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Hydropower design under uncertainties

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PREFACE

Hydropower plants are still the most important renewable energy resource worldwide. Hydropower is also the most efficient electricity production and has a very high flexibility in combination with reservoirs. Nevertheless, the construction of hydropower plants, especially in the case of large schemes, requires high investments with long payback periods. Thus, future uncertainties have to be considered in early design stages in order to obtain robust and flexible projects with high resilience. With his research, Dr. Felix Oberrauch made a significant contribution by showing how hydropower projects have to be designed with advanced methods which allow to take into account the future uncertainties.

Very large hydropower project developments are often in the public focus associating them with significant cost overrun and bad performance. With the slogan "Small is beautiful" in the public awareness often preference is given to the development of small hydropower. Dr. Oberrauch analyzed for the first time in a systematic way with a coherent sample of realized projects the uncertainties of small and large hydropower projects in Switzerland regarding cost overrun and production overestimation. He could show that small hydropower projects, on average, can have similar range of cost overrun as large projects. However, the probability that small projects exceed the estimated costs is smaller than for large projects. Nevertheless, the sample analysis revealed that small hydropower projects have a tendency to more extreme cost overruns than large facilities. Based on the Swiss hydropower dataset Dr. Oberrauch showed how the uncertainties of construction cost and energy production forecasts can be implemented in the economical evaluation of a project.

As novel contribution for the engineering practice Dr. Oberrauch presented a new framework which allows a straightforward selection of the design objective and the required design method in order to consider uncertainties in early design stages of hydropower projects. He showed how the methods of Robust Decision Making, Info-Gap Decision Theory and Flexible Design have to be formulated and applied to a real hydropower project. Dr. Oberrauch discusses in detail the value and the limitations of each approach and gives final recommendations for their application.

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Prof. Dr. Anton Schleiss Prof. Dr. Matthias Finger

Abstract

The design of hydropower is determined by estimates and long-term forecasts. These forecasts and estimates are highly uncertain and make performance evaluation and design choices challenging.

Performance evaluation of hydropower projects is affected by a number of uncertainties such as construction cost estimates and energy production forecasts. Recent studies indicate dramatic cost overruns for large hydropower schemes. Accuracy of energy production forecasts are questioned, especially in light of future climate change.

It is generally assumed that the risk associated with small plants is much lower compared to large hydropower projects. Policy makers, developers, environmental and conservation organizations, and NGOs often tend to adhere to the principle “small is beautiful”. Small hydropower plants have been intensively supported in many countries despite a knowledge gap about uncertainties affecting small hydropower plants.

Based on an evidence-based approach, cost overruns of small and large Swiss hydropower projects were analyzed and compared. In addition, the reliability of mid-term and long-term energy production data was examined.

The results show that small hydropower projects, on average, suffer a similar range of cost overrun as large projects. However, the chance that small projects will exceed the estimated costs is much smaller than for large projects. On the other hand, small hydropower projects tend to have more extreme cost overruns than large facilities. This long tail to adverse outcomes indicates a potential for improvement, especially in terms of the methods used for estimating the construction costs, including quality of design, and in terms of appropriate approaches to controlling actual construction costs.

Compared to previous research studies on cost overrun of large international hydropower schemes, the results on Swiss projects show that the average cost overrun is significantly below the figures derived from global databases.

In addition, small hydropower plants show a tendency for energy production overestimates. In contrast, the production of large hydropower projects in the long term was on average 8% higher than the estimated figures. About 80% of the projects reached or exceeded the production targets.

These findings challenge the current assumption that large hydropower schemes are generally highly risky structures and that small hydropower projects should be preferred to reduce associated threats.

In addition, the results enable a more comprehensive political debate on the current subsidizing system for small hydropower projects. Also, based on the derived statistical distributions of uncertainties, this allows a more comprehensive performance evaluation of hydropower projects.

Beside the characterization and assessment of uncertainties of small and large hydropower projects in Switzerland, a register of political, commercial and project uncertainties was established. The register can be applied as a basis for a project-specific assessment of uncertainties.

The other part of the study focuses on design methods that are useful for the management of uncertainties. Hydropower projects face long-term uncertainties, such as electricity price and future inflow. Whereas it is commonly agreed that these forecasts are highly uncertain, there remains the question of how to make design decisions under the consideration of uncertainties with the final aim to decrease the threats and increase the opportunities.

Various past research studies have suggested and applied different design methods to overcome this problem. Recent studies focused on Robust Decision Making. Other studies applied real option valuations for hydropower schemes. Another method that has been identified as a promising approach is the Info-Gap Decision Theory, but it has not been formulated and applied to hydropower projects up to now. There is very limited experience with the application of these methods in real hydropower projects.

To promote their application in the engineering practice, a new framework for hydropower projects is introduced, allowing a straightforward selection of the design objectives including robustness, versatility, flexibility, or interoperability. Depending on the design objectives, different mitigation or exploitation methods (design methods) can be applied. The framework covers the design methods: Robust Decision Making, Info-Gap Decision Theory, Portfolio Planning, Adaptation of Operation Rules and Real Option Analysis as well as Flexible Design.

In addition, the Robust Decision Making, Info-Gap Decision Theory and Flexible Design methods were formulated and applied to a real hydropower project. The value and the limitations of each approach are described and final recommendations for their application and further development are made.

Keywords

Hydropower design, uncertainties, cost overrun, Outside View, reference class forecast, Robust Decision Making, Info-Gap Decision Theory, Flexible Design

Zusammenfassung

Langfristige Prognosen wie Zuflüsse und Energiepreise sowie Abschätzungen von Baukosten sind für die Projektierung von Wasserkraftanlagen nötig. Diese Abschätzungen und Prognosen sind mit grossen Unsicherheiten behaftet und erschweren sowohl die Bewertung als auch die Auslegung der Anlagen.

Aktuelle Studien weisen auf signifikante Kostenüberschreitungen bei grossen Wasserkraftanlagen hin. Dazu kommt, dass die langfristigen Zufluss-Abschätzungen durch den Klimawandel erschwert werden. Das führt zu einer zunehmenden Zurückhaltung bei Investitionen in die Grosswasserkraft.

Es wird derzeit davon ausgegangen, dass die Kleinwasserkraft deutlich tieferen Risiken ausgesetzt ist als die Grosswasserkraft. Sowohl die Politik als auch zahlreiche Umweltverbände, NGOs und Projektentwickler bevorzugen Kleinwasserkraft. Des Weiteren wird Kleinwasserkraft in zahlreichen Ländern stark subventioniert, obwohl es keine fundierten Studien zu den Unsicherheiten in der Kleinwasserkraft gibt.

Um diese Lücke zu schliessen, wurden im Zuge dieser Arbeit Kostenüberschreitungen und die Genauigkeit von Energieabschätzungen sowohl für kleine als auch grosse Wasserkraftanlagen in der Schweiz untersucht. Dazu wurden historische Daten ausgewertet.

