. The following cells use the previous flow through the turbine with an Excel function to find the proper value from a head loss table, chapter 4.3.
(I) This is the head that is used in the power calculations. It is found by subtracting the head loss in (H) and the "Turbine center height" variable from the basic input variables, see figure 6.1, form the reservoir elevation in (E).

Flow through turbine

(J) Gives the primary flow in [m^3/s] needed to generate the power given as "primary power", see chapter 6.2.2, using the power equation seen below for flow. This flow is depended on varying head from (I), varying efficiency and more from basic input variables.

$$Q[m^3/s] = \frac{P[W]}{H[m] * g[m/s^2] * \eta * \rho[\mathrm{kg/m^3}]} \tag{11}$$

(Bernoulli, D.)

(K) The same flow as in (J) converted to [Gl/day].

(L) Shows the secondary flow in [m^3/s] needed to generate the power given as "secondary power", see chapter 6.2.2, with the same terms as the flow in (J). Except for the fact that there is a control variable on this value, "Generation min. volume", chapter 6.2.2. This flow is only calculated if the current volume of the reservoir is higher than the volume stated in the control variable, else the flow is set as zero.

(M) Flow from (L) converted to [Gl/day].

(N) Value of flow for spillway power, from (O) converted to [m^3/s].

(O) This shows flow in [Gl/day] that could have gone over the spillway but was diverted through the turbines instead. This cell uses the "Minimum flow for spillway power" variable seen in figure 6.1. The formula compares the expected spillway flow from column (T) to the above mentioned minimum, if the expected flow is equal or bigger the flow in the cell is set as the minimum flow else it is set to zero

Reservoir volume

(P) Here is the change in volume for one day shown in [Gl/day]. This value is found by subtracting the leakage in (G), flow for primary and secondary power in both (K) and (M) from the inflow in (C). This change can be both a positive and a negative value, hence respectively the reservoir volume will increase or decrease.

(Q) This cell contains the volume in [Gl] of the reservoir after the day ends. A formula with a double check is used to get the correct volume. The first check compares the volume before day starts plus the change in volume to the maximum reservoir volume, if it is equal or bigger the volume after is set as the maximum. Then there is a check to see if the new volume is going to be less than the reservoir minimum, if so it is set as the minimum. Otherwise the volume after becomes the volume before plus the change in volume, as previously noted in (P) the change in volume can be positive or negative.

Reservoir

(R) Cell indicates weather the reservoir is empty or not. "1" means reservoir is empty and "0" means the reservoir is not empty.

(S) This cell indicates if the reservoir is full or not. "1" means the reservoir is full and "0" means the reservoir is not full.

Spillway

(T) Is the expected flow in [Gl/day] over the spillway, if nothing is diverted through the turbines. There is a check in the formula such that if the reservoir is full (S) then the excepted flow over spillway is the volume before (D) plus the change in volume (P) subtracted from “reservoir maximum volume” variable, from basic input variables seen in figure 6.1. If the reservoir is not full then the expected flow is set to zero.

(U) This is the actual flow in [Gl/day] over the spillway, when some water is diverted through the turbines. If the expected flow from (T) is bigger than or equal to the variable minimum flow for spillway power, from basic input variables seen in figure 6.1 then the actual flow (U) becomes the expected flow from (T) minus the “minimum flow for spillway power” variable. If not the actual flow is set to zero.

(V) Convert the flow in (U) to [m^3/s].

Power generation

(W) This cell holds the value for total power generated in [MW] from all three power types; primary P_{100}, secondary P_{80} and spillway P_{50}.

(X) Here is the primary power in [MW]. The control on this cell makes sure that the inflow (C) plus reservoir volume before (D) is bigger or equal to the variable “minimum flow for primary power”, see figure 6.1. If not then no primary power is generated and cell set to zero. Same equation for power as used above.

(Y) This is “1” if the power in (X) is bigger or equal to what is stated in the “primary power” variable in chapter 6.2.2 and “0” if not.

(Z) Secondary power in [MW] is displayed in this cell, the same power formula as above is used with flow referring to cell (L). So when there is flow in (L) secondary power is generated, else this is zero.

(AA) When generated, spillway power in [MW] is shown here. When there is flow in (O) power is generated, when not then no power is generated.

Energy generation

(AB) This cell shows primary energy E_{100} in [GWh] generated in one day, based on the power generated in (X).

(AC) This cell shows secondary energy E_{80} in [GWh] generated in one day, based on the power generated in (Z).

(AD) This cell shows spillway energy E_{50} in [GWh] generated in one day, based on the power generated in (AA).

6.2.2 Main control variables

This chapter discusses the main control variables, some of which the operator adjusts when running the simulations. The cells containing variables in the model that are mainly adjusted by the operator are enclosed with a thick black border. Parts of the model are shown in this section as small screenshots, just containing these main control variables.

	A	B	C	D	E
1		Main variables			
2	47	47,0	[MW]	Power Contract	
3		2,5	[kr/KWh]	Price of energy sold	
4		4,7	[kr/KWh]	Price of energy bought	
5		80%	[%]	Turbine design load	
6		58,8	[MW]	Total installed capacity	
7		80%	[%]	Actual turbine load	

Figure 6.3 Contract value & turbine design load.

On the figure here above there are two important control variables. First, the “Power Contract” in green, this is the variable that controls how big in [MW] the contract with the hypothetical power intensive customer can be. The second one is the “Turbine design load” by adjusting that the operator controls the turbine efficiency and hence the overall efficiency the power plant runs at. Also important variables are the two values for energy prices, one for energy sold and the other for energy bought (Úlfar Linnet, LV). The bottom two variables are discussed in chapter 6.3.

27		Secondary Power (for one year)		
28	72	72	[Gl]	Generation min. volume

Figure 6.4 Volume limit for secondary power.

The control variable “Generation min. volume” has the role of controlling if secondary power is generated or not. For example like on the figure above, secondary power is not generated unless the reservoir volume exceeds 72 [Gl].

43		Spillway Power (for one year)		
44		11,8	[MW]	Max. possible power
45		0,0	[MW]	Actual used power

Figure 6.5 Value for spillway power.

The figure above shows the control variable “Actual used power”, that is the spillway power in [MW] requested from the model operator. When enough water is flowing over the spillway this power can be generated, otherwise spillway generation is zero. When power is generated from spillway water the actual load on the turbine goes higher than the design load, thus affecting the efficiency of the system.

6.3 Output variables and graphs

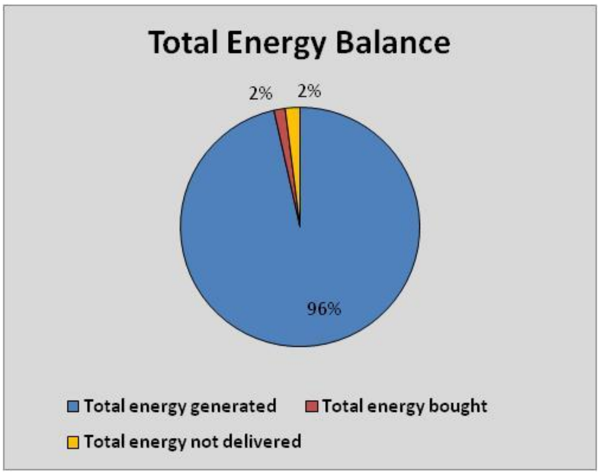
This chapter contains screenshots and descriptions on how the model operator can monitor output from the simulations. This output is both in the form of raw numbers just as well as graphs. Below is the first figure showing the main summary of economic and energy outputs for one average year.

Main variables		
47,0	[MW]	*Power Contract*
2,5	[kr/KWh]	*Price of energy sold*
4,7	[kr/KWh]	*Price of energy bought*
80%	[%]	*Turbine design load*
58,8	[MW]	***Total installed capacity***
80%	[%]	*Actual turbine load*
397,3	[GWh]	***Total energy generated***
6,2	[GWh]	*Total energy bought*
411,7	[GWh]	*Total energy contract*
8,2	[GWh]	*Total energy not delivered*
403,5	[GWh]	*Total energy delivered*
979,6	[Mkr]	*Income without spillway*
979,6	**[Mkr]**	***TOTAL REVENUES***

Figure 6.6 Summary of main output, per year.

On the figure above energy in [GWh] for one year is broken down into all possible subcategories. The important variable “Total installed capacity” is depended on the cells B2 and B5. In the end everything revolves around the variable “Total Revenues”, the higher this value gets the better. So by adjusting control variables and running simulations optimal design is found when this “Total Revenues” variable is at its highest value.

On the graph below is an example of how some of these main summary results from the numerical values above are displayed in the model, more examples in Appendix H.



Graph 6-2 Total energy balance.

On the screenshot below is an example of how the model displays all three different types of power possible generated in the simulation; i.e. primary, secondary and spillway.

16		***Primary Power (for one year)***		
17		90%	[%]	*Contract - always delivered*
18		42,3	[MW]	*Contract - always delivered*
19	**100%**	370,548	[GWh]	*Contract - always delivered*
20		98,47%	[%]	*Ratio generated*
21	*98%*	364,888	[GWh]	*Energy generated*
22	*2%*	5,660	[GWh]	*Energy bought*
23		926,4	[Mkr]	*For "all" energy sold*
24	*912,2*	26,6	[Mkr]	*For energy bought*
25		**899,8**	**[Mkr]**	***Income primary***
26				
27		***Secondary Power (for one year)***		
28	*72*	**72**	[Gl]	*Generation min. volume*
29		10%	[%]	*Contract*
30		4,7	[MW]	*Contract*
31	**100%**	41,172	[GWh]	*Contract - full capability*
32		80%	[%]	*Contract - min. delivered*
33		32,938	[GWh]	*Contract - min. delivered*
34		20%	[%]	*Ratio can be skipped*
35		8,234	[GWh]	*Energy can be skipped*
36	*79%*	32,396	[GWh]	*Energy generated*
37	*20%*	8,234	[GWh]	*Energy not delivered*
38	*1%*	0,541	[GWH]	*Energy bought*
39		82,3	[Mkr]	*For "all" energy sold*
40		2,5	[Mkr]	*For energy bought*
41		**79,8**	**[Mkr]**	***Income secondary***
42				
43		***Spillway Power (for one year)***		
44		11,8	[MW]	*Max. possible power*
45		0,0	[MW]	*Actual used power*
46		0%	[%]	*Ratio generated*
47		0,000	[GWh]	*Energy generated*
48		0,0	[Mkr]	*For energy sold*
49		**0,0**	**[Mkr]**	***Income spillway***

Figure 6.7 Summary showing all power types.

In cells B17 and B29 the division of how much is considered primary power and how much is considered secondary power is shown, according to contract. Also the corresponding values defined by the contract in [MW] and in [GWh] per year in the cells below.

This also shows how much energy is actually generated. How much energy is bought, only in the case of primary and secondary. In the case of secondary, how much energy can be skipped, i.e. not delivered at all to the customer. The variable defining the amount of secondary energy that does not have to be delivered, i.e. can be skipped is in cell B34.

The spillway power variable “Max. possible power” is calculated from the variables in cells B2 and B6 from figure 6.6 above. This variable defines how much power can be requested for generation when possible. The three income values at the bottom of each colored area make up the “Total Revenues” value in figure 6.6.

