DEPARTMENT FOR INDUSTRIAL ECONOMICS
AND TECHNOLOGY MANAGEMENT

OPTIMAL REVISION AND UPGRADING
OF HYDROPOWER PLANTS UNDER
UNCERTAINTY

A CASE STUDY OF HYDROPOWER PLANTS IN STAVROPOL
RUSSIA

MASTER THESIS 2005
Stud. Tech.

THOR ANDRE LUNDER
Preface

This is the master thesis written during spring 2005 at NTNU, department of Industrial Economics and Industrial Management.

I would like to thank my supervisor Stein-Erik Fleten (NTNU), Ragnar Ottosen and Thorvald Nielsen (Rosnor Energo) for good support and valuable feedback. I would also like to thank Håkon Olav Iglebæk from Powel for helping me with the program VTG Revision used in the thesis.

Oslo, 27th June 2005

-----------------
stud.tech. Thor Andre Lunder
Summary

In this thesis I have discussed various issues concerning investments in upgrading of a power plant in the Stavropol region in Russia, owned by Stavropol Energo. The power plant is currently being upgraded with assistance from Norplan and Rosnor Energo, which I have cooperated with during the thesis. The profitability of the business is first of all dependent on future prices for electricity. Russia is currently undergoing a deregulation of their power markets, and this will have huge influence on the future prices for electricity. The first part gives an overview about the deregulation process as well as demand and supply side for electricity in Russia. This also includes some macroeconomics about Russia. I have further described the uncertainty an investor have to cope with when investing in hydropower generation facilities.

During the writing of the thesis, I observed that the maintenance routines were based on old methods, and not on the profit maximizing maintenance routines we know from deregulated markets. I chose therefore to suggest some changes on this area, with special emphasis on the turbines. The different wear on turbines and routines for maintenance on them are described in an own chapter.

The main analysis is carried out with VTG Revision, a program developed at SINTEF. The program does a net present value analysis of hydropower plants with technical as well as market details as input. I have focused on two of the stations located at the Kuban river.

To deal with the uncertainty for future prices for electricity, I used a real option approach. The future prices are modeled as a Geometric Brownian Motion (GBM). The problem is solved with Stochastic Dynamic Programming in a decision tree, where I have done backwards calculation presuming always optimal decision making in the future. The model underlines the value of waiting for information and the “cost” for uncertainty. The input in the model is the results from VTG. At the end of the thesis are some sensitivity analysis which indicates the significance for the value to wait.
# Contents

**Figures**........................................................................................................................................ 3
1  Introduction..................................................................................................................................... 5
2  Sources and collection information............................................................................................ 7
   2.1  In general.................................................................................................................................. 7
   2.2  Technical information on the plants....................................................................................... 7
   2.3  Information on the Russian market.......................................................................................... 8
3  The electricity market in Russia ...................................................................................................... 9
   3.1  Restructured Power Systems................................................................................................. 9
   3.2  Organization of the Russian power market.......................................................................... 10
   3.2.1  FOREM.............................................................................................................................. 11
   3.2.2  NP ATS ............................................................................................................................. 12
3.4  Restructuring plan...................................................................................................................... 13
   3.3.1  Deregulation process: status in 2004.............................................................................. 16
   3.5  Energy resources in Russia.................................................................................................... 18
   3.6  Large hydro energy in Russia............................................................................................... 20
   3.7  Prices for electricity in Russia............................................................................................... 21
   3.6.1  Export and Import ............................................................................................................ 23
4  Uncertainty and scenario analysis of future prices for electricity.............................................. 26
   4.1  Uncertainties when investing in the power plant .................................................................. 26
   4.1.1  Economy-wide factors....................................................................................................... 26
   4.1.2  The future prices for electricity in Russia......................................................................... 26
   4.1.3  Factors under the control of the policy-makers............................................................... 26
   4.1.4  Factors under the control of the company....................................................................... 27
   4.1.5  Fuel price and, to a lesser extent, availability risks......................................................... 27
   4.1.6  Financial risks arising from the financing of investments.............................................. 28
   4.2  Scenario analysis of future demand, supply and price......................................................... 28
   4.2.1  Current situation............................................................................................................... 28
   4.2.2  Price and demand development in Russia......................................................................... 29
   4.2.3  Scenario 1......................................................................................................................... 30
   4.2.4  Scenario 2......................................................................................................................... 31
5  Inspection routines for the turbines................................................................................................. 33
   5.1  Turbine runners....................................................................................................................... 34
   5.2  Labyrinth seal rings ............................................................................................................... 35
   5.3  Turbine shaft and shaft sealing box....................................................................................... 36
   5.4  Turbine bearing...................................................................................................................... 37
   5.5  Guide vanes and face plates................................................................................................. 39
   5.6  Spiral casing and draft tube................................................................................................. 41
6  Strategies for maintenance............................................................................................................. 44
   6.1  RCM-analysis......................................................................................................................... 46
7  Analysis with VTG revision............................................................................................................ 47
   7.1  About VTG Revision.............................................................................................................. 47
   7.2  Market description in the VTG model.................................................................................. 48
   7.3  VTG revision analysis of HES2 and HES1........................................................................... 50
   7.4  Investment costs.................................................................................................................... 52
   7.5  Results from the VTG analysis............................................................................................. 54
8  Real Option Approach.................................................................................................................... 56
   8.1  Real Option and NPV theories............................................................................................... 56
# 8.2 Uncertainty and real options in restructured power systems
# 8.3 A Stochastic Dynamic Model for Optimal Investment
# 8.4 Main assumptions in the model
# 8.5 Results from the real option approach
# 9 Suggestions to further work
# 10 Conclusion
# 11 References