Die Ergebnisse zeigen, dass die Kleinwasserkraft im Durchschnitt einer ähnlich grossen Kostenüberschreitung ausgesetzt ist wie die Grosswasserkraft. Allerdings ist die Wahrscheinlichkeit einer Kostenüberschreitung bei kleinen Anlagen deutlich geringer als bei grossen Anlagen, jedoch ist eine aussergewöhnlich hohe Kostenüberschreitung bei kleinen Wasserkraftanlagen häufiger zu beobachten. Die relativ häufigen sehr hohen Kostenüberschreitungen weisen auf ein deutliches Verbesserungspotential in Hinsicht der Projektierung, Kostenabschätzung, Ausschreibung sowie Kostenkontrolle am Bau von Kleinwasserkraftanlagen hin.

Im Vergleich zu anderen Studien mit Fokus auf Grosswasserkraftanlagen weltweit zeigt die Auswertung, dass Schweizer Grosswasserkraftwerke von deutlich geringeren Kostenüberschreitungen betroffen waren.

Des Weiteren wird gezeigt, dass für kleine Anlagen eine Tendenz zur Überschätzung der Energieproduktion besteht. Dagegen hatten 80% der Grosskraftwerke in der Stichprobe der Schweizer Anlagen eine langfristig höhere Produktion als ursprünglich in der Planung angenommen.

Diese Erkenntnisse stellen damit die Annahme, dass Grossanlagen deutlich risikoreichere Investitionen darstellen als Kleinwasserkraftanlagen, zunehmend in Frage. Die Ergebnisse sind nicht nur für eine umfassendere politische Ausrichtung in Hinsicht der Subventionspolitik von Bedeutung,

sondern erlauben eine Berücksichtigung der Unsicherheiten in der Projektierung und Evaluierung von Wasserkraftanlagen. Dafür wurden Verteilungsfunktionen der Kostenüberschreitung und Energieprognosen ermittelt, und die verschiedenen Methoden für den Evaluierungsprozess werden aufgezeigt.

Für eine projektspezifische Evaluierung von Unsicherheiten wurde ein Register für Wasserkraftprojekte mit möglichen politischen, kommerziellen und projektspezifischen Unsicherheiten erstellt. Dieses Register kann als Grundlage für eine projektspezifische Evaluierung herangezogen werden.

Ein weiterer zentraler Teil der Studie beschäftigt sich mit Auslegungsmethoden, welche die langfristigen Unsicherheiten bei der Auswahl von Auslegungsparametern berücksichtigen. In dieser Studie werden die langfristigen Unsicherheiten des Zuflusses unter Einwirkung des Klimawandels und der Energiepreise berücksichtigt. Es steht ausser Frage, dass diese Abschätzungen von grossen Unsicherheiten betroffen sind, allerdings stellt sich die Frage, wie man eine Wasserkraftanlage unter Berücksichtigung dieser Unsicherheiten auslegen sollte, um einerseits negative Risiken zu reduzieren und andrerseits Opportunitäten zu nutzen.

Verschiede Forschungsarbeiten haben bereits innovative Auslegungsmethoden für die Wasserkraft vorgeschlagen und teilweise angewandt. Dazu zählen unter anderem „Robust Decision Making“, Realoptionenanalyse und „Info-Gap Decision Theory“. Allerdings bedarf es einer zusätzlichen Bestätigung ihrer Anwendbarkeit und ihres Nutzens in der Wasserkraftplanung.

Einerseits wurde die vielversprechendsten Methoden entsprechend den Anforderungen in der Wasserkraft in einer neuen konzeptionellen Leitlinie organisiert, die die Anwendungen in der Ingenieurspraxis fördern soll. Die Leitlinie zeigt je nach angestrebten Planungszielen „Robustness“, „Versatility“, „Flexibility“ oder „Interoperability“ verschiede Methoden auf, welche sich für die Anwendung in der Wasserkraft eignen.

Darüber hinaus wurden die Methoden „Robust Decision Making“, „Info-Gap Decision Theory“ und „Flexible Design“ erstmals gemeinsam an einer typischem Auslegungsfragestellung angewandt. Nach- und Vorteile der einzelnen Ansätze werden aufgezeigt und Empfehlungen für die Anwendung und Weiterentwicklung werden gemacht.

Schlüsselwörter

Auslegung von Wasserkraftanlagen, Unsicherheiten, Kostenüberschreitung, Outside View, Reference-Class Forecast, Robust Decision Making, Info-Gap Decision Theory, Flexible Design

Contents

Chapter 1 Introduction

The design of hydropower is determined by estimates and long-term forecasts. These forecasts and estimates are highly uncertain and make performance evaluation and design choices challenging. Effective values deviating from the estimates can have a significant impact on the success of a hydropower project.

This study contributes to the description and characterization of uncertainties affecting hydropower projects. It analyzes the accuracies of cost estimates and energy production forecasts of realized small and large hydropower projects in Switzerland.

In addition, a register of political, commercial and project uncertainties has been elaborated, allowing a project-specific assessment of uncertainties.

Finally, this study provides support for design methods taking uncertainty of long-term forecasts into account. These methods are seeking an active way to avoid threats or to exploit of opportunities by means of appropriate design choices or design strategies. Robust Decision Making, Info-Gap Decision Theory and Flexible Design were applied to a real hydropower project.

1.1 Context

1.1.1 Uncertainties of Small and Large Hydropower Projects in Switzerland

Performance evaluations of hydropower projects are affected by the uncertainties of construction cost estimates and energy production forecasts. They do not only influence decisions on project investments, but also political preferences in terms of subsidizing systems.

Several publications show that hydropower projects suffer significant cost overrun. Ansar et al. (2014) describe a mean cost overrun of 96% based on a global sample size of 245 large dams. Bacon and Besant-Jones (1998) calculated an average cost overrun of 27% for 71 hydropower projects in developing countries. The Word Commission on Dams (WCD, 2001) derived an average cost overrun of 56% for a data sample consisting of 81 hydropower, irrigation and multipurpose projects. Sovacool et al. (2014) give an average cost overrun of 71% based on 61 hydro facilities.

In research, less attention was given to the accuracy of energy production forecasts. The only identified study (WCD, 2001) on the accuracy of long-term energy production forecasts concludes that hydropower plants have on average met expectations for power delivery, but with considerable variability, much of it on the downside.

The studies on dramatic cost overruns of hydropower schemes support the current trend of preferring small hydropower plants over large-scale schemes.

It is generally assumed that the risk associated with small plants is much lower compared with large hydropower projects. Policy makers, developers, environmental and conservation organizations, NGOs and various researchers (e.g. Ansar et al., 2014; Dursun and Gokcol, 2011; Sovacool et al., 2014) tend to adhere to the principle "small is beautiful".

Supporting systems to push small hydropower have been introduced in several countries. Also in Switzerland the feed-in tariff system was launched in 2008. According to the Energy Strategy 2050 (BFE, 2012), it is intended make small hydropower one of the major sources of additional renewable energy.

Small hydropower plants have been intensively supported in many countries despite a knowledge gap about uncertainties affecting the performance of small hydropower plants. Studies on the actual performance of cost estimates and energy production forecasts are outstanding.

In addition, recent research works show high cost overrun for international large hydropower plants. The accuracy of cost estimates and energy production forecasts for large Swiss hydropower plant has not been analyzed so far.