7 RESULTS

This chapter covers how the results of this project are obtained using the model to run simulations. The main result is the recommended installed capacity in [MW] for this proposed project. To obtain this a few main control variables, see chapter 6, have to be adjusted and set. The final result is determined with economical optimization, .i.e. the result that gives the highest total revenues. Next chapter covers how the model variables were adjusted and then following a chapter with final outcome.

7.1 Variable adjustment

Generation min. volume

First the variable “Generation min. volume”, B28 in figure 6.7, has to be determined. Several iterative simulations were performed to investigate the behavior of this variable. The conclusion was that this variable “Generation min. volume” has an optimum installed capacity, i.e. highest income, irrespective of the volume value set in the variable itself.

An example of one such iterative analysis can be seen in Appendix I, as seen the optimum installed capacity is around 45 [MW] for all possible volumes tested, note this is just an example. That is to say that the optimum installed capacity is the same for different values of this reservoir control variable, but what does changes is the income [Mkr]. Thus the value of the “Generation min. volume” variable that yields the highest income is optimal.

Doing this for the partial flow data set used in this project indicates that the variable “Generation min. volume” should be set to 72 [Gl], which is optimal. This means that secondary power production is only attempted when the reservoir volume exceeds 72 [Gl].

Design load

When determining the design load of the power plant there are several things to consider. First, having the design load variable, B5 in figure 6.6, adjusted such that the power plant runs on maximum turbine efficiency giving highest power output, which means 80% load see figure 2.4. It also means that the lower the load is the higher the installed capacity needs to be, hence higher capital cost. Meaning a tradeoff between power output and capital cost.

For this project the decision is to have the design load as 80%, leading to maximum efficiency, see Appendix K. The following factors are in support of this decision;

- On a normal day plant is running with highest power output per used water.
- The possibility of increasing or decreasing load but still being close to maximum efficiency (not possible when running at 100%).
- Having spinning reserves and possibility of using spillway water when available.
- According to data (Appendix E & F), average flow [m^3/s] is increasing.
- The possibility to meet a sudden or a permanent increase in demand from customer.

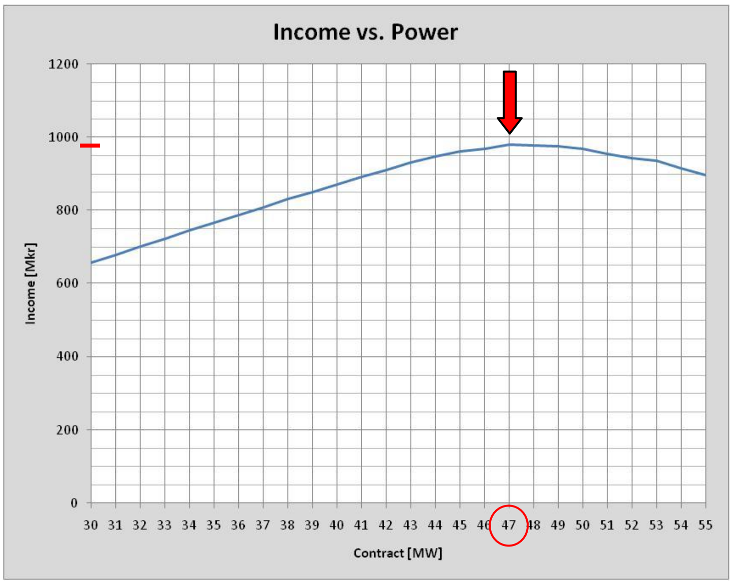
Power contract

Having the above two variables fixed and adjusting the variable “Power contract” will lead to different results for the output variable “Total Revenues”, both seen in figure 6.6.

Running several iterative simulations and plotting the outcome will lead to conclusion for optimal contract power, a value in [MW].

7.2 Final outcome

Running simulations and plotting results has led to the graph seen below. The red arrow is pointing to the optimal point, with revenues of 979,6 [Mkr] and power contract of 47 [MW], see Appendix J for more details from model.

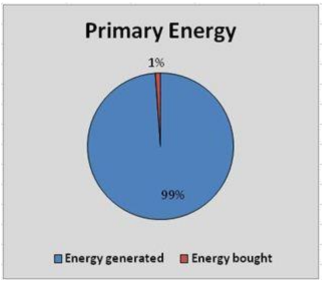


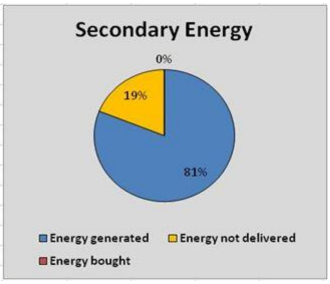
Graph 7-1 Optimal point.

The behavior of the graph above can be explained by dividing the graph up in to three subsections; left side, top or optimal point and right side. See more details below.

Left side

The left side of the optimal point or from 30 [MW] and up has rising revenues because the system itself is able to generate most or all of the power needed. The system is also mostly able to avoid buying secondary power by utilizing the curtailment option in the contract, see chapter 5.3. The more power generated and sold the higher the revenues gets on the left side, but as soon as buying power becomes necessary to fulfill the contract the top of the graph is reached, see examples below of point just before top.





Graph 7-2 Left side, just before optimal.

Optimal point

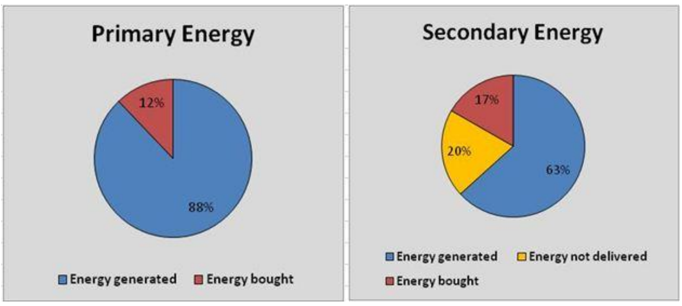
Around the top is the economical optimal point for this project. This point has the power contract as 47,0 [MW] which on 80% load leads to installed capacity of 58,8 [MW]. This power contract equals the energy of 411,7 [GWh] on a yearly basis 24/7, with a demand of energy delivery of 403,5 [GWh] per year. The system is allowed not to deliver 8,2 [GWh] per year. Out of those 403,5 [GWh] that are delivered 397,3 [GWh] were generated in the proposed power plant, the remains of 6,2 [GWh] were bought. As seen on the prices below there is a net loss of buying energy to sell it back. All this leads to a total revenues of 979,6 [Mkr] per year, this is without possible spillway power (see chapter 7.3).

Main variables		
47,0	[MW]	*Power Contract*
2,5	[kr/KWh]	*Price of energy sold*
4,7	[kr/KWh]	*Price of energy bought*
80%	[%]	*Turbine design load*
58,8	[MW]	*Total installed capacity*
80%	[%]	*Actual turbine load*
397,3	[GWh]	*Total energy generated*
6,2	[GWh]	*Total energy bought*
411,7	[GWh]	*Total energy contract*
8,2	[GWh]	*Total energy not delivered*
403,5	[GWh]	*Total energy delivered*
979,6	[Mkr]	*Income without spillway*
979,6	**[Mkr]**	***TOTAL REVENUES***

Figure 7.1 Main results

Right side

The right side of the optimal point, see graph 7-1, is where the loss from having to buy energy is lowering the total revenues. The contract must be fulfilled and all energy that cannot be generated or not delivered is bought with a net loss of 2,2 [kr/KWh]. So the higher the contract is the lower the total revenues will be. Below is an example where the power contract has been set to 55 [MW], right most side of graph 7-1. In such a case around 12% of primary energy and 17% of secondary energy needs to be bought.



Graph 7-3 Right side, far from optimal.

This confirms the previously mentioned optimal point and the recommended installed capacity of 58,8 [MW] for this specific project parameters and inflow data.

Principal dimensions

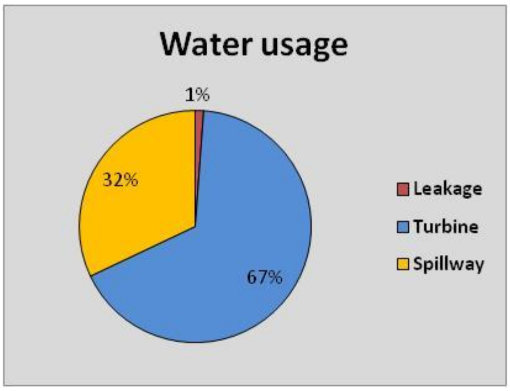
Here below is a table that summarizes the principal dimensions from this project. These values are from primary and secondary production only and without spillway power.

Average inflow to power plant	[m^3/s]	46,2
Average used head	[m]	112,4
Reservoir full supply level	[m.asl]	172
Reservoir lowest level	[m.asl]	155
Intake reservoir	[Gl]	100
Installed capacity	[MW]	58,8
Generating capacity	[GWh/yr]	397,3

Table 7-1 Principal dimensions.

7.3 Including spillway power

More economical value can be gained by utilizing the potential spillway power. The water usage when there is no spillway power production can be seen from the final water usage graph in Appendix J. That indicates that 58% of the water is flowing through the turbine, 1% is leakage and 41% is flowing over the spillway. By utilizing the spillway water as much as possible when water is flowing over the spillway, the water usage can be improved. As seen on the graph below;



Graph 7-4 Improve water usage with spillway power.

Additionally from raising the amount of water flowing through the turbine up to 67%, the power plant could also increase its revenues. The increase could be as much as somewhere over 100 [Mkr] per year, which is close to 10% of the previous revenues, see Figure 7.1.

8 CONCLUSIONS

The aim of the project was to determine the appropriate size of a hydropower system for a specific location. In more detail the aim was to determine the recommended installed capacity for the proposed hydropower plant.

As the way this solution was reached by striving for maximum output, it is reasonable to assume that the solution is in the higher range, close to a maximum. The exact result is that recommended installed capacity should be 58,8 [MW]. According to the project's outcome, around 397,3 [GWh] of energy could be generated in one full year.

Comparing the above mentioned energy outcome to values for the same project location done by the National Energy Authority (NEA) in Iceland (www.os.is). In the NEA project specifications maximum reservoir elevation is 175 [m.asl] and installed capacity 40 [MW]. Comparing these similar projects using the same load factor in both cases indicates that the two results are within ~5% difference from one another. This confirms that the result of this thesis is close to what others have found for the same project location.

For further investigation in this location it is recommended to look into the possibility of increasing the reservoir volume to improve water utilization. Possible by having another separated reservoir more upstream in the Hólmsá River, in the Hólmsárlón area. It would also be interesting to simulate this as a two or more turbine system and figure out how water utilization would then behave.

REFERENCES & BIBLIOGRAPHY

Árnason, Hörður. (2010). *Haustfundur Landsvirkjunar 2010.* Available: http://www.landsvirkjun.is/media/2010/Haustfundur_LV_Hordur_Arnarson.pdf. Last accessed 15 January 2011.

Elíasson, Jónas (1997). *Virkjanafræði*. 5th ed. Iceland: University of Iceland. p5-207.

Halldórsson, Steinar I. steinar@almenna.is. Project parameters. 13 December 2010.

IMO. (2010). *Hydrology*. Available: http://en.vedur.is/. Last accessed 15 January 2011.

Jóhannesson, Helgi. helgij@lvp.is. Hólmsárvirkjun. 20 July 2010.

Linnet, Úlfar. ulfarlinnet@lvp.is. Info. 11 November 2010.

Linnet, Úlfar. ulfarlinnet@lvp.is. Holmsa data. 28 October 2010.

Linnet, Úlfar. ulfarlinnet@lvp.is. Final Thesis. 27 October 2010.

Mannvit (2010). *Litlar vatnsaflsvirkjanir*. Iceland: Iðnaðar- og viðskiptaráðuneytið. p1-105.

Orkustofnun. (2003). *Vatnsaflskostir, 2. áfangi.* Available: http://www.rammaaaetlun.is/media/nidurstada-faghopa/Vatnsafl-tafla-8mars.pdf. Last accessed 15 January 2011.

Orkustofnun. (2002). *Vatnsaflskostir, 1. áfangi.* Available: http://www.landvernd.is/natturuafl/skyrsla/skyrsla/vidauki_a1.pdf. Last accessed 15 January 2011.

Rarik & Landsvirkjun. (2009). *Hólmsárvirkjun.* Available: http://www.red.is/projects-in-iceland/hlmsarvirkjun-en. Last accessed 15 January 2011.

Steingrímsson, Benedikt et al.. (2007). *Master plan.* Available: http://www.rammaaaetlun.is/media/virkjanakostir/2-afangi/Enska-timarit-fra-SIJ-25feb.pdf. Last accessed 15 January 2011.

Material directly used from following RES professors:

Elías Elíasson, Landsvirkjun power company.

Kristín M. Hákonardóttir, Verkís engineering firm.

Pálmi R. Pálmason, Verkís engineering firm.

Þorbergur S. Leifsson, Verkís engineering firm.

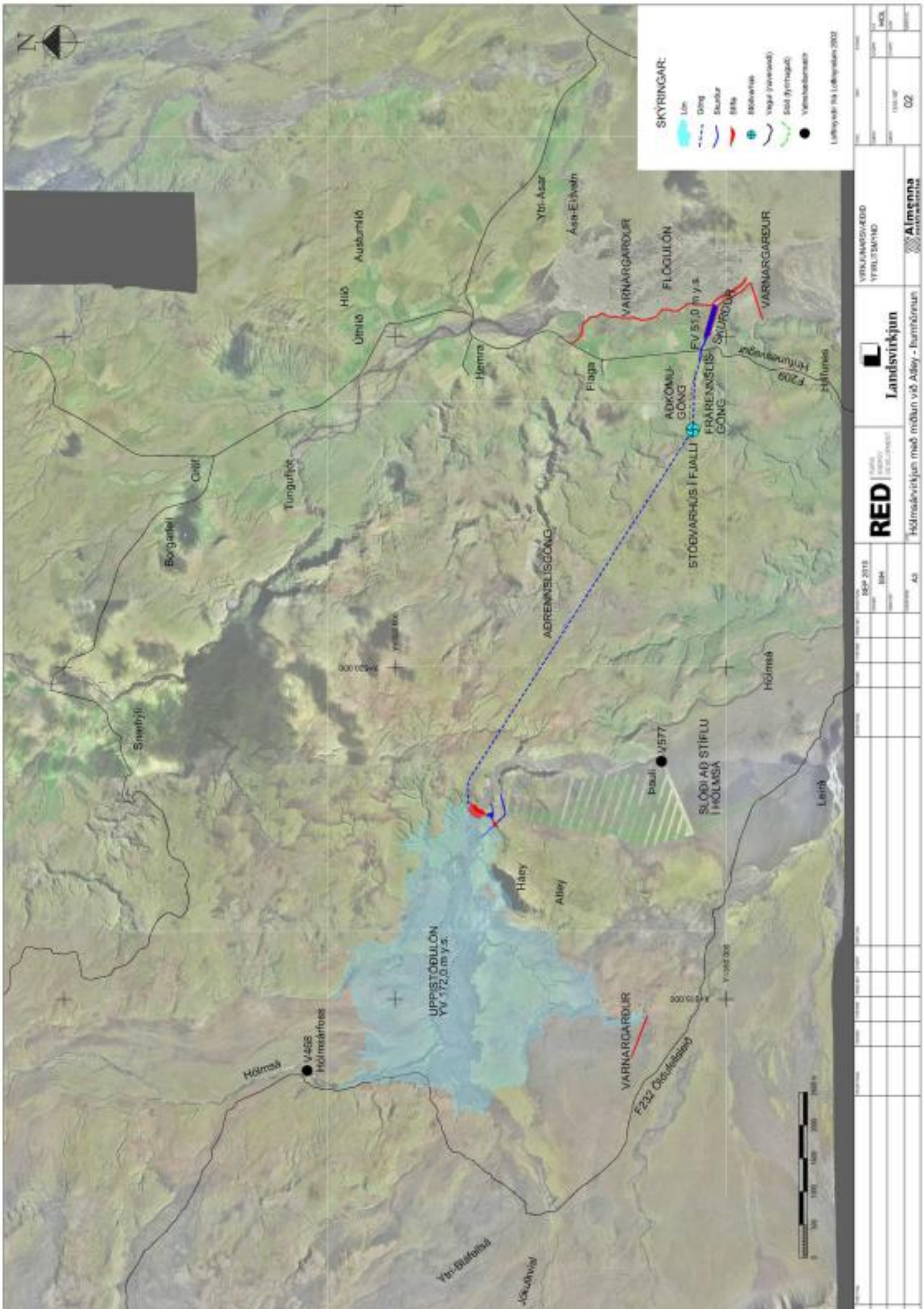
APPENDIX A – TURBINE EFFICIENCY

Load [%]	*Efficiency* [%]
20%	70,0%
25%	76,0%
30%	79,0%
35%	82,0%
40%	84,0%
45%	86,0%
50%	88,0%
55%	89,0%
60%	90,0%
65%	91,0%
70%	92,0%
75%	92,5%
80%	**93,0%**
85%	92,3%
90%	91,5%
95%	90,8%
100%	90,0%

APPENDIX B – RESERVOIR ELEVATION AND VOLUME

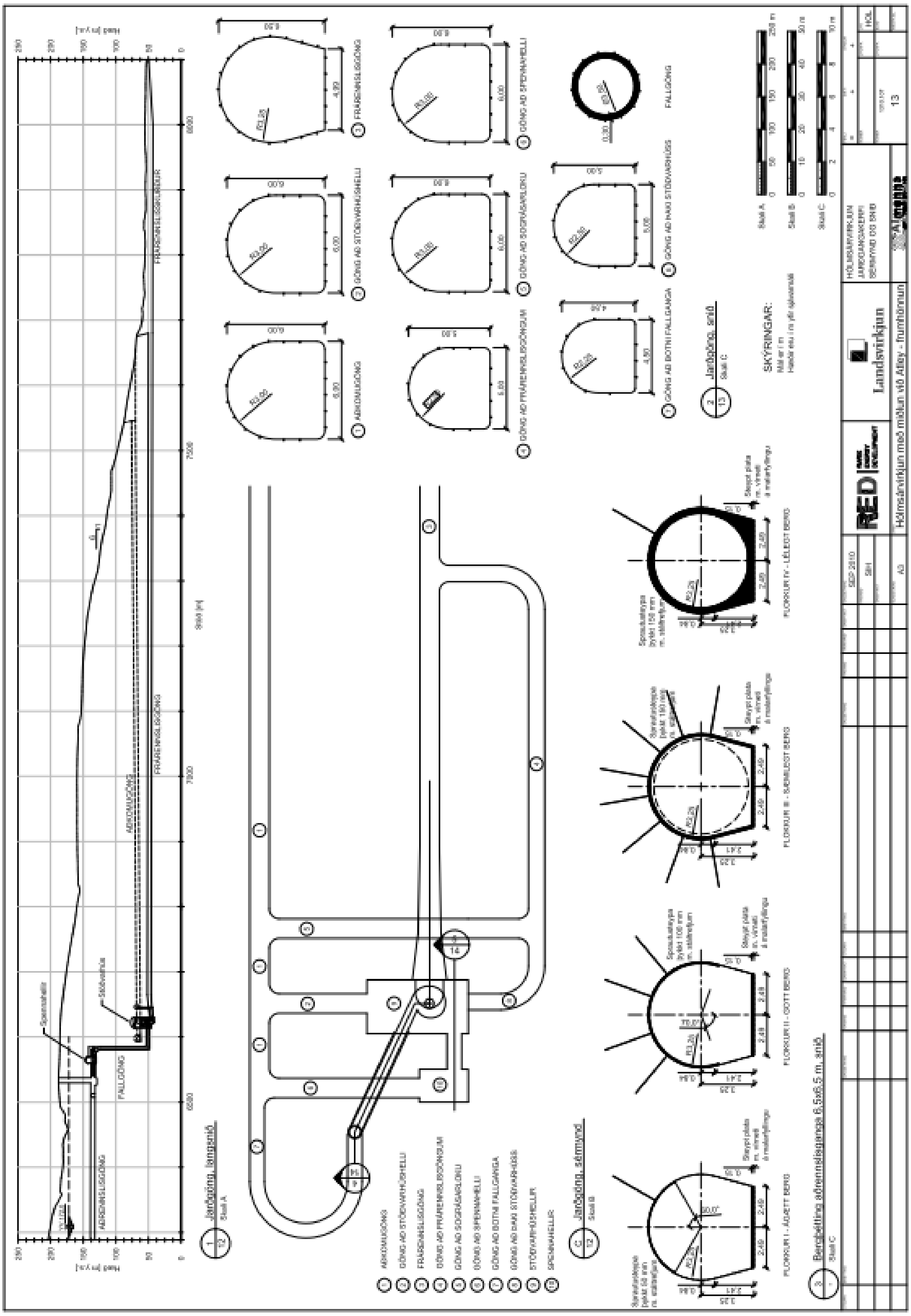
Gl	m.asl
0,000	155
2,805	156
6,008	157
9,608	158
13,606	159
18,002	160
22,795	161
27,986	162
33,574	163
39,560	164
45,944	165
52,725	166
59,904	167
67,481	168
75,456	169
83,828	170
92,597	171
100,000	172

APPENDIX C – MAP OF LOCATION



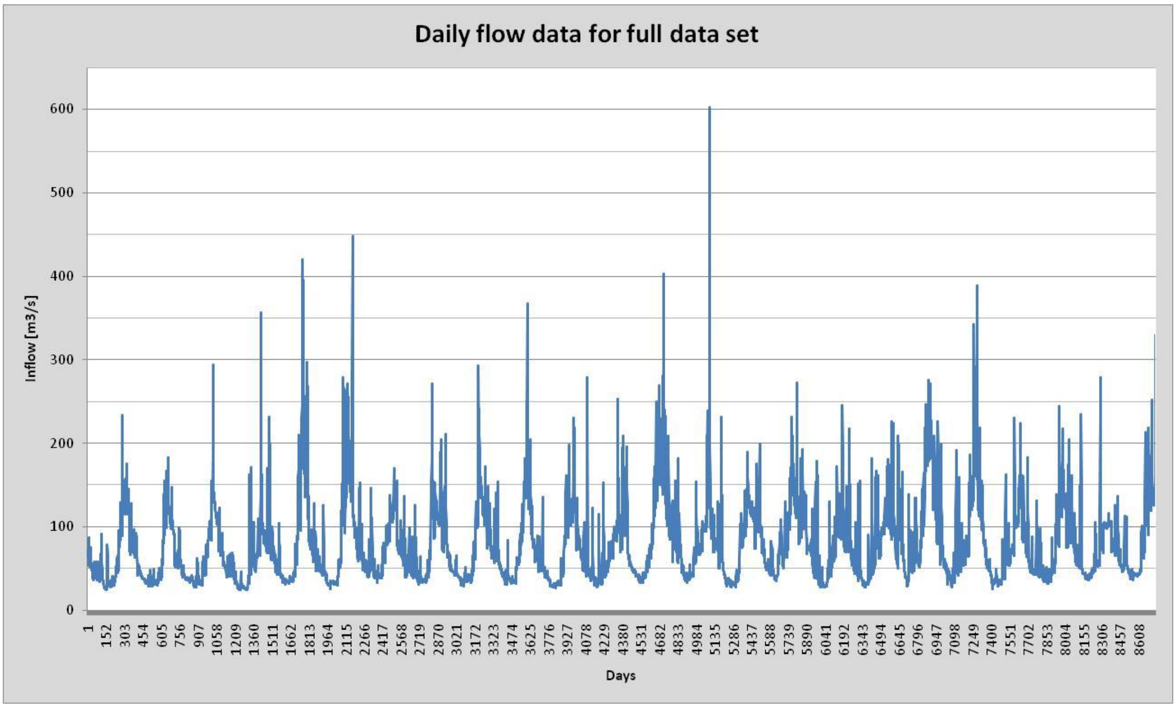
(Steinar I. Halldórsson, AV)