APPENDIX A
APPENDIX B
APPENDIX C
Figures

Figure 3.2.1: Illustration of the main participants involved in electric power delivery in a deregulated power system [Botterud '03] ................................................................. 10
Figure 3.3.1: Power generation in Russia, June 2004 .......................................................... 11
Figure 3.3.2: Average daily prices on ATS. Prices in RUB on the left y-axes ...................... 12
Figure 3.4.1: Russian power sector after restructuring [IEA '03] ........................................ 16
Figure 3.4.2: Management of RAO UES, June 2005 [RAO UES '04] .................................. 17
Figure 3.5.1: Generation capacity split and fossil fuel for generation in Russia .................. 18
Figure 3.5.2: Estimated short-term marginal costs in Russia 2004 .................................... 19
Figure 3.5.3: Age structure of Russian power generation plants ...................................... 19
Figure 3.5.4: Consumption distribution in Russia [Hubert '03] .......................................... 20
Figure 3.6.1: Hydro-Energetic Resources in Russia ........................................................... 21
Figure 3.7.1: Total electricity consumption in Russia [Ottosen '04] ..................................... 22
Figure 3.7.2: Forecast for electricity consumption [RAO UES, '04] .................................... 22
Figure 3.7.3: Historical and estimated inflation in Russia [EIU '05] .................................... 23
Figure 3.7.4: Concentration and inter-regional trade in Russia ......................................... 24
Figure 3.7.5: Concentration and inter-regional trade in Russia ......................................... 25
Figure 4.2.1: Supply and demand curve for Russia in 2004 [Ottosen '04] ............................ 28
Figure 4.2.2: Shift in Supply 2005-2010 [Ottosen '04] ...................................................... 29
Figure 4.2.3: Shift in demand 2005-2010 [Ottosen '04] .................................................... 30
Figure 4.2.4: Price scenario 1 for 2010 [Ottosen '04] ......................................................... 31
Figure 4.2.5: Price scenario 2 for 2010 [Ottosen '04] ......................................................... 32
Figure 5.1.1 Turbine runner; runner wear and cracks [Daleng '94] ..................................... 34
Figure 5.2.1 Labyrinth seal; seal wear and scoring [Daleng '94] ......................................... 35
Figure 5.3.1 Turbine shaft; cracks [Daleng '94] ................................................................. 36
Figure 5.3.2 Shaft seal; worn seal [Daleng '94] ................................................................. 37
Figure 5.4.1 Turbine bearing; wear of bearing surface [Daleng '94] .................................. 38
Figure 5.4.2 Turbine bearing; water in bearing [Daleng '94] ............................................. 39
Figure 5.5.1 Guide vanes damage; guide vane wear [Daleng '94] ...................................... 40
Figure 5.5.2 Wear in the guide vanes [Skåre '05] .............................................................. 41
Figure 5.6.1 Spiral casing and draft tube damage type; wear [Daleng '94] ......................... 42
Figure 5.6.2 Spiral casing and draft tube damage type; cracks [Daleng '94] ...................... 42
Figure 5.6.1: Strategy development for maintenance .......................................................... 44
Figure 5.6.2: Model for developing strategy for maintenance .......................................... 45
Figure 7.1.1: Main steps in the VTG software .................................................................. 48
Figure 7.2.1: Price model in VTG with yearly drift of 10%. Prices in local currency (RUB) . 49
Figure 7.2.2: Seasonal patterns for electricity prices in the Stavropol region .................. 50
Figure 7.3.1: Basic description of HES2 .......................................................................... 51
Figure 7.3.2: Water flow in the Kuban river over one year ............................................... 51
Figure 7.3.3: Head of water variance as a function of water flow .................................... 52
Figure 7.3.4: Loss of head as a function of water flow, aggregate 1 ................................. 52
Figure 7.3.5: Efficiency as a function of the flow ............................................................. 53
Figure 7.3.6: Total new and old efficiency for the power plant HES1 ............................... 53
Figure 7.4.1: Costs for upgrading of turbines at HES2 ..................................................... 54
Figure 7.5.1: Results from the VTG-Revision analysis on HES1 and HES2 ......................... 55
Figure 8.1.1: Illustration of an investment option .............................................................. 57
Figure 8.1.2: Two important analytical dimensions in investment planning ..................... 58
Master thesis: Optimal Revision and Upgrading of Hydropower plants under Uncertainty

Figure 8.2.1: Expected shadow price for electricity following a GMB with drift 10% p.a. ..... 59
Figure 8.3.0.1: Bionic tree model for shadow price development .................................. 60
Figure 8.5.1: Trigger prices and option values for different volatilities and shadow prices .... 64
Figure 8.5.2: Significance of volatility .............................................................................. 64
Figure 8.5.3: Illustration of the threshold volatility ............................................................ 65
Figure 8.5.4: F(S) as a function of volatility, s and shadow price, S ................................. 65
Figure 8.5.5: NPV and F as a function of volatility, s and shadow price, S ......................... 66
Figure 8.5.6: NPV and F as a function of volatility, s and shadow price, S ......................... 67
Figure 8.5.7: The trigger prices for different volatilities, given NPV=0 today ................. 67
11 References

[ Hubert '03] Hubert, F., *Reform of Russian Power Industry: Which Lessons from Abroad?*, Humbold Universitat zu Berlin and State School of Economics in Moscow, March 2002


[ Powel ‘03] Powel ASA, *Powel VTGRevisjon – Brukermanual (in Norwegian)*, Trondheim 2004


Master thesis: Optimal Revision and Upgrading of Hydropower plants under Uncertainty


[ABS Consulting ’05] ABS Consulting, Homepage with presentation about the RCM method


[NP ATS ‘05] Information from np-ats.ru

[RAO UES ‘05] Information provided from RAO UES’s home pages

[Daleng ‘04] Daleng, J, Lecture notes from the classes of “Optimal Maintenance, 2005


[Skåre 05’] Skåre, Lecture notes from the classes of “Optimal Maintenance, 2005

[Strømberg and Bjørkqvist ‘04] Strømberg, M and Bjørkqvist, O, Variety reduction maintenance and renewal strategies, Mid University, Sweden

[Langdal ‘05] Langdal, Lecture notes from the classes of “Optimal Maintenance, 2005

[Solvang ‘05] Solvang, E, Lecture notes from the classes of “Optimal Maintenance, 2005

[Røvang ‘05] Røvang, Lecture notes from the classes of “Optimal Maintenance, 2005
Master thesis: Optimal Revision and Upgrading of Hydropower plants under Uncertainty


[Norplan ‘05] Interviews with staff from Norplan during the process of the writing

[Dixit and Pindyck ‘04] Dixit and Pindyck, *Investment under Uncertainty*, 2004