The traditional way of integrating the cost overrun uncertainty into the planning process is to make a contingency provision. A common approach is to estimate cost contingency on the basis of predetermined guidelines. More comprehensive project evaluations, such as by applying the Expected Value (ENPV), Value at Risk (VaR) and Value at Gain (VaG) criteria, are not typically applied in hydropower projects as the probability distributions of the uncertain factors are not available.

1.1.2 Management of Uncertainties

Uncertainty in forecasts of hydrology, electricity price, ecological conditions and preferences, sedimentation as well as irrigation demand, water supply or flood retention volume in multipurpose projects complicates the choices of design parameters of hydropower plants.

Climate change as one of the driving factors of hydrological uncertainties has been given a lot of attention during the last few decades of research. The Intergovernmental Panel on Climate Change (2007) records that energy production and energy demand are especially sensitive to climate change.

In Switzerland, a slight decrease in annual discharge is anticipated in Ticino and in South Wallis until 2100, whereas no significant change of the discharge situation is estimated in the North Alps (SGHL and CHy, 2011). However, the impact on hydropower plants is expected to show large variation depending on the location and characteristics of a particular catchment area. Project-specific impact studies can be based on the report and data elaborated for the extensive research project "Swiss Climate Change Scenarios CH2011" (CH2011, 2011). Different model chains are available to allow for an assessment of the modelling uncertainty. Even though climate change projections make it possible to run various inflow projections and thus come up with estimates of power productions, there is lack of knowledge and experience with practical application in hydropower projects as to which design choices to make under the consideration of this uncertainty.

Another uncertain factor is the future electricity price. Electricity prices have a direct impact on the performance parameters and consequently on the design decisions. Decisions regarding the active storage capacity and the installed capacity depend significantly on the forecast of the electricity price. The forecast period has to cover the entire economic lifetime of a hydropower plant, which can be up to 80 years. Such long-term processes can be significantly influenced by unpredictable events. The longer the forecast period is, the more likely it is that pivotal events will change the underlying economic and relationships that all models attempt to replicate (Craig et al. 2002). Also Switzerland faced such unpredictable events in recent history. The impacts of the Fukushima nuclear accident on the European energy policy, the wind and solar substitution policies, or the liberalization of the Swiss energy market were difficult or impossible to predict.

In addition, due to the liberalization of the electricity market, electricity suppliers are faced with an increasingly complex market situation. In the context of a liberalized market, not only the forecasts are becoming less confident, but there are also limited management possibilities to compensate wrong or non-optimal decisions. In a monopolistic situation, design errors could be compensated by increasing rates to match real costs, while in a competitive environment, they would result in a loss that would jeopardize the durability of the company or at least reduce the cost effectiveness of a project (Gollier et al., 2005).

Also if ongoing research should improve the accuracy of climate change projections and electricity price forecasts, a high uncertainty will remain and finally lead to a demand for adequate design methods that incorporate these uncertainties into the planning process.

Various research projects have suggested and applied different design methods. Recent studies focused on Robust Decision Making (RDM) in hydropower projects (e.g. Cervigni et al., 2015; Nassopoulos et al. 2012). Other studies applied real option valuations to hydropower schemes (Wang, 2008; Bockman, 2006; Michailidis and Mattas, 2007; Elverhøi et al., 2010; Fertig et al., 2013). The Information-Gap Decision Theory (IGDT) was suggested by Ray and Brown (2015) as a potential approach to deal with climate change uncertainties, but has not been applied for hydropower projects so far.

However, the traditional engineering task still is to optimize the hydropower plant so that it will meet the forecasted scenario, then followed by sensitivity analyses as a standard part of good engineering practice.

According to the author's opinion, there are two main reasons why these approaches are not used in engineering practice. Firstly, there is no framework providing guidance for pragmatic selection of an adequate design method for hydropower projects. Secondly, experience with the application of the design methods in real hydropower projects is limited or, in the case of IGDT, non-existing for the moment.

1.2 Objectives

This study focuses on the following three principal research aims:

- Characterization and assessment of uncertainties affecting hydropower projects

- Elaboration of a method for project-specific assessment of uncertainties
- Adaptation and formulation of new design methods for incorporation of uncertainties into the design process.

The uncertainties characterization and assessment process focuses on small and large hydropower projects in Switzerland and is aimed at the elaboration of statistical distributions of uncertainties. Therefore, the outside view has been selected. Historical data of the small and large hydropower plants as constructed was collected and analyzed.

A crucial part of this study is the assessment of uncertainties of small hydropower plants, as these schemes have been intensively supported in many countries despite a lack of detailed information on related uncertainties.

In addition, the study aims to provide the required statistical distributions of cost overrun and production overestimation to enable a more comprehensive performance evaluation of small and large hydropower schemes.

The second research aim focuses on a method for a project-specific assessment of uncertainties. A register of political, commercial and project uncertainties was established, which can be applied as a basis for assessing a risk-adjusted performance parameter, such as NPV, of a project

The final main part of the study focuses on design methods that allow for management of uncertainties. One objective is to provide a framework with guidance for engineers on the potential application of promising methods. The other main objective was to formulate, apply and test the methods on a real hydropower project.

Beside the identification of the values and limitations of the different methods, that part of the study is intended to provide a basis for the application of the methods in the engineering practice and to close the gap between research and hydropower engineering practice. It contributes to the improvement of traditional engineering approaches to designing hydropower schemes with the final aim to lead to better design choices decreasing the threats and increasing the opportunities.

This study contributes to a better understanding of uncertainties affecting hydropower projects and application of innovative design methods for management of uncertainty in the hydropower sector.

1.3 Structure

Figure 1 gives an overview of the study's structure in connection with the three main research aims.

The first part of the study, which includes Chapter 2, Chapter 3 and Chapter 4, provides basic information on the conventional design approach, definitions of terms frequently used in this study, and a short summary on the uncertainties of hydrology and electricity price forecasts, as driving factors for the application of new design methods.

The second part focuses first on the assessment of uncertainties in Swiss hydropower projects on the basis of the outside view (see Chapter 5), then followed by the project-specific assessment (see Chapter 6), the framework of the design methods and the various approaches applicable to stand-alone hydropower plants (see Chapter 7 to Chapter 11).

Since Chapter 5, Chapter 7 and Chapter 9 are intended for publication, some redundancy may be present in the literature review. In addition, as this study deals with a number of different issues, relevant literature of the specific topics is summarized at the beginning of each chapter for the sake of better readability.

The outlines of the chapters are as follows:

Chapter 2 provides a high-level overview on the traditional approach of hydropower design with focus on the choice of plant size. The motivation is to show that hydropower planning is characterized by a process that covers several planning phases and considers various constraints. The planning phases and the constraints are also limiting for a potential application of design methods and have therefore to be considered.

Chapter 3 gives the definitions of the words risk, uncertainty, opportunity and threat, because these terms are not ordinarily part of the discourse of engineering and there is no unique definition available. Also, the concept of strategic misrepresentation and optimistic bias is introduced, motivating the approach selected for the assessment of the uncertainties of hydropower projects, namely the outside view.

Chapter 4 characterizes the uncertainties of electricity price and hydrology. It shows the magnitude of accuracy of climate change projections based on a literature review. In addition, it explains the complexity of electricity price forecasts and summarizes the main driving uncertainties. It also includes a retrospective analysis to indicate how accurate historical electricity price predictions have been.

Chapter 5 describes the assessment of the uncertainties of small and large hydropower projects in Switzerland. It summarizes the current state of research and provides details on the research method and the data samples. It describes the analyses of the estimated and actual construction costs and energy production figures. The chapter concludes with political implications and with implications on the design and planning of hydropower projects.

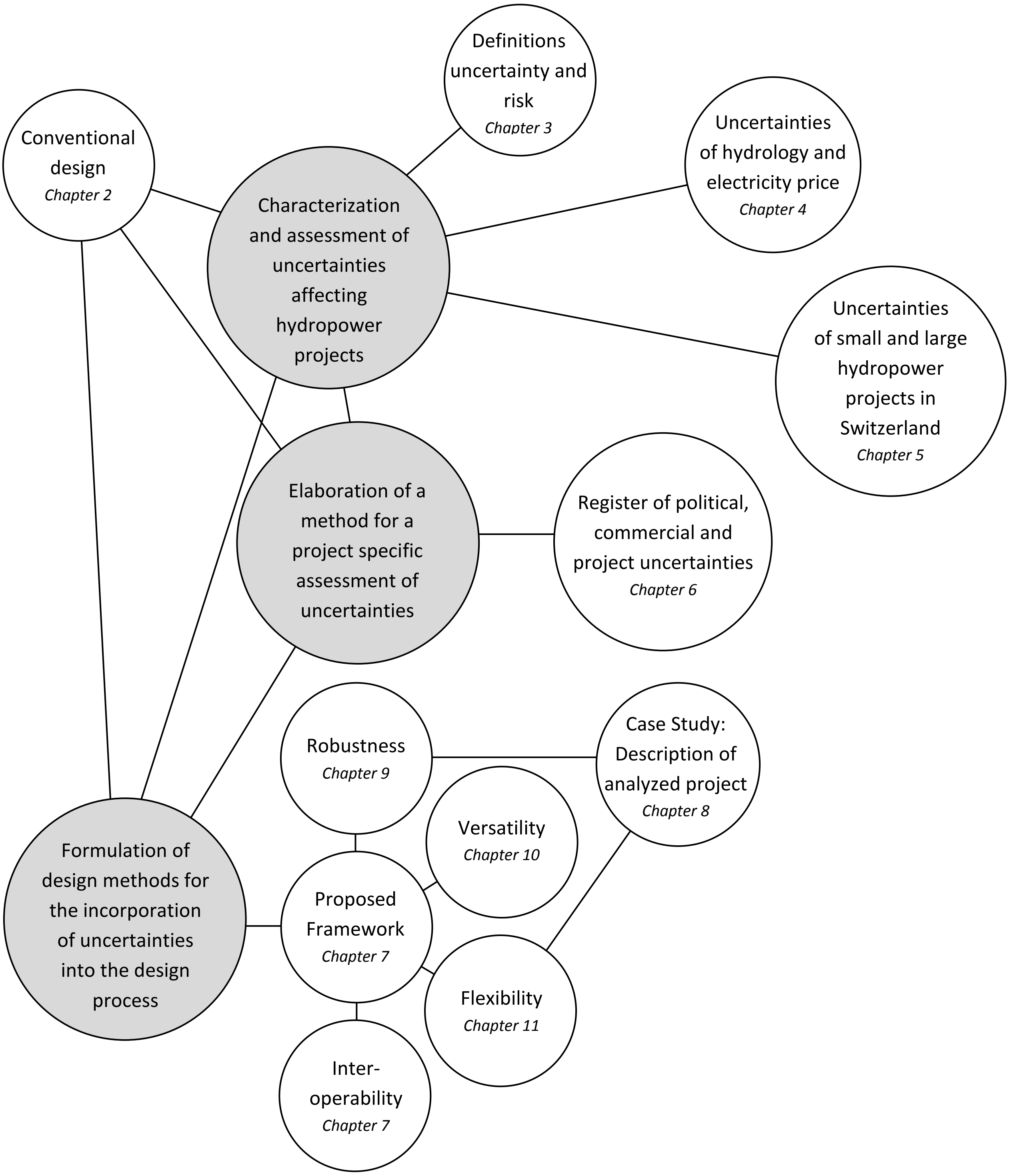

Figure 1: Sketch of thesis outline. Main research aims (grey bubbles), topics and chapters (white bubbles).

Chapter 6 presents the concept of a project-specific assessment. A project-specific assessment can be developed from a performance-oriented register of uncertainties. The register gives an overview on the wide field of uncertainties potentially affecting a hydropower project and can also be used as a basis for the preparation of project-specific assessments of uncertainties.

Chapter 7 describes the framework that is foreseen as guidance on the application of the different design methods considering long-term uncertainties. Design methods are organized and adapted to the design objective they are focused on. The framework makes a distinction between design methods that require structural modifications, on the one hand, and non-structural measures on the other.

Chapter 8 gives an overview of the hydropower project selected for the case study. Its main part describes the elaboration of the climate change projection required for the application of the different design methods.

Chapter 9 describes the design methods that are suggested in cases where robustness is selected as design objective. The Info-Gap Decision Theory and Robust Decision Making methods are introduced and applied to the case study.

Chapter 10 introduces a brief discussion of design objective versatility. Even though versatility was not applied in the case study, because it is not an adequate method in this case, a description is provided to give an overview on the different possible approaches.

Chapter 11 focuses on the methods and tools leading to a flexible system. Real Option Analysis and the more general approach of Flexible Design are described and finally it is shown how the Flexible Design was applied to the case study. The chapter concludes with the value and limitations of this approach.

Chapter 2 Design of Hydropower Plants

2.1 Introduction

The following chapter gives a short overview on the traditional approach of hydropower design with focus on the choice of plant size. The main parameters characterizing the size of a hydropower plant are installed capacity and active storage. The choice of these parameters is in general a process that covers several planning phases and considers various constraints. The plant size is selected based on economic performance parameters in consideration of the different constraints.

Finally, identified gaps in the traditional approach and key aspects characterizing the planning process of hydropower plants are described.

2.2 Conventional Design

Design procedures for hydropower engineers are described in several documents. Widely used are Wasserkraftanlagen (Giesecke and Mosonyi, 2005), Hydropower Development published by Norwegian Institute of Technology (1992), Economic and Environmental Principles and Guidelines for Water and Land Resources Implementation Studies (Water Resources Council, 1983) and by the US Corps of Engineers Planning Guidance Notebook, Engineering Circulars and Engineering Regulations (especially EM 1110-2-1701, 1985).

Hydropower project development starts with the identification of water–related needs and opportunities, followed by developing alternative plans that provide for those needs and opportunities, and by selecting the project alternative that most effectively and efficiently provides for the needs and opportunities (US Department of the Interior Bureau of Reclamation, 1987). Typical needs and opportunities, also known as purposes, are:

- Energy production: base load energy, peak energy, reserve energy
- Irrigation
- Industrial or municipal water supply
- Flood control.

The focus of this research work is on the selection of an adequate plant size. For international projects, the process for the selection of the best alternative and determination of the plant size covers in general the following planning phases:

- Master Plan: The master plan formulates a development plan for a basin and lists the various projects of the scheme in order of merit.
- Pre-Feasibility Study: The purpose of the prefeasibility study is, generally speaking, to establish a list of hydropower projects economically and technically feasible. It is basically a study of alternatives with the selection of the best-suited one, often preceded by an inventory of the master plan type.

- Feasibility Study: The feasibility study will comprise the optimization of the main parameters and the layout of the selected alternative. Its main objective is to prepare a full report containing sufficiently detailed information based on reliable field investigations, adequate for submission to international financial agencies for loan application.

Planning phases in Switzerland are slightly different in structure (SIA, 2014). Typically, the final plant size is selected in “Project Studies” (see Figure 2). The report and drawings prepared during this phase are used as a basis for the concession agreements and therefore design discharge and design water levels are contractually fixed.

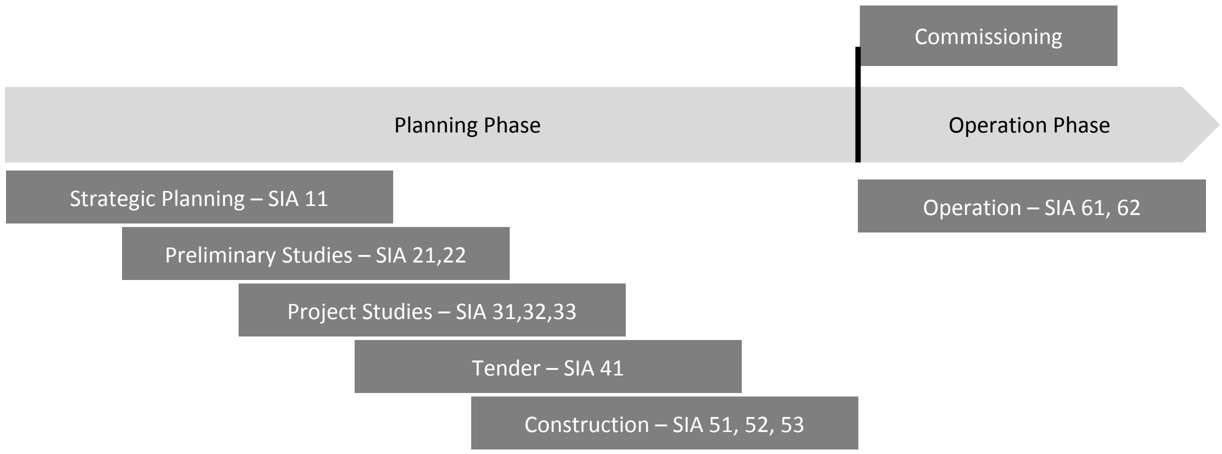

Figure 2: Planning phases in Switzerland

Before the plant size can be determined a stepwise project framing for the salient features of the project has to be carried out. Alternatives are evaluated based on engineering, power market, economic, hydrologic, environmental, and social conditions and criteria. For the selection of the alternatives, preliminary design and estimates must usually be elaborated before the most economical design can be selected.

In general, a number of alternative concepts such as the following are examined:

- Alternative project locations
- Alternative project configurations
- Alternative purposes (multi-purpose scheme, energy production)
- Alternative types of storage (seasonal, weekly, daily or run-of scheme)
- Alternative operation regimes (base load, peaking, reserve energy)
- Alternative dam sites
- Alternative dam heights
- Different dam types
- Alternative types of spillways
- Alternative power house locations
- Alternative types of power houses (underground, pitch, open ground)
- Alternative sizes and numbers of units
- Different waterway alignments
- Different types of waterway

During the planning phases, progressive refinements in technical, economic, environmental and social evaluations are carried out. Solid project development practices also include progressive re-examination.

The identification of needs and the selection of alternatives should be based on a comprehensive and participatory assessment (WCD, 2001). The WCD report mentions that unsatisfactory social outcomes of past dam projects are linked to cases where affected people played no role in the planning process. A transparent and participate approach can reduce conflicts and can increase public acceptability.

The IHA hydropower sustainability assessment protocol (IHA, 2011) shows the importance of a stakeholder engagement during the optimization process of a hydropower project. In a best case findings form directly affected stakeholders have been thoroughly and timely taken into consideration for the selection of alternatives.

An outcome of this typically long, resource-intensive and iterative process and, in good cases, participative and transparent process is the plant size as determined by active storage and installed capacity. Active storage and installed capacity are referred to as global design parameters.

Active Storage

According to the EM 1110-2-1701 (1985), active storage is defined as *the portion of the live storage capacity in which water normally will be stored or withdrawn for beneficial uses, in compliance with operating agreements or restrictions*.

In a first step, the constraints for the dam height in a specific location are defined. There can be physical (topography, geology), social or environmental as well as non-power operating constraints, such as flood control storage. The full supply level (FSL) of a specific active storage is then defined by deducting freeboard requirements and flood control storage requirements, if any. The minimum operation level (MOL) is defined by drawdown limitations, physical constraints, or non-power requirements. At a later stage, it is often related to tourism or environmental requirements.

Installed Capacity

The installed capacity is the sum of the rated capacities of all of the units in the power plant. The rated capacity of a unit is the capacity it is designed to deliver at a given head, discharge and efficiency. Sometimes the installed capacity is also known as nominal capacity (EM 1110-2-1701, 1985).

The installed capacity is calculated using the power equation:

$$P = \rho \cdot g \cdot \eta \cdot Q_d \cdot H_n \qquad (1)$$

where

P = power output of all units (installed capacity), W
ρ = density of water, kg/m^3
g = acceleration of gravity, m/s^2
η = overall efficiency of all units (including efficiency of turbines, generator, transformer)
Q_d = design discharge of power plant, m^3/s
H_n = net head, m.

2.2.1 Selection of Plant Size

Typically the selection of plant size consist of the following three main working steps, which are refined in each planning phase:

Definition of Needs

Generally, this study consist of a comparison between projected electricity supply and predicted demand. Typically, the analysis differentiates between annual energy demand, peak and off-peak energy for various months and reserve energy. Especially for smaller hydropower plants, the needs are defined on the basis of the national energy strategies (e.g. BFE, 2012)

Identification of Constraints

The identification of constraints is an ongoing process and typically several new constraints are identified during the planning phases up to the feasibility study. The most common constraints are listed below:

<u>Physical Constraints</u>

- Geological conditions of all project components (dam, reservoir, waterways, powerhouse)
- Topographical site conditions
- Technical constraints of project components (dam height depending on dam type, maximum turbine head, etc.)
- Sedimentation
- Limitation of access

<u>Environmental Constraints</u>

- Land use
- Resettlements
- Protected areas
- Cultural heritages
- Fish migration (limitations in dam height for fish migration facilities)

<u>Non-Power Operating Constraints</u>

- Minimum discharge requirements (ecological flow, tourism, river rafting etc.)
- Storage release schedule for downstream uses (navigation, irrigation, water supply, etc.)
- Flood control requirements

- Minimum reservoir elevation requirements for other purposes (tourism, navigation, irrigation, etc.)
- Maximum discharge limits to reduce the risk of bank erosion
- Limitation to do hydropeaking

Optimization of Plant Size

Energy production is simulated for a number of different active storages, alternative installed capacities and various operating patterns.

The range of installed capacity of run-of schemes is selected on the basis of typical figures of plant factor and usable inflow, characterized by the flow duration curve. The annual plant factor (PF_A) is given by the following function:

$$PF_A = \frac{P_A}{8760 \cdot IC} \tag{2}$$

where P_A is the average annual energy expressed in kWh and *IC* the installed capacity in kW. Often run-of schemes are optimized in the range of an exceedance probability of 10% to 40% and of a plant factor between 30% and 70%. In Switzerland about 75% of the run-of schemes have a plant factor between 30% and 70%.

For storage schemes the installed capacity depends significantly on the services to be provided. Most of the storage schemes have a plant factor between 10% and 40%. Seasonal, weekly and daily storages are analyzed, depending on the identified constraints and needs.

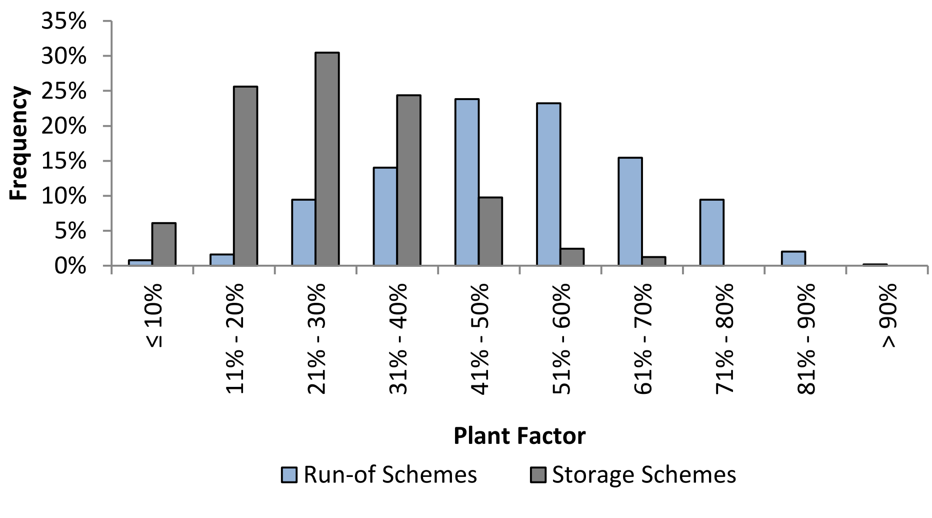

Figure 3: Frequency of plant factors of existing run-of schemes in Switzerland (run-of schemes: n = 499, storage schemes: n = 82, source of data: BFE, 2015)

For each alternative a preliminary design and a cost estimation are prepared. Based on these data, the economical key parameters are calculated and typically integrated in a multi-criteria analysis.

2.3 Performance Parameters

For the evaluation of project alternatives and optimization of the plant size, typically one of the following performance parameters is applied:

- Net Present Value (*NPV*)
- Levelized Cost of Electricity (*LCOE*), or
- Internal Rate of Return (*IRR*).

These parameters are used as monetizable attributes to evaluate the project performance over the life of the project and are calculated with a discounted cash flow model.

NPV is given by

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+i)^t} \tag{3}$$

where C_t is the net cash flow at time t, i is the discount rate, and T is the total number of time periods.

LCOE is calculated with the following formulas:

$$PV_{costs} = \sum_{t=0}^{T} \frac{CAPEX_t + OPEX_t}{(1+i)^t} \tag{4}$$

$$PV_{PA} = \sum_{t=0}^{T} \frac{P_{At}}{(1+i)^t} \tag{5}$$

$$LCOE = \frac{PV_{costs}}{PV_{PA}} \tag{6}$$

where PV_{costs} is the present value of the total costs; *CAPEX* (capital expenditure) is the investment cost; *OPEX* (operational expenditure) is the operation cost; i, t and T are defined as for equation (3); PV_{PA} is the present value of the total energy production, and P_A is the average annual energy production.

IRR is the annual discount rate at which the present worths of two streams of cash flow (positive and negative) are equal. That means the *NPV* equals zero (see equation 3). Generally, a project design with a higher IRR is preferred if the risks are similar.

For details on the application of hydropower projects, reference is made to Goldsmith (1993) and Malovic et al.(2015).

The traditional performance parameters, which are based on the Discounted Cash Flow (DCF) method, have clear advantages (see also Mun, 2002):

- Consistent decision criteria for all projects
- Same results independent of risk preferences of investors
- Quantitative
- Relatively simple
- Accepted and widely applied in the hydropower sector
- Transparent, simple to communicate to decision makers

However, the DCF has several disadvantages, which have been discussed in several articles and books (e.g. Mun, 2002; de Neufville and Scholtes, 2011).

For the sizing of plants in hydropower projects, especially the following shortcomings have to be mentioned.

Usually, the weighted average cost of capital (WACC) is applied for the discount rate. The WACC is defined as the after-tax weighted average of an investor's entire source of finance. All uncertainties or risks are accounted for by a constant WACC. The performance parameters are highly sensitive to WACC, and the effect is generally difficult to estimate. A small variation of the WACC can significantly change the results and affect the selected plant size. In addition, as uncertainties associated with a project may change during the course of a project, a constant WACC is questionable especially for projects with a very long economic lifetime, such as hydropower projects.

The results of a DCF are point estimates and ignore the variability of the input values of a hydropower project. All major input factors (e.g. energy production, electricity price, CAPEX) are associated with major uncertainties. Monte Carlo simulations taking into account relevant probabilities can be carried out. However, because of the complexity of a hydropower project and the difficulties to assess reliable probabilities, this approach is typically not applied to hydropower projects.

Furthermore, the DCF is not able to capture managerial flexibility (Trigeorgis, 1996). The DCF is based on the assumption that all and any decisions (including design decisions) are made right now. It neglects the possibility of design adjustments, i.e. the flexibility of a hydropower scheme.

2.4 Gaps of Conventional Design Strategy

The traditional engineering task is to optimize the hydropower plant so that it meets the forecasted scenario, followed by sensitivity analyses as a standard part of good engineering practice. Normally, scenarios involving variations of electricity price, inflow, WACC and construction costs are carried out to determine the effects of such changes.

There are numerous hydropower projects where the forecasts were not matching the effective values and where the plants did not reach the expected performance. Consequently, hydropower is strongly associated with risks and this makes many developers skeptical about hydropower. This is a major reason why some hydropower projects will never be constructed and thus unable to contribute to sustainable energy supply.

Whereas the standard procedure is mainly focused on financial and contractual risk management, opportunities to manage uncertainties via the technical design are mostly ignored.

2.5 Conclusions

Conventional hydropower design is characterized by the following key aspects:

- Determination of the global design parameters typically covers a long planning period with several planning phases
- Constraints are identified over several planning phases and take the findings of various technical disciplines into account
- A number of parties and stakeholders are participating during these planning phases
- Preliminary designs are prepared in order to provide an adequate basis for cost estimations
- Optimization studies are typically carried out for a limited range of installed capacity and active storage, as various constraints narrow the design range
- The best alternative is selected based on a performance parameter sometimes integrated in a multi-criteria analysis while taking physical and non-physical constraints into account
- Uncertainties are not directly integrated into the determination of the plant size.

Chapter 3 Uncertainties and Risks

3.1 Introduction

The focus of this research work is on uncertainties having a potentially significant impact on the performance of a hydropower plant.

To help to describe the uncertainties of hydropower projects, this work deliberately uses the four words risk, uncertainty, opportunity and threat. As these terms are not ordinarily part of the discourse of engineering with no unique definition being available, definitions are given below. In addition, Chapter 3.3 describes different methods to characterize uncertainties.

A special issue in large infrastructure projects is strategic misrepresentation and optimistic bias. These factors can significantly influence the accuracy of forecasts. One intention of this study is to provide a holistic view on uncertainties affecting hydropower projects, and to avoid a purely technical view; the concept of psychological and political-economic explanations for inaccurate forecasts is presented in Chapter 3.4.

Finally, the role of a project team involved in a hydropower project is discussed in respect to uncertainties.

3.2 The Terms Risk, Uncertainty, Opportunity and Threat

Risk and uncertainty are terms applied in a wide range of applications. The definitions vary not only by fields of application, but also from project to project. Also in the field of hydropower design there is no uniform or generally accepted understanding of the terms.

Some of the most recognized guides on project management published by the US Project Management Institute (PMI) and the UK Association for Project Management (APM) define the term 'risk' as follows:

Risk – an uncertain event or condition that, if it occurs, has a positive or negative effect on a project objective (PMI, 2000)

Risk – an uncertain event or set of circumstances that, should it occur, will have an effect on the achievement of the project's objectives (Simon et al., 1997)

These definitions refer to upside and downside effects and offer a broad view of possible effects on project objectives. The definitions include also opportunities or so called upside effects and thus are in line with the aim of the present study, which is to incorporate upside as well as downside effects into the design process.

However, as argued by Ward and Chapman (2003), the term risk is widely associated with adversity, implying that project risks are potential downside effects or, in the wording of Ward and Chapman, *"things that might go wrong".*

Also, in hydropower engineering the term risk is generally defined as potential adverse effects on project performance or failure of structures, for example seismic risk, flood risk, etc.

This is not limited to the engineering domain, but risk is typically associated with downside effects also by other stakeholders involved in hydropower projects. Politicians, financers, environmental experts, contractors, NGOs, affected local populations etc. often consider risks to be “things that might go wrong”. Environmental risks, financial risks, safety risks are clearly associated with hazard, bad consequences or loss. As several parties will become involved in the development of a hydropower project, it will be very difficult to avoid misunderstandings in terms of what a risk is and to the effect that risk is not associated with down-side effects only.

Because of this common understanding of the term risk in the hydropower community and among stakeholders, the term uncertainty is preferred over the term risk.

According to Ward and Chapman (2003), uncertainty is simply *lack of certainty*.

Uncertainty covers both tails of the distributions around engineering projects. Consequently, uncertainty can be either an opportunity for better project performance (upside effect) or a threat (downside effect).

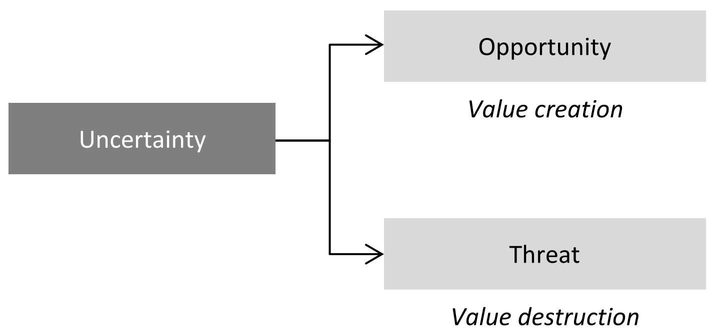

Figure 4: Uncertainty, opportunity and threat

As described by Van Asselt and Rotmans (2002) and Walker (2003), uncertainty can prevail in situations where a lot of information is available. It has to be noted that additional information or knowledge can either decrease or increase uncertainty. New knowledge on complex processes may illuminate that our understanding of such processes is even more limited or that such processes are even more complex than thought before.

3.3 Characterization of Uncertainties

Uncertainties affecting hydropower projects can cover the entire spectrum of levels from the unachievable ideal of complete deterministic understanding at one end of the scale to total ignorance at the other.

The terminology used to distinguish between the various levels of uncertainty described by Walker et al. (2003) is suitable also for hydropower projects.

One limit is the **determinism**, which is an ideal situation in which the knowledge is absolutely precise. No uncertainty exists, and the decision maker knows everything precisely.

Statistical uncertainty is uncertainty that can be quantified adequately in statistical terms. Phenomena described by statistical uncertainty require a reasonably good description of the process by a model and require the data applied for calibration to be representative of the circumstances for the selected application. One example of statistical uncertainty in hydropower projects is the uncertainty of short-term variation of the inflow. A stochastic model is used to measure the probabilities of uncertainty.

Scenario uncertainty refers to scenarios as a plausible description of how the system and/or its driving forces may develop in the future. Scenarios are usually applied to describe future conditions or processes and cover the range of possible outcomes. The main difference to statistical uncertainty is that it is questionable or impossible to formulate probabilities.

Typically, this group includes uncertainties that can be shaped by Design Methods. Long-term electricity price or inflow forecasts are generally described by scenarios.

Recognized ignorance is fundamental uncertainty about the functional relationships and the statistical properties. Because of the weak basic knowledge, no reliable scenarios can be developed. This category of uncertainty can further be divided into reducible ignorance and irreducible ignorance. Reducible ignorance can be resolved as example by getting additional knowledge by further research.

Recognized ignorance can be also described with the term of the “known unknown”.

Total ignorance is at the end of the scale and the contrary of determinism. It summarizes all phenomena that we do not even know that we do not know, i.e. the “unknown unknown”.

We even do not know the full extent of our ignorance, as indicated by the arrow in Figure 5.

Figure 5: The progressive transition between determinism and total ignorance
(Source: Walker et al., 2003)

Brown (2004) proposes a similar terminology for uncertainties as Walker et al (2003), but extended by additional criteria, namely if the uncertainties are bounded or unbounded (see Figure 6). For bounded uncertainty all possible outcomes are deemed known, whereas for unbounded uncertainty some or all possible outcomes are deemed unknown. Statistical uncertainties falls into the group of bounded uncertainty, as quantitative probabilities require a knowledge of all possible outcomes. If possible outcomes can be described, but no probabilities are known, uncertainties can be described by scenarios.

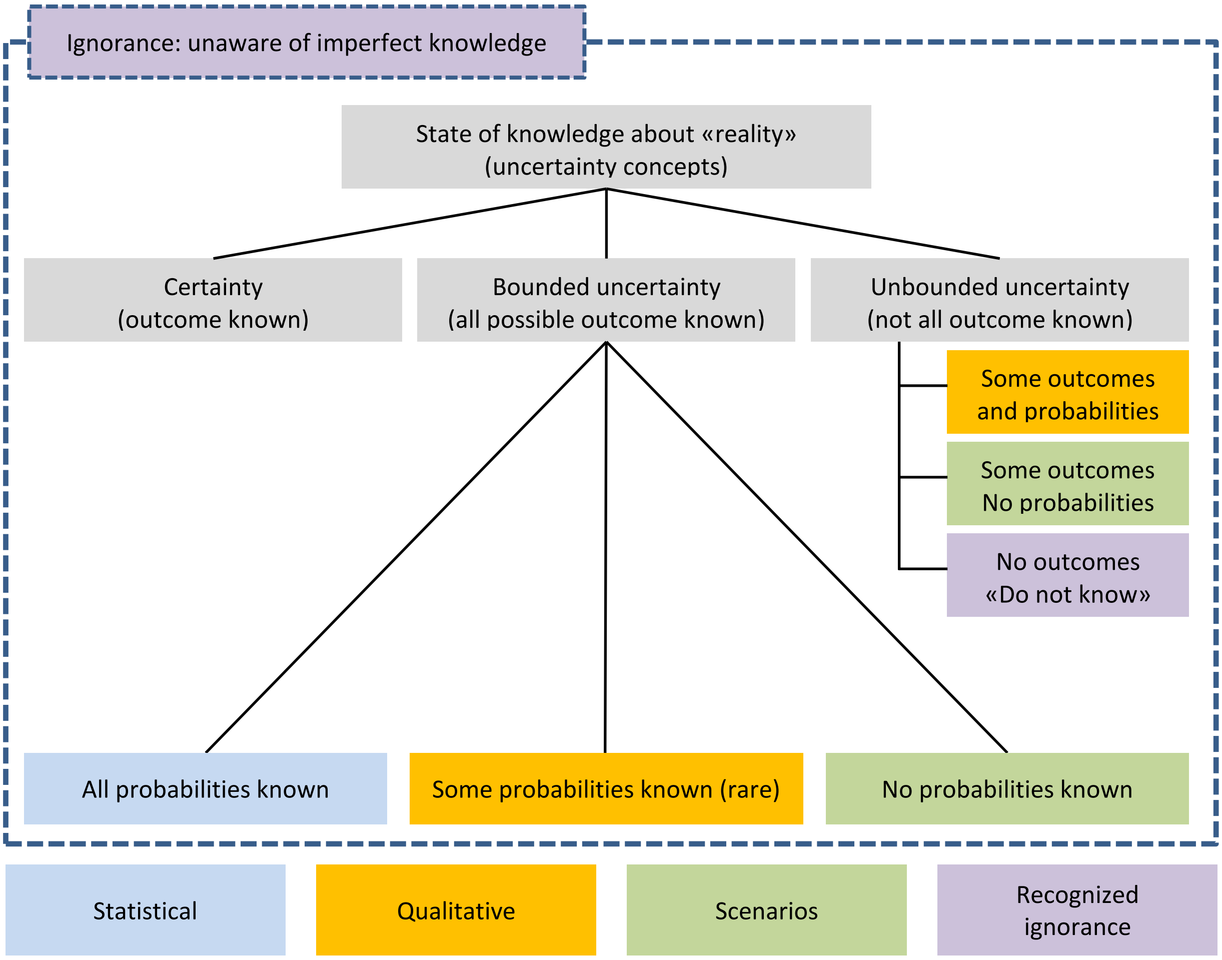

Figure 6: Taxonomy of imperfect knowledge resulting in different uncertainty situations (Brown, 2004)

3.3.1 Nature of Uncertainty

Walker et al. (2003) distinguish the nature of uncertainty into the following two categories:

- Epistemic uncertainty: Uncertainty from imperfect knowledge
- Stochastic uncertainty: Uncertainty due to inherent variability

Epistemic uncertainty can be reduced by additional studies, data collection etc., whereas stochastic uncertainty is non-reducible.

An essential point in measures for the exploration and mitigation of uncertainty is whether or not factors can be influenced by the project team. Therefore it is useful to distinguish uncertainty into the following categories:

- Exogenous uncertainty stems from factors or events outside of the control of the project team. Political and commercial uncertainties of hydropower projects are typical examples for this category. Typically, this category also includes certain project uncertainties like hydrological uncertainties.

- Endogenous uncertainty stems from factors or events that can be influenced by the project team. One example in the hydropower business is inadequate high-risk allocations at the contractor's site, which might lead to bankruptcy of the contractor. Another example is geological uncertainties some of which can be reduced by additional site investigations.

3.4 Inaccuracy of Forecast – Psychological and Political-Economic Explanations

Flyvbjerg documented in his work (2002, 2006) that large engineering projects have significant inaccuracy in forecast of costs, demand etc. Based on large data samples of projects, he argues that the main reasons for this inaccuracy are optimistic bias and strategic misrepresentation. These psychological and political-economic explanations much better account for inaccurate forecasts than technical explanations.

Technical explanations for forecasting errors, such as imperfect techniques, inadequate data, honest mistakes, inherent problems in predicting the future, lack of experience on part of forecasts, are not sufficient to explain biased errors in forecast.

Strategic misrepresentation summarizes the effect when forecasters and planners overestimate benefits and underestimate costs for strategic reasons in order to increase the likelihood of obtaining the necessary approval and funding for their projects.

Optimistic bias is a cognitive predisposition found with most people to judge future events in a more positive light than is warranted by actual experience.

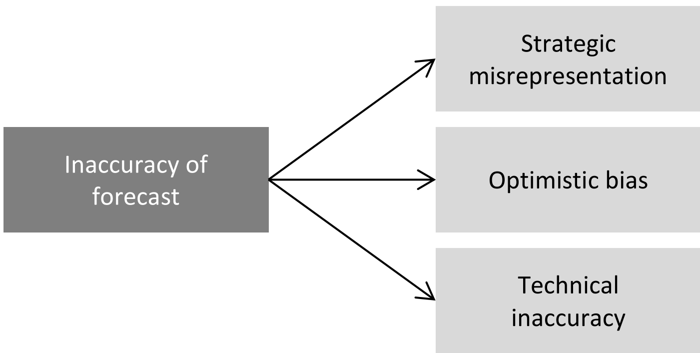

Figure 7: Inaccuracy of forecast

Ansar et al. (2014) applied the "outside view" to data of large hydropower projects and describe systematic cost underestimations. Strategic misrepresentation and optimistic bias are the explanations for these unexpected high cost overruns.

The "outside view" allows an estimation of uncertainties, including also psychological and political-economic effects. Therefore it is based on the assumption that the range of observed data is a reasonable proxy for the future, but this is not true for some of the factors influencing the performance of hydropower projects. Especially for uncertainties in terms of hydrology under the influence of climate change and electricity price, the historical observation cannot explain the full range of future scenarios.

Another disadvantage is that the “outside view” approach limits the possibility of analyzing the underlying causes and the relationships between uncertainties – a crucial condition for the application of exploration or mitigation measures.

3.5 The Project Team

The available knowledge and experience in a project team is an essential criterion for the description of uncertainties for a specific hydropower project. A project team, including developer, owner, owner’s engineer, contractors’ engineers, contractors etc., may not have or represent the full extent and current state of knowledge and experience in the field of hydropower or for a specific project. A gap might exist between the knowledge in the project team and the state of knowledge in relevant disciplines of hydropower projects. There may be a host of factors that are currently unknown in the project team but that would in fact be knowable, if the right resources and analyses