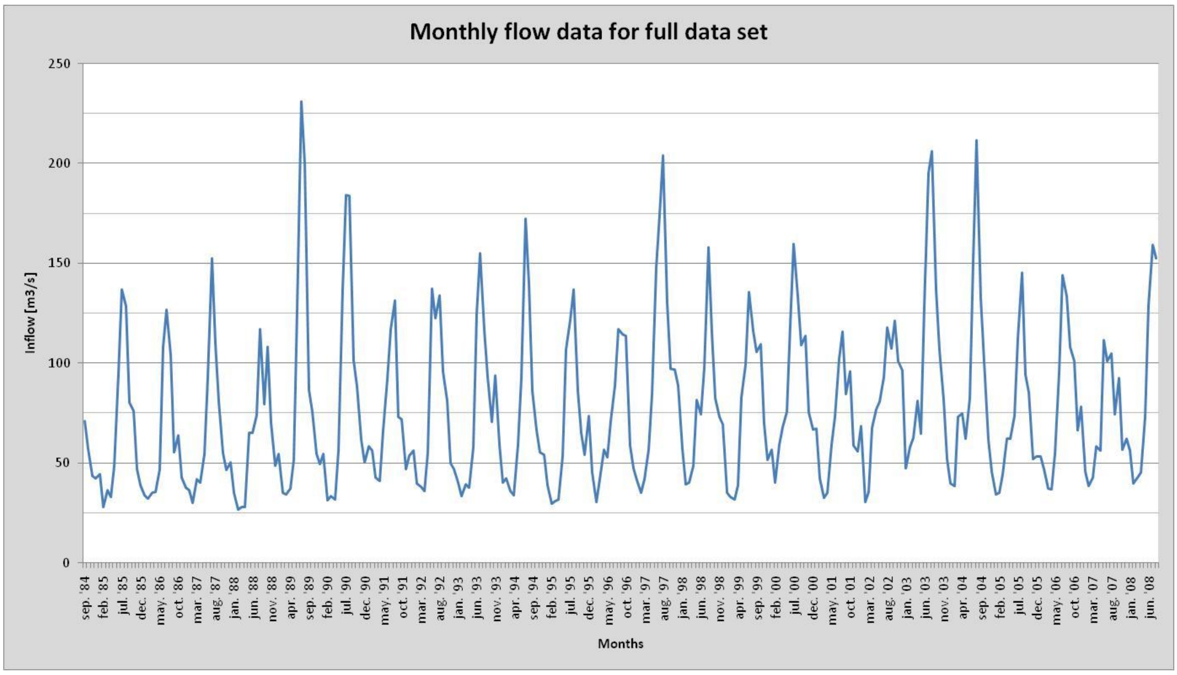
APPENDIX D – DRAWINGS OF SYSTEM

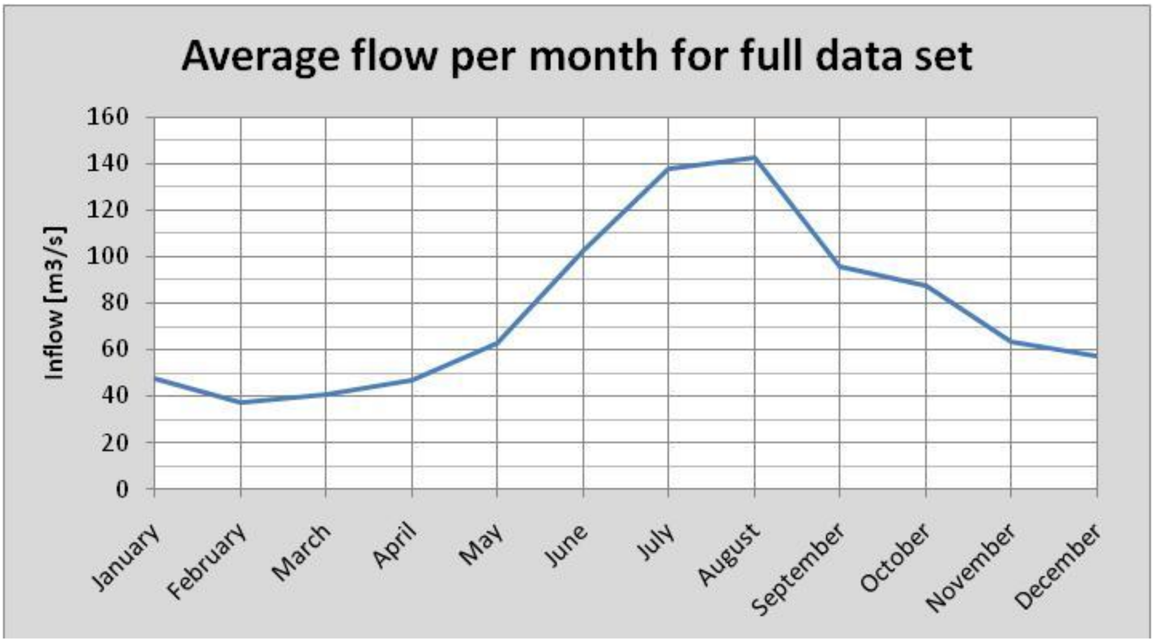


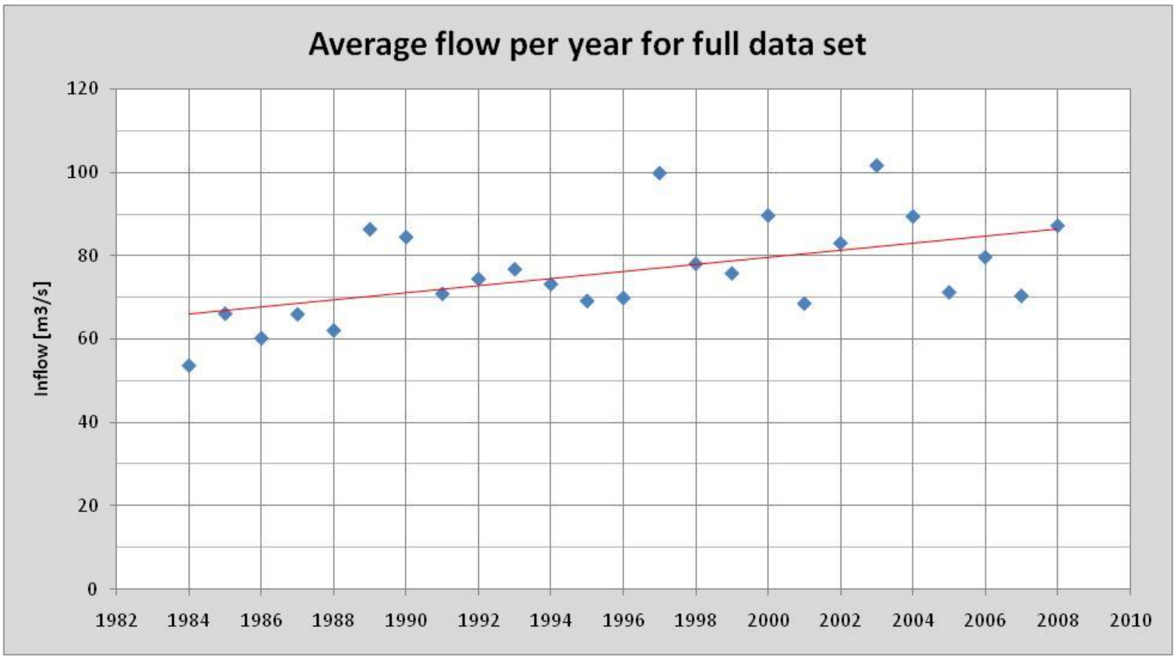
(Steinar I. Halldórsson, AV)

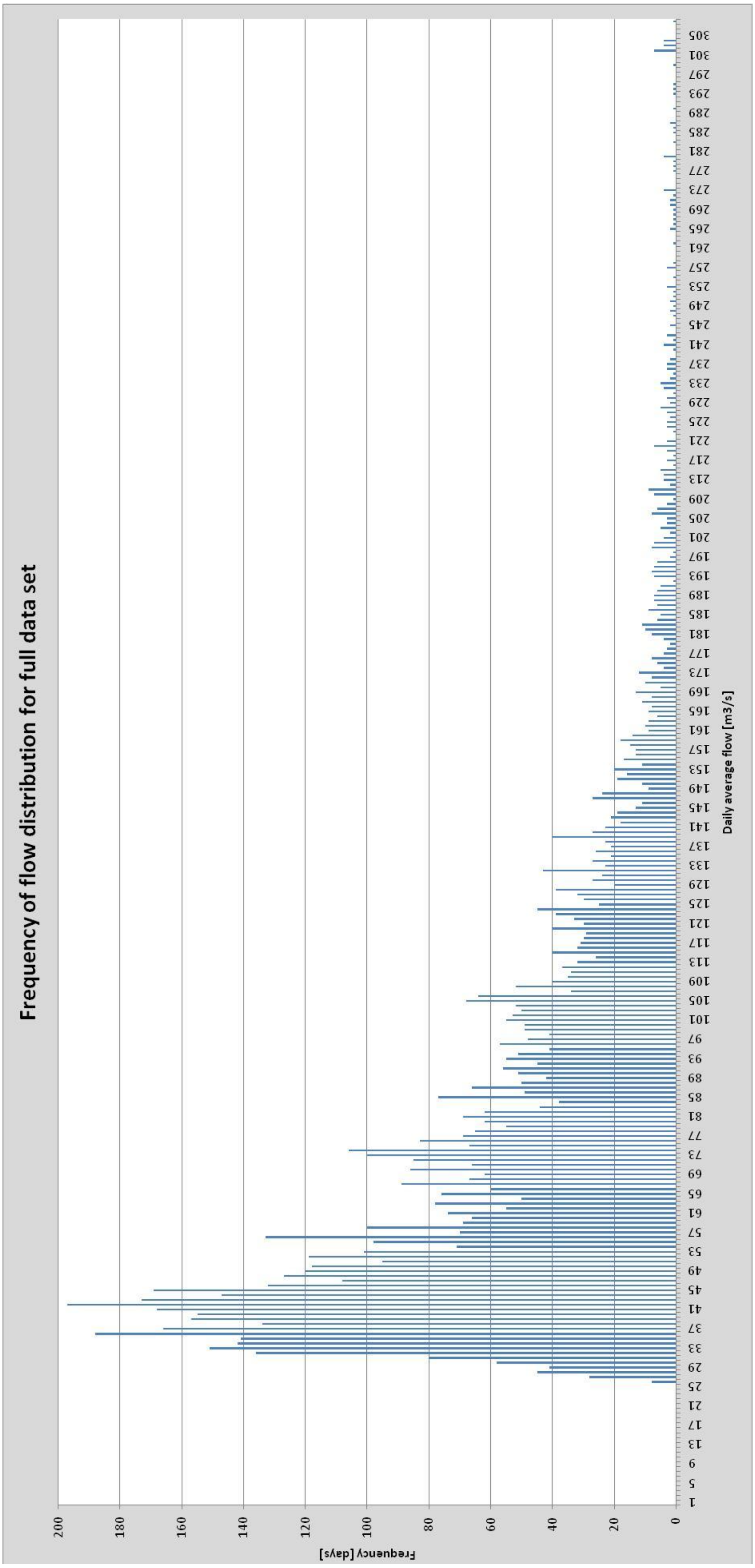
APPENDIX E – FULL DATA SET ANALYSIS





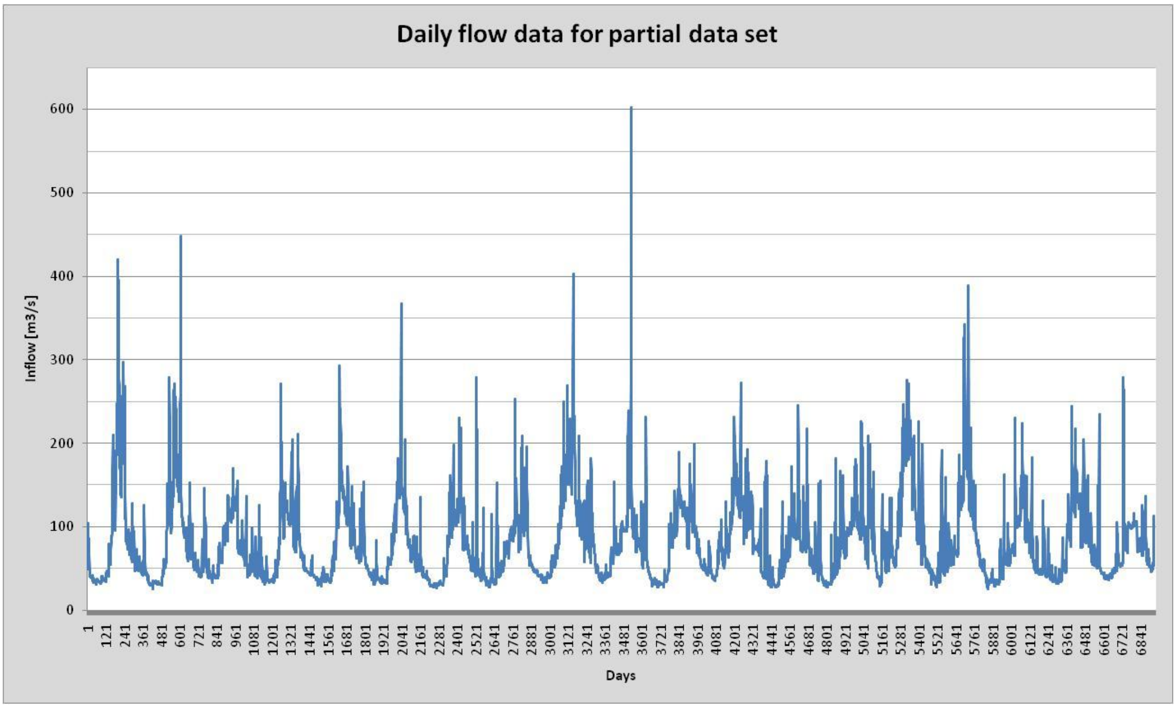

Average flow per month for full data set
Inflow [m3/s]
0
20
40
60
80
100
120
140
160
January
February
March
April
May
June
July
August
September
October
November
December

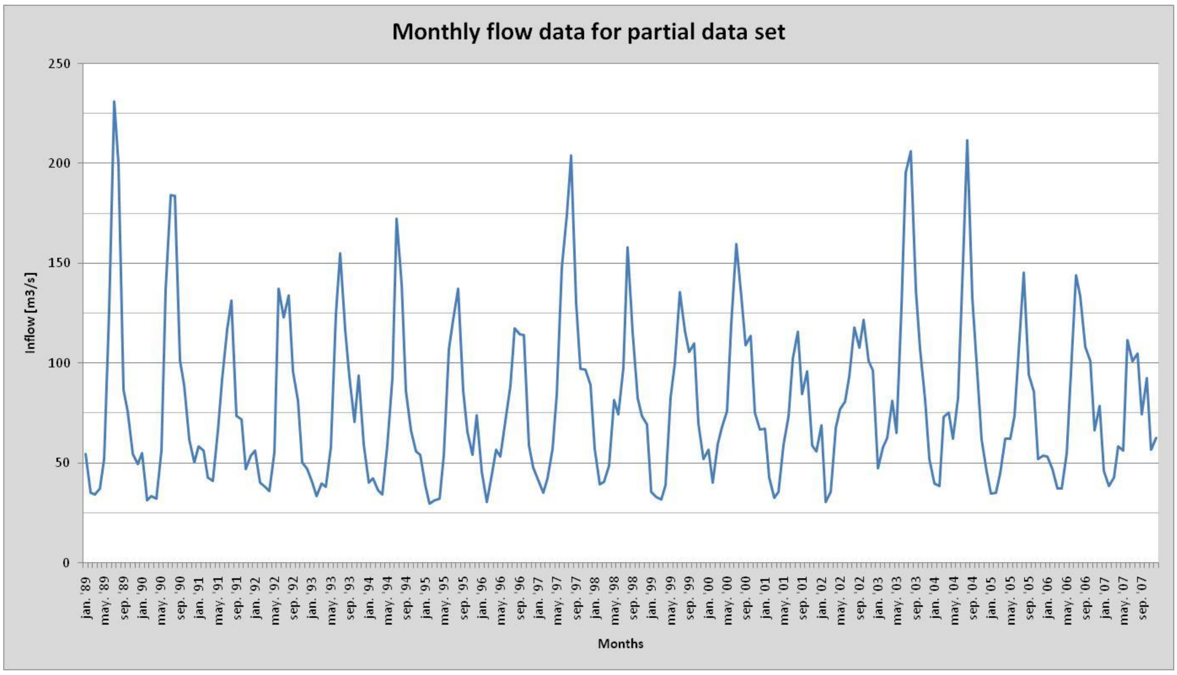

Average flow per year for full data set
Inflow [m3/s]
0
20
40
60
80
100
120
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010

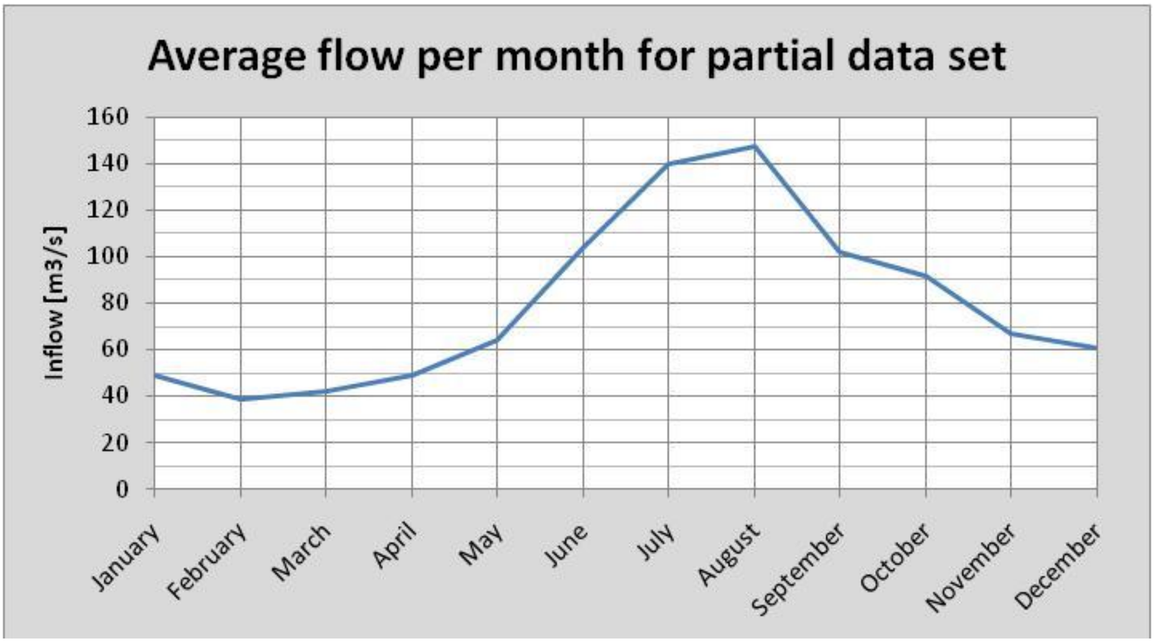


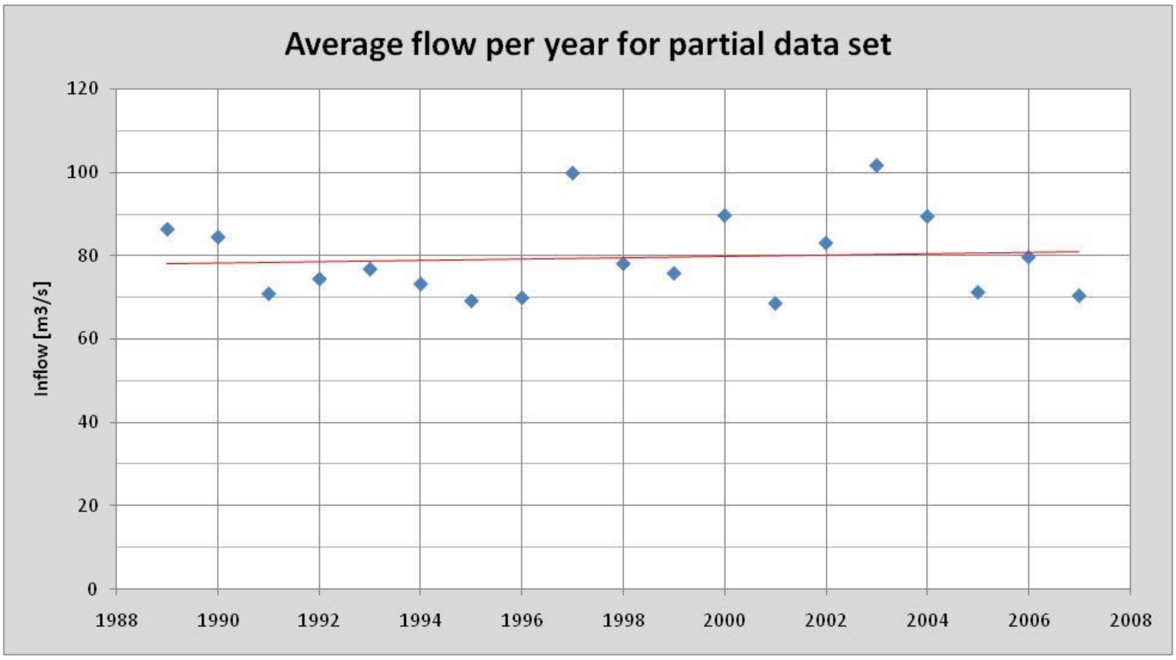
Frequency of flow distribution for full data set
Frequency [days]
Daily average flow [m3/s]

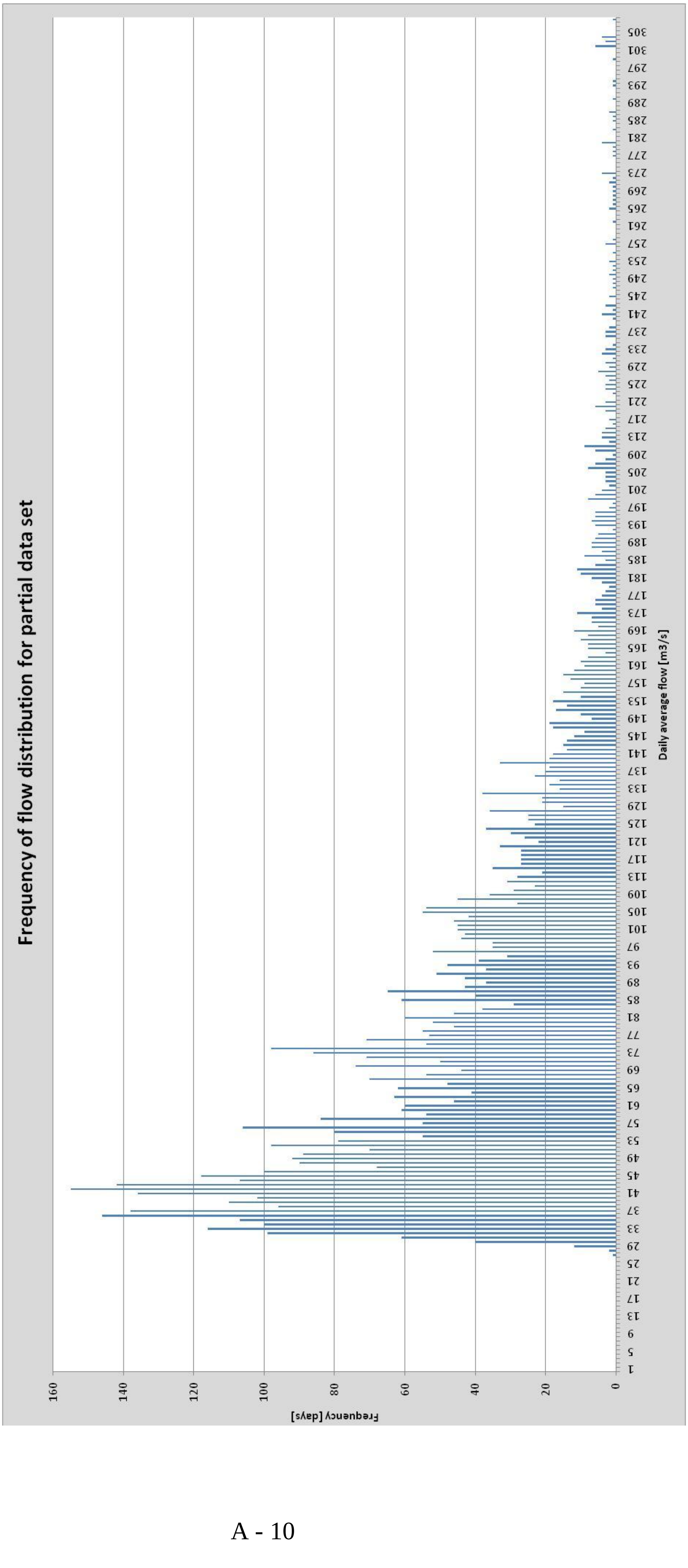
APPENDIX F – PARTIAL DATA SET ANALYSIS

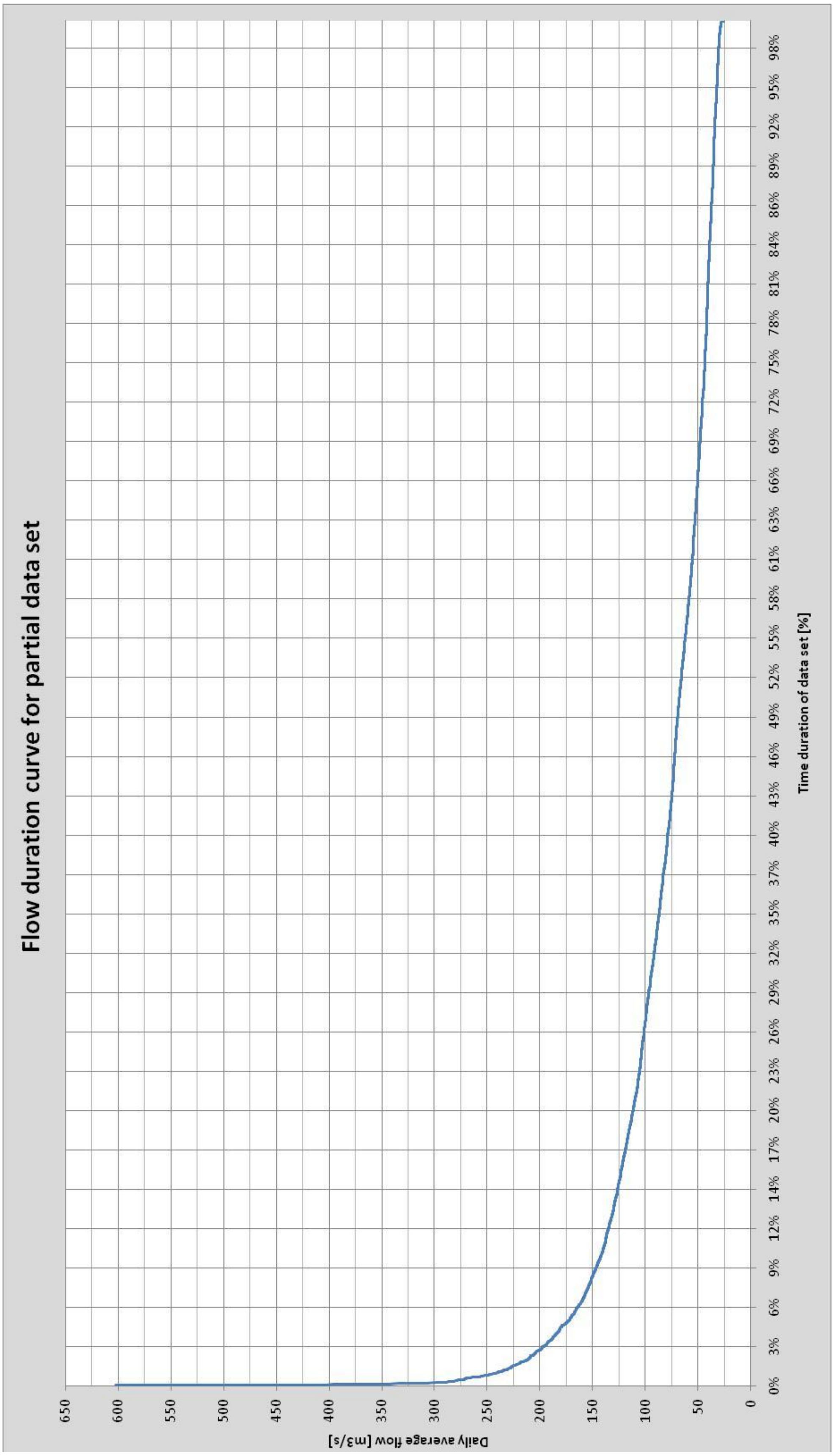




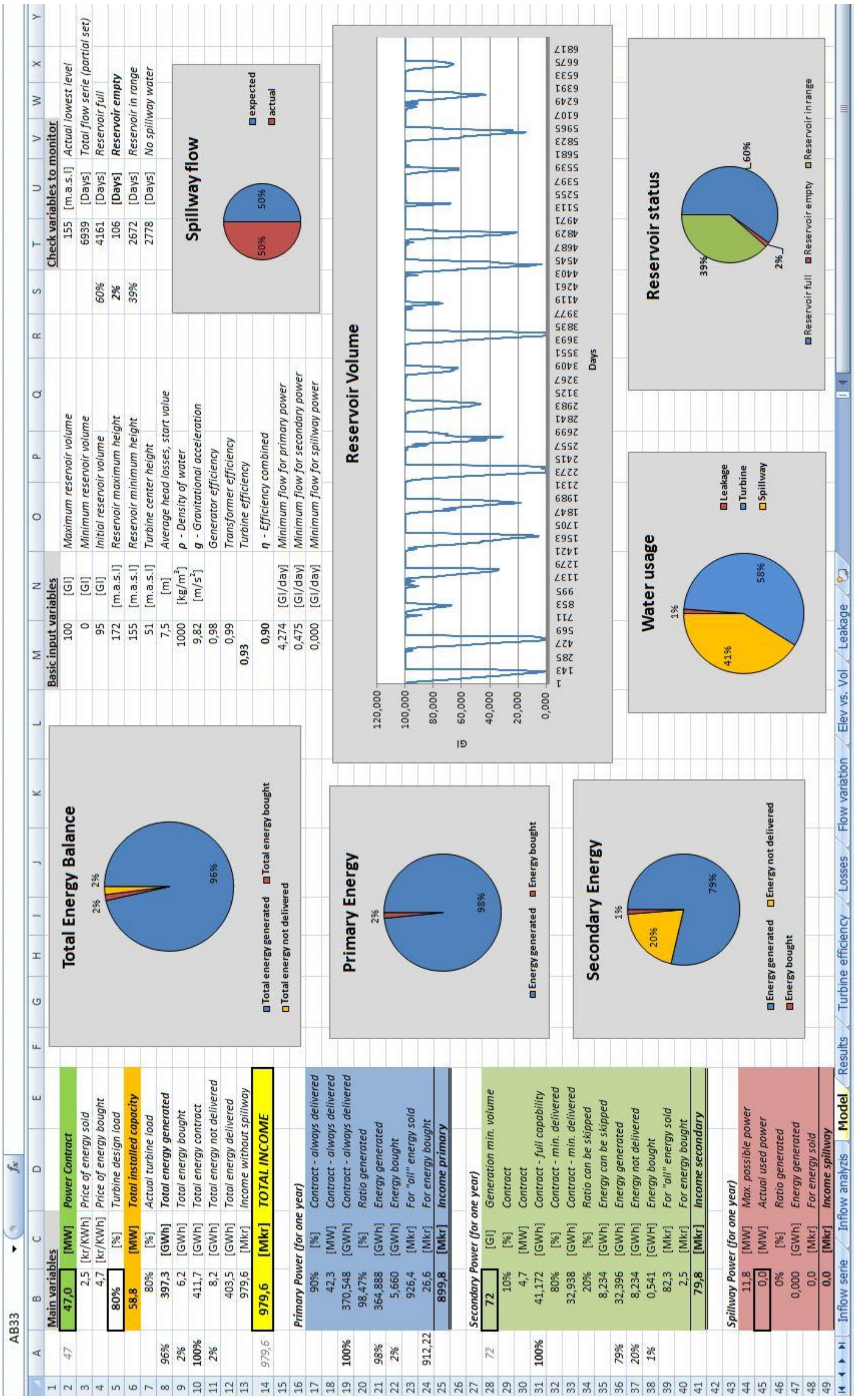

Average flow per month for partial data set
Inflow [m3/s]
160
140
120
100
80
60
40
20
0
January
February
March
April
May
June
July
August
September
October
November
December


Average flow per year for partial data set
Inflow [m3/s]
120
100
80
60
40
20
0
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008


Frequency of flow distribution for partial data set
Frequency [days]
Daily average flow [m3/s]
0
20
40
60
80
100
120
140
160


Flow duration curve for partial data set
Daily average flow [m3/s]
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0%
3%
6%
9%
12%
14%
17%
20%
23%
26%
29%
32%
35%
37%
40%
43%
46%
49%
52%
55%
58%
61%
63%
66%
69%
72%
75%
78%
81%
84%
86%
89%
92%
95%
98%
Time duration of data set [%]

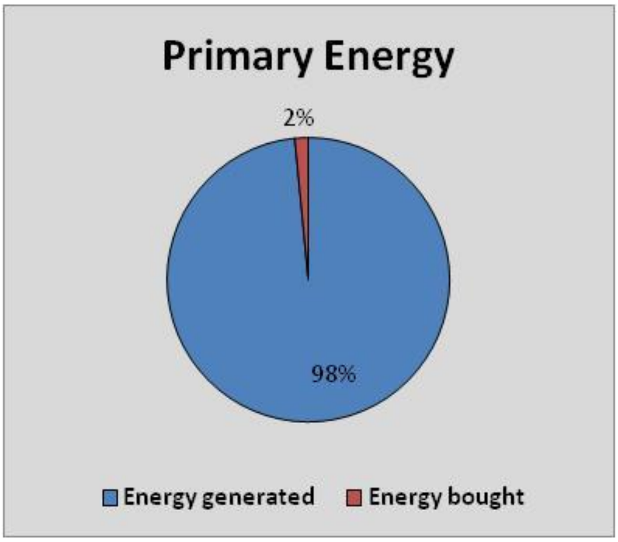
APPENDIX G – EXCEL MODEL (EXAMPLE)

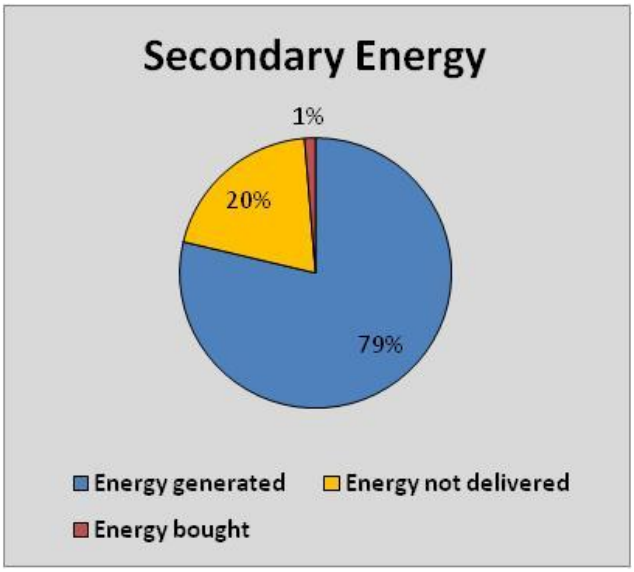


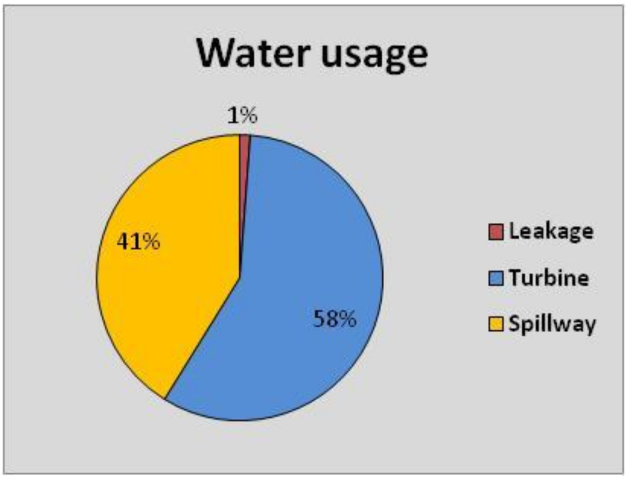
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
50															
51	*River data*			*Reservoir vol.*	*Reservoir*	*Leakage*		*H - Head data*		*Q - Total flow through turbine*					
52		$[m^3/s]$	[Gl/day]	[Gl]	[m.a.s.l]	$[m^3/s]$	[Gl/day]	[m]	[m]	$[m^3/s]$	[Gl/day]	$[m^3/s]$	[Gl/day]	$[m^3/s]$	[Gl/day]
53	Day #	Inflow	Inflow	Before	Elevation	Flow	Flow	Lost	Used	Q_{100}	Q_{100}	Q_{80}	Q_{80}	Q_{50}	Q_{50}
54	1	52,8	4,562	95,000	171	0,97	0,084	7,5	112,5	42,44	3,666	4,72	0,407	0,00	0,000
55	2	49,3	4,258	95,404	171	0,97	0,084	6,6	113,4	42,09	3,637	4,68	0,404	0,00	0,000
56	3	68,5	5,917	95,537	171	0,97	0,084	6,6	113,4	42,09	3,637	4,68	0,404	0,00	0,000
57	4	104,6	9,041	97,329	171	0,97	0,084	6,6	113,4	42,09	3,637	4,68	0,404	0,00	0,000
58	5	91,7	7,921	100,000	172	1,00	0,086	6,6	114,4	41,72	3,605	4,64	0,401	0,00	0,000
59	6	85,9	7,423	100,000	172	1,00	0,086	6,6	114,4	41,72	3,605	4,64	0,401	0,00	0,000
60	7	85,9	7,423	100,000	172	1,00	0,086	6,6	114,4	41,72	3,605	4,64	0,401	0,00	0,000
61	8	81,4	7,036	100,000	172	1,00	0,086	6,6	114,4	41,72	3,605	4,64	0,401	0,00	0,000
62	9	75,8	6,553	100,000	172	1,00	0,086	6,6	114,4	41,72	3,605	4,64	0,401	0,00	0,000
63	10	72,5	6,262	100,000	172	1,00	0,086	6,6	114,4	41,72	3,605	4,64	0,401	0,00	0,000
64	11	71,5	6,179	100,000	172	1,00	0,086	6,6	114,4	41,72	3,605	4,64	0,401	0,00	0,000
65	12	65,3	5,640	100,000	172	1,00	0,086	6,6	114,4	41,72	3,605	4,64	0,401	0,00	0,000
66	13	48,6	4,202	100,000	172	1,00	0,086	6,6	114,4	41,72	3,605	4,64	0,401	0,00	0,000
67	14	44,5	3,843	100,000	172	1,00	0,086	6,6	114,4	41,72	3,605	4,64	0,401	0,00	0,000
68	15	46,4	4,009	99,751	171	0,97	0,084	6,6	113,4	42,09	3,637	4,68	0,404	0,00	0,000
69	16	43,5	3,760	99,636	171	0,97	0,084	6,6	113,4	42,09	3,637	4,68	0,404	0,00	0,000
70	17	42,2	3,650	99,271	171	0,97	0,084	6,6	113,4	42,09	3,637	4,68	0,404	0,00	0,000
71	18	41,3	3,567	98,796	171	0,97	0,084	6,6	113,4	42,09	3,637	4,68	0,404	0,00	0,000
72	19	40,2	3,470	98,238	171	0,97	0,084	6,6	113,4	42,09	3,637	4,68	0,404	0,00	0,000
73	20	39,7	3,428	97,583	171	0,97	0,084	6,6	113,4	42,09	3,637	4,68	0,404	0,00	0,000

	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD
50															
51	*Reservoir vol.*		*Reservoir*		*Spillway*			*P - Power production*					*E - Energy generation*		
52	[Gl/day]	[Gl]	[1 or 0]	[1 or 0]	[Gl/day]	[Gl/day]	$[m^3/s]$	[MW]	[MW]	[1 or 0]	[MW]	[MW]	[GWh]	[GWh]	[GWh]
53	Change	After	Empty	Full	Expected	Actual	Actual	Total	P_{100}	OK	P_{80}	P_{50}	E100	E80	E50
54	0,404	95,404	0	0	0,000	0,000	0,00	47	42,3	1	4,7	0,0	1,015	0,113	0,000
55	0,133	95,537	0	0	0,000	0,000	0,00	47	42,3	1	4,7	0,0	1,015	0,113	0,000
56	1,792	97,329	0	0	0,000	0,000	0,00	47	42,3	1	4,7	0,0	1,015	0,113	0,000
57	4,916	100,000	0	1	2,246	2,246	25,99	47	42,3	1	4,7	0,0	1,015	0,113	0,000
58	3,829	100,000	0	1	3,829	3,829	44,32	47	42,3	1	4,7	0,0	1,015	0,113	0,000
59	3,332	100,000	0	1	3,332	3,332	38,56	47	42,3	1	4,7	0,0	1,015	0,113	0,000
60	3,332	100,000	0	1	3,332	3,332	38,56	47	42,3	1	4,7	0,0	1,015	0,113	0,000
61	2,945	100,000	0	1	2,945	2,945	34,08	47	42,3	1	4,7	0,0	1,015	0,113	0,000
62	2,461	100,000	0	1	2,461	2,461	28,48	47	42,3	1	4,7	0,0	1,015	0,113	0,000
63	2,170	100,000	0	1	2,170	2,170	25,12	47	42,3	1	4,7	0,0	1,015	0,113	0,000
64	2,087	100,000	0	1	2,087	2,087	24,16	47	42,3	1	4,7	0,0	1,015	0,113	0,000
65	1,548	100,000	0	1	1,548	1,548	17,92	47	42,3	1	4,7	0,0	1,015	0,113	0,000
66	0,111	100,000	0	1	0,111	0,111	1,28	47	42,3	1	4,7	0,0	1,015	0,113	0,000
67	-0,249	99,751	0	0	0,000	0,000	0,00	47	42,3	1	4,7	0,0	1,015	0,113	0,000
68	-0,116	99,636	0	0	0,000	0,000	0,00	47	42,3	1	4,7	0,0	1,015	0,113	0,000
69	-0,365	99,271	0	0	0,000	0,000	0,00	47	42,3	1	4,7	0,0	1,015	0,113	0,000
70	-0,475	98,796	0	0	0,000	0,000	0,00	47	42,3	1	4,7	0,0	1,015	0,113	0,000
71	-0,558	98,238	0	0	0,000	0,000	0,00	47	42,3	1	4,7	0,0	1,015	0,113	0,000
72	-0,655	97,583	0	0	0,000	0,000	0,00	47	42,3	1	4,7	0,0	1,015	0,113	0,000
73	-0,696	96,887	0	0	0,000	0,000	0,00	47	42,3	1	4,7	0,0	1,015	0,113	0,000

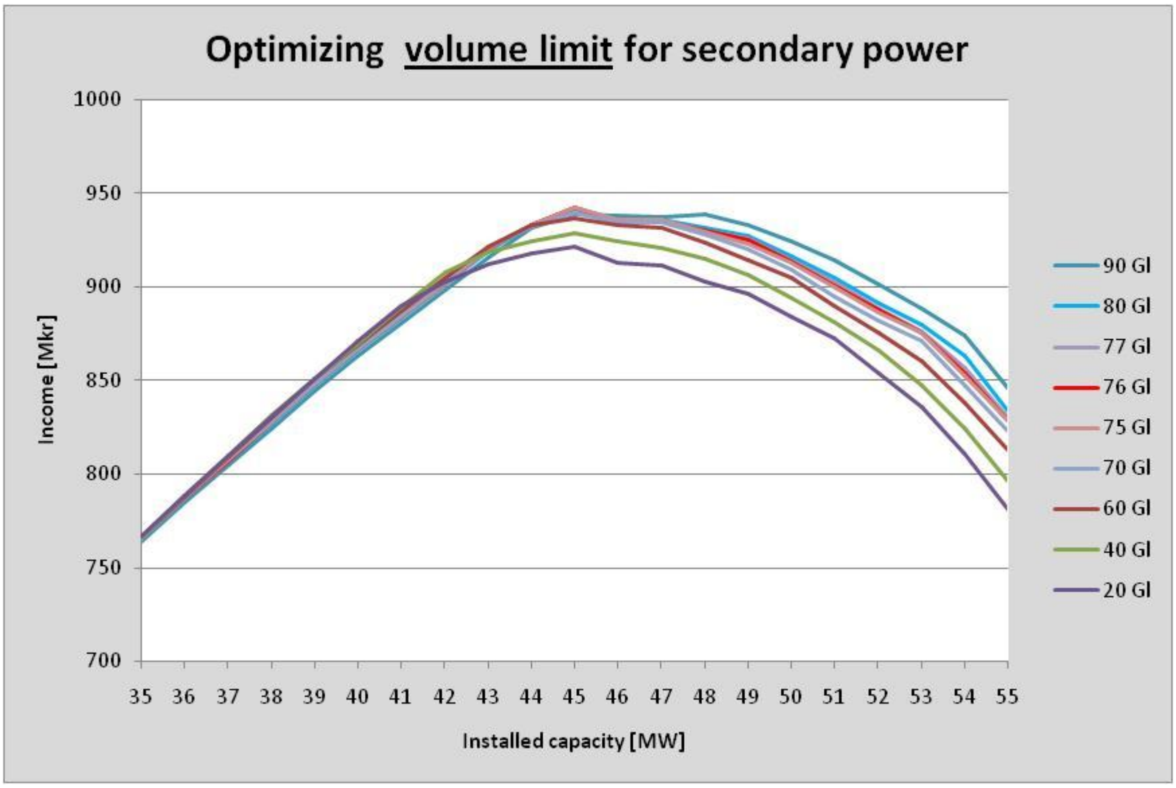
APPENDIX H – ENERGY GENERATION & WATER USAGE (EXAMPLE)

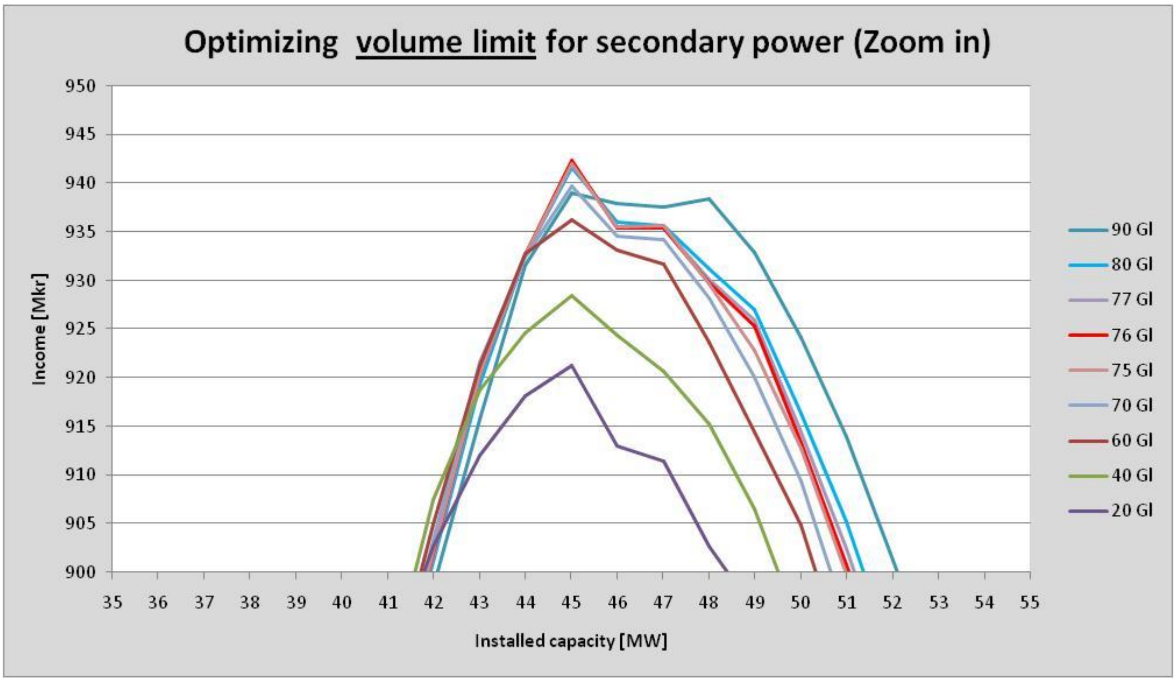






APPENDIX I – VOLUME FOR SECONDARY POWER (EXAMPLE)

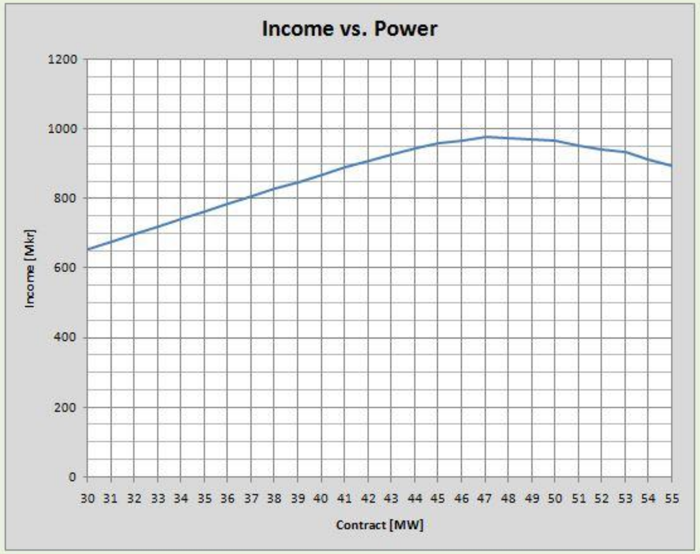


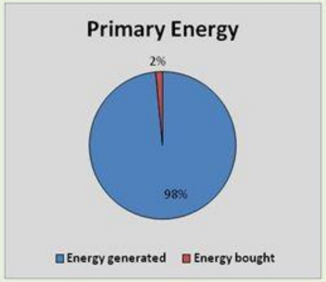


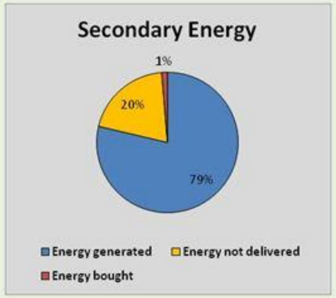
APPENDIX J – MODEL FINAL RESULTS

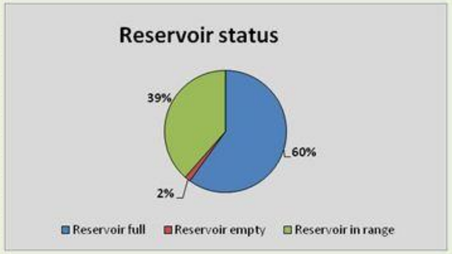
Case #1		
80%	Turbine design load	
72 [Gl]	Reservoir minimum volume for secondary power	

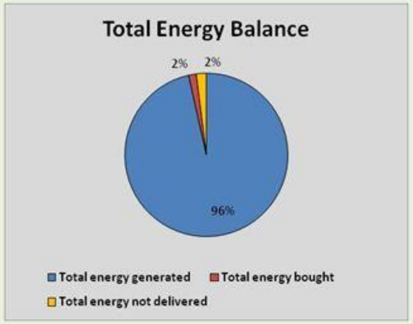
Contract	Income
30	657,0
31	678,9
32	700,8
33	722,7
34	744,6
35	766,3
36	787,9
37	809,0
38	830,0
39	850,7
40	871,3
41	891,0
42	910,7
43	930,5
44	947,4
45	962,1
46	968,9
47	979,6
48	977,5
49	974,1
50	967,2
51	954,6
52	943,0
53	936,1
54	914,6
55	895,9

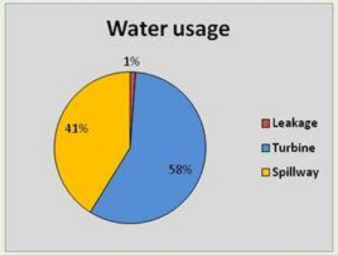












Main variables		
	47 [MW]	Power Contract
	2,5 [kr/KWh]	Price of energy sold
	4,7 [kr/KWh]	Price of energy bought
	80% [%]	Turbine design load
	58,8 [MW]	Total installed capacity
	80% [%]	Actual turbine load
96%	397,3 [GWh]	Total energy generated
2%	6,2 [GWh]	Total energy bought
100%	411,7 [GWh]	Total energy contract
2%	8,2 [GWh]	Total energy not delivered
	403,5 [GWh]	Total energy delivered
	979,6 [Mkr]	Income without spillway
	979,6 [Mkr]	TOTAL INCOME
Primary Power (for one year)		
	90% [%]	Contract - always delivered
	42,3 [MW]	Contract - always delivered
1	370,5 [GWh]	Contract - always delivered
	98% [%]	Ratio generated
98%	364,9 [GWh]	Energy generated
2%	5,7 [GWh]	Energy bought
	926,4 [Mkr]	For "all" energy sold
	26,6 [Mkr]	For energy bought
	899,8 [Mkr]	Income primary
Secondary Power (for one year)		
72	72 [Gl]	Generation min. volume
	10% [%]	Contract
	4,7 [MW]	Contract
100%	41,2 [GWh]	Contract - full capability
	80% [%]	Contract - min. delivered
	32,9 [GWh]	Contract - min. delivered
	0,2 [%]	Ratio can be skipped
	8,2 [GWh]	Energy can be skipped
79%	32,4 [GWh]	Energy generated
20%	8,2 [GWh]	Energy not delivered
1%	0,5 [GWH]	Energy bought
	82,3 [Mkr]	For "all" energy sold
	2,5 [Mkr]	For energy bought
	79,8 [Mkr]	Income secondary
Spillway Power (for one year)		
	11,8 [MW]	Max. possible power
	0 [MW]	Actual used power
	0 [%]	Ratio generated
	0 [GWh]	Energy generated
	0 [Mkr]	For energy sold
	0 [Mkr]	Income spillway

APPENDIX K – TURBINE LOAD SENSITIVITY