Profitability analysis of hydropower maintenance and reinvestment projects

T.M. Welte & E. Solvang  
SINTEF Energy Research, Norway

O. Øen, R. Jordet & P. Golberg  
E-CO Energi, Norway

B. Børresen  
Multiconsult, Norway

ABSTRACT
The article describes an approach for technical-economic analysis of the profitability of maintenance and reinvestment project alternatives (options) in hydropower plants. The analysis compares project alternatives with regard to scope and timing to identify the most profitable alternatives. The steps in the analysis approach are briefly described in the paper, and the approach is illustrated by an example from the Norwegian hydropower company E-CO Energi. The example is based on a reinvestment project where the turbine governor must be replaced and where replacement of the turbine governor might be combined with the replacement of the Pelton wheel. The aim of the analysis was to identify a good timing of governor and wheel replacement and if the governor and wheel replacement should be grouped.

INTRODUCTION
Hydropower plant operators carry out inspection and condition monitoring of critical equipment to identify needs for maintenance measures because of degraded or unacceptable technical condition of the equipment. Norwegian power companies must prioritize maintenance and reinvestment to maintain acceptable technical and financial risk. This applies primarily to power plants that have not extensively been renewed over the last 20-30 years. Renewal may incur substantial costs associated with the renewal measure itself, as well as loss of revenue when production units must stop. Waiting too long to implement renewal measures on critical equipment may lead to failures and serious consequences with regard to costs, loss of revenue, injury on personnel, damage to environment and loss of reputation.

In order to take the right decisions with regard to the scope and timing of maintenance and reinvestment projects, technical and economic analyses of relevant project alternatives must be conducted. The analyses include the costs and impacts of project alternatives that improve the technical condition. Alternatives may also include projects that provide increased turbine efficiency and increased production capacity. The technical analysis covers evaluation of the technical condition and expected residual life of critical equipment as well as estimation of the associated probability of failure. The economic analysis is based on a net present value (NPV) approach. Costs and loss of income due to failure are calculated by multiplying the probability of failure with the consequence of failure.

E-CO Energi and several other Norwegian power companies have performed technical-economic analysis of specific projects in collaboration with SINTEF Energy Research in a research project called FRAM (Business framework for world class maintenance and reinvestment analyses) organized by Energy Norway. The aim of the project was to test models and tools developed by SINTEF Energy Research in previous projects. The project has also made recommendations regarding implementation of technical-economic analysis of maintenance and reinvestment projects in the power companies' organization. Two reports prepared in the project and written in Norwegian, (Solvang and Istad, 2013a; Solvang and Istad 2013b) describe models, tools and recommendations.

Models and tools that are used for profitability analysis of hydropower maintenance and reinvestment projects are briefly presented in the next section. Thereafter, the organization and implementation of maintenance and reinvestment project analysis at E-CO Energi is presented. A case is presented afterwards illustrating application of models and tools by a project on turbine governor replacement in a hydropower station at E-CO Energi. Then, the results from the technical-economic analysis are presented and discussed, and finally the paper is summarized and conclusions are drawn.
MODELS AND TOOLS

Figure 1 shows the model for technical-economic analysis of maintenance and reinvestment projects from the FRAM research project (Solvang and Istad, 2013a). The boxes in the middle with yellow color are the main steps in the analysis process. The boxes to the left provide input to the analyses, while the boxes to the right include results. The three boxes at the bottom of the figure with orange color are important additional processes considering continuous improvement of the analysis process.

![Figure 1: Model for technical-economic analysis.](image)

Each of the steps in the analysis and improvement process in Figure 1 is briefly described below.

**Analysis process**

Documentation is developed continuously throughout the analysis process and starts with an initial project description and develops further until a final documentation of results, recommendations and assumptions.

**Establish scope**

- Prepare initial (draft) project description with information about the background and goals.
- Limit the analysis (e.g. system limits).
- Determine solution alternatives and analysis period.
- Prepare final project description.

**Establish data basis**

- Collect information on the technical condition and maintenance history for the components.
- Determine the technical condition and associated residual lifetimes.
- Establish failure models and data for estimation of failure probability.
- Determine the consequences of failure.
- Determine costs of maintenance and reinvestment measures.
Estimate risk and benefits
- Estimate the probability of failures included in the analysis.
- Estimate the economic risk resulting from failures.
- Assess risk regarding HSE incidents and damage to the environment as a result of failures.
- Calculate the total costs and revenues for each solution alternative (present value).
- Calculate the profitability of each solution alternative referred the reference alternative.
- Perform a sensitivity analysis.

Present results
- Prepare final documentation of results, recommendations and assumptions.
- Develop summary with recommendations tailored to different decision makers.

Improvement process
These additional steps contribute to the quality of the current analysis as well as experience transfer to other project analysis and other employees.

Quality assurance (review)
- Verify data, assumptions, results, recommendations and stored documentation. Quality assurance is carried out for all analyses, but adapted to the individual project and the purpose of the analysis.
- Conduct joint review of several analyses to see these in context, for example an annual review of all analyses that year. The purpose is to ensure that the analyses are according to the template.
- Update the analysis approach when needed, for example as a result of conducted quality assurance and annual joint review of project analyses.

Update analysis if new assumptions
- Examine and perform analysis if it needs updating as a result of new data and assumptions.
- Make recommendations considering experience transfer for later analysis.

Archive results digitally
- Store data, assumptions, results and recommendations digitally.
- Perform electronic signing that filing is performed according to the present template.
- Ensure that everyone who needs information has good access to it digitally.

Failure model
SINTEF Energy Research has developed a failure model and a tool (EFP – Estimation of Failure Probability) that calculates the annual failure probability for a given failure mechanism of a component based on information about the technical condition and the degradation process. Figure 2 shows the main elements of the failure model and the links between these.

Components are described in terms of Failure mechanisms and Technical condition in the failure model. Criteria for the classification of deterioration states are needed in order to determine the technical condition of the component. The physical design, material variants, insulation level, manufacturing, etc. will often be decisive for whether a failure mechanism is significant for a given component. The arrow in Figure 2 from Design to Failure mechanisms illustrates that. Two in principle identical components can have different failure mechanisms as a result of differences, for example, regarding the materials.
The probability of *Failures* increases as the technical condition deteriorates. When a component fails the *Consequences* depends on the barriers or the *Consequence reducing measures* (protection, physical barriers, etc.). Although there are established barriers to prevent or limit the consequences of failures, there are ‘holes in the fence’ that can lead to unwanted consequences caused by the failures. This is illustrated in Figure 2.

The consequences of a failure can be more or less serious. The probability that a very serious event or accident happens is normally less than the probability of less serious consequences. A failure can have consequences in terms of costs, poor quality, personal injury, environmental damages, loss of reputation, etc. The associated *Risk* of a failure (unwanted event) is the combination of the probability and the consequence of the failure.

*Preventive measures* in the figure are maintenance actions to mitigate wear-out and repair faults (corrective maintenance) as well as renewal. These actions can also be in form of new or modified *Consequence reducing measures*. Relevant preventive measures for a component normally depend on the *Failure mechanisms* of the component as illustrated by an arrow in the figure.

The EFP tool for calculation of failure probability is based on a degradation model with five condition states where 1 is the best state (as good as new), 4 a critical state with very degraded condition, and 5 the fault state. A general description of the states is presented in the following table. The state description is according to the definitions given in the Energy Norway’s handbooks for inspection and condition monitoring of hydropower components (Energy Norway, 2015). For each component and failure mechanism, a more specific definition of each state is given in the handbooks.
Table 1: General description of deterioration states (Energy Norway, 2015).

<table>
<thead>
<tr>
<th>State</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No indication (&quot;as good as new&quot;)</td>
</tr>
<tr>
<td>2</td>
<td>Some indications of deterioration. The condition is noticeable worse than &quot;as good as new&quot;. (Minor deterioration).</td>
</tr>
<tr>
<td>3</td>
<td>Serious deterioration. The condition is considerable worse than &quot;as good as new&quot;. (Major deterioration).</td>
</tr>
<tr>
<td>4</td>
<td>The condition is critical. Serious considerations should be made to repair immediately.</td>
</tr>
<tr>
<td>5</td>
<td>The component is unable to fulfil the function (Fault).</td>
</tr>
</tbody>
</table>

Using the state model, the life of a component can be seen as movement through different states, starting at state 1 and then moving through successive states until either state 5 occurs or corrective maintenance is performed which may bring the component back to a better condition. For a situation without maintenance, a run through all states is illustrated in Figure 3, and the resulting curve is denoted life curve. The time a component spends in a given state (i.e. the residence or sojourn time in state $j$) can be modelled as a stochastic variable. This is illustrated by the probability distributions in Figure 3. The resulting mathematical model is a semi-Markov process; see Welte (2008), Welte and Eggen (2008) and Welte (2009) for further details. The semi-Markov model is implemented in the EFP tool and can be used to estimate the failure probability based on a given condition or age.

![Figure 3: Degradation model based on five condition states.](image)

Note that the described degradation model requires that degradation is observable, that is, it must be possible to define different states and reveal the technical condition by condition monitoring and inspections. In situations where this is not given or where the definition of states is difficult, the EFP tool offers a simplified method for failure probability calculation based on an estimate of the expected remaining lifetime and the 10th percentile of the remaining lifetime.

**PROJECT ANALYSIS AT E-CO ENERGI:**

Reinvestments in E-CO Energy are based on a long-term plan, where all possible future projects should be registered. The plan is set up based on age of equipment, knowledge of technical condition and other relevant factors. Before detailed project planning starts, the analysis group within E-CO is responsible of performing technical and economic analysis of different project alternatives. One of the alternatives should be a minimum solution that covers the minimum upgrade that has to be done in order to keeping the equipment reliable. This alternative is used as a reference, which the results of the other alternatives are compared against. The technical analysis is done by evaluating historical data, having meetings with technical and maintenance personnel and
interviews with energy planners. For capacity creep projects, simulations on how increased energy can increase profit might be performed.

All collected data are put into the spreadsheet for technical-economic analysis. One person is in charge of the calculations, but the results are discussed within the analysis group to ensure the calculations are correct, and based on these discussions, the calculations are updated. The results of the technical-economic analysis are finally described in a report. The report states the technical importance of the upgrade, gives an overview of the results of the calculations and discusses advantages for the different alternative solutions. Health, safety and environment arguments and other information that is relevant to the project would also be discussed in this report. The report gives a recommendation, and is sent forward to the investment committee. Based on the report, the investment committee makes a decision on the alternative they recommend. If the project is recommended of the investment committee, it is forward to E-CO’s CEO or E-CO’s board (depending on total project cost) for approval. When a project is approved, it is handed forward to a project leader.

CASE TURBINE GOVERNOR

The case presented here is based on an analysis carried out by E-CO Energi for a hydropower station where a Pelton turbine is installed and where a decision must be made to replace the turbine governor and the Pelton wheel. Some modifications of the original analysis are done to better illustrate the use of the technical-economic analysis tool.

The hydraulic turbine governor and the injectors are at the time when the analysis has been carried out 41 years old. These components have thus reached the expected end of life, and reinvestment plans must be prepared. Failure modes and consequences that have been considered in the analysis are:

- Minor damage that can be quickly repaired.
- Failure that requires dismantling, cleaning and adjustments.
- Failure in needle steering. Delivery time for materials and manufacturing of new slides. Estimated outage time 3-4 months.
- Deflector loosens due to vibrations caused by fault in needle steering and deflector servo. Pelton wheel and injectors are damaged by loose reflectors. Estimated outage time 18 months.
- As before, but in addition generator damage due to vibrations. Repair work on turbine and generator done in parallel. Estimated outage time 18 months.

The replacement of the governor including injectors will result in an increased efficiency of approx. 0.5 %.

The Pelton wheel is only 10 years old when the analysis was carried out. Nevertheless, also reinvestment alternatives where the Pelton wheel is replaced are included in the technical-economic analysis. A new wheel has an expected additional increase of efficiency by 0.3 %, since the new wheel design will be optimized for the new injectors. Initially, the failure probability of the existing wheel was estimated based on the wheel age. At a later stage, the failure probability estimation was updated after new inspection results were obtained that showed that the condition is 1.83. This means that the wheel condition is still in state 1, but close to state 2. The condition estimates an average resulting from different types of condition assessment. For illustration purposes, we included alternatives in the paper that show how the updated information of wheel condition influences the calculation results. The analysis includes also two different estimates of the runner lifetime (30 and 50 years), which shows the sensitivity of the results on different lifetime assumptions.

In addition to the income from selling the electricity from increased power production on the electricity market, the power companies will receive an additional income from the electricity certificate market for this increased power production, because power producers that increase their production from existing power plants on a permanent basis are eligible for electricity certificates in Norway. The goal of the electricity certificate scheme is to contribute
to the achievement of the countries’ goals to increase the renewable electricity production; see NVE (2015) for more details on the Norwegian-Swedish electricity certificate market.

TECHNICAL-ECONOMIC ANALYSIS

Different reinvestment alternatives have been analysed that differ from each other by replacement year, and if replacement of hydraulic governor and Pelton wheel are grouped or not. In addition, alternatives are included that represent sensitivity analyses where the assumptions on the Pelton wheel's lifetime and condition are changed. The alternatives are described in the upper part of table Table 3.

Probability of failure

The probability of failure of the old hydraulic governor was calculated by the simplified method already mentioned above based on two estimates provided by experts from E-CO Energi. The estimate of the expected remaining lifetime was 10 years. In addition, the probability of failure within 5 years was estimated to be 10 %. A Gamma distribution were fit to the two estimates, which then was used to calculate the probability of failure for the old governor.

For the new governor and the existing and new Pelton wheels, the above described 5-states degradation model was applied. The estimates for the sojourn times in states 1-4 (provided by experts from E-CO Energi as mean sojourn time and 10th percentile) are given in the Table 2. The first (quite conservative) estimate of the expected wheel lifetime was given as 30 years by E-CO Energi. Since this seems to be quite short, we also included additional alternatives in the economic analysis were we assumed a lifetime of 50 years of the wheel.

Table 2: Estimates for mean sojourn time (and 10th percentile) for states 1 – 4.

<table>
<thead>
<tr>
<th></th>
<th>Mean sojourn time (10th percentile) [years]</th>
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<tbody>
<tr>
<td></td>
<td>State 1</td>
</tr>
<tr>
<td>New hydraulic governor</td>
<td>17 (10)</td>
</tr>
<tr>
<td>Pelton wheel, expected lifetime 30 years</td>
<td>7 (5)</td>
</tr>
<tr>
<td>Pelton wheel, expected lifetime 50 years</td>
<td>11.7 (8.3)</td>
</tr>
</tbody>
</table>

The life curve for the existing wheel was assumed to be the same as the life curve for the new wheel, because the existing Pelton wheel is quite new (only 10 years old) and the design of a new wheel (from a lifetime perspective) would be similar to the old one. The difference of failure probability is a result of the age difference of 10 years, or a result of the condition difference between a new wheel (state 1.0) and the existing wheel (state 1.83). Assuming that $F(t)$ is the cumulative failure probability distribution of a new wheel, $F(t|T\geq10\text{ years})$ and $F(t|\text{state}=1.83)$, respectively, are then the conditional failure probability distributions of the 10 years old wheel and the wheel in state 1.83, respectively. Details on calculating the failure probabilities can be found in Welte (2008), Welte and Eggen (2008), Welte (2009) and Rausand and Høyland (2004). The EFP tool has been used for calculations of the failure probability, and mathematical equations and algorithms required for calculations are implemented in the tool.

Note that the different way to calculate the failure probability can have an effect on the results. This is illustrated in Figure 3. When calculating the conditional failure probability $F(t|T\geq10\text{ years})$, the resulting probability distribution becomes usually quite "broad" (large standard deviation), because the real technical condition of the wheel is not taken into account. This may result in conservative lifetime estimates and high failure risk. Since the wheel is still in a quite good condition, we should base the failure probability calculations on the technical condition.
An example for the failure probabilities over the analysis period of 30 years is presented for the hydraulic governor in Figure 3. Depending on when the replacement is scheduled, that is, either no replacement at all (A0), replacement in 2015 (A1, A3, A4) or replacement in 2018 (A2), the resulting failure probabilities for different alternatives and components are as illustrated in Figure 4. Without making economic calculations, but only taking a look on the failure probabilities of the old governor, it becomes clear that the governor should be replaced as soon as possible.

Costs and profitability
Economic analysis based on a NPV approach was used in the next step to estimate costs, risks and profitability for each alternative. The costs for the project alternative (i.e. costs for maintenance and reinvestment alternatives) are put into the tool (spreadsheet) for economic analysis. The costs associated with failure of the different components is assessed, e.g. by using an event-tree approach, see Rausand and Høyland (2004). Then, the economic risk resulting from failure is then estimated by calculating the product of the failure costs and the annual failure probability. All other costs (e.g. income/revenue due to increased efficiency) are afterwards included in the calculations, and the result (net present value) for the different alternatives is calculated as the sum of the total investment costs, the risk due to failure before replacement and the revenues. In addition, the benefit of each option referred to the reference alternative (A0) is calculated. The results are summarized in the table below.

Note that the calculations include only economic figures that are related to or influenced by the different investment alternatives. This means that costs, incomes and risks that are constant and the same for all different alternatives are not taken into account. For example, only the additional income because of increase in power production due to higher efficiency is included in the analysis, but not the income generated by the "baseline" power production of the equipment (i.e. the part of the production not influenced by A0-A4). Thus, the analysis may result in negative net present values for the different alternatives. Therefore, the benefit of the alternatives is better illustrated by comparing alternatives A1-A4 with the baseline alternative A0.
Table 3: Results from economic analysis (all costs in 1000 NOK).

<table>
<thead>
<tr>
<th>Governor &amp; injectors</th>
<th>A0</th>
<th>A1a</th>
<th>A1b</th>
<th>A2</th>
<th>A3a</th>
<th>A3b</th>
<th>A3c</th>
<th>A4a</th>
<th>A4b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Governor</td>
<td></td>
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<tr>
<td>&amp; injectors</td>
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<td>old</td>
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<tr>
<td>new in year</td>
<td>2015</td>
<td>2018</td>
<td>2015</td>
<td>2015</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelton wheel</td>
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</tr>
<tr>
<td>new in year</td>
<td>2015</td>
<td>2018</td>
<td>2020</td>
<td>2025</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>expected lifetime [yrs]</td>
<td>30</td>
<td>30</td>
<td>30*</td>
<td>30</td>
<td>50</td>
<td>30*</td>
<td>30</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Investment costs</td>
<td>-26 638</td>
<td>-23 708</td>
<td>-26 166</td>
<td>-26 166</td>
<td>-23 856</td>
<td>-23 856</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Risk (failure costs)</td>
<td>-8 269</td>
<td>-8 229</td>
<td>-22 887</td>
<td>-8 309</td>
<td>-7 195</td>
<td>-9 490</td>
<td>-5 772</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revenue/income</td>
<td>33 313</td>
<td>30 316</td>
<td>30 316</td>
<td>27 088</td>
<td>27 088</td>
<td></td>
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<tr>
<td>Result (NPV)</td>
<td>-26 638</td>
<td>-8 269</td>
<td>-22 887</td>
<td>-8 309</td>
<td>-7 195</td>
<td>-9 490</td>
<td>-5 772</td>
<td></td>
<td></td>
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<tr>
<td>Benefit</td>
<td>39 617</td>
<td>39 657</td>
<td>39 554</td>
<td>30 116</td>
<td>40 166</td>
<td>36 953</td>
<td>40 671</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Failure probability for Pelton wheel estimated based on technical condition (state = 1.83)

The most beneficial reinvestment alternatives are A3b and A4b. These two alternatives are conditioned on the assumption that the Pelton wheel lifetime is 50 years. When assuming a lifetime of 30 years, A3c is the best alternative. The results show that when using the real condition as basis for calculating failure probability (A1b and A3c), the risk estimates are lower than when using the age of the Pelton runner for calculating the failure probability.

Based on the results from the technical-economic analysis, it can be concluded that the governor should be replaced already in 2015 and that the existing wheel can be kept for minimum five to ten years. A new analysis should be carried out in some years, or when new information of the technical condition of the equipment is available, to decide on replacement of the wheel. Future analyses may also include new reinvestment alternatives and the grouping of the wheel replacement with other maintenance and reinvestment projects.

**CONCLUSION**

The paper presented an approach for technical-economic analysis of reinvestment alternatives. An example has been described, which illustrates the practical application to hydropower reinvestment projects. Technical-economic analysis is a valuable approach for comparison of project alternatives and to identify the most profitable alternatives. The tools presented in this paper provide help to the users to apply more advanced analysis methods and mathematical models in hydropower maintenance and reinvestment decision making. Furthermore, they offer a structured approach to the user, including documentation of the analysis process and the analysis results.

A practical challenge is the definition of a suitable and representative set of alternatives covering the range of the most relevant reinvestment alternatives and including optimal or near-optimal alternatives (e.g. earliest and latest replacement year, assuming that the optimal replacement year is somewhere in-between the two alternatives). Furthermore, practical applications of the approach have shown that many analysis results are quite sensitive to the choice of input values. The approach allows for including sensitivity by the definition of different alternatives, as illustrated by the presented examples where the replacement year or different ways to analyse the failure probability are included in the alternatives. As already pointed out in the description of the analysis approach, further sensitivity analysis should be carried out to identify the influence of various model parameters on the analysis results.
REFERENCES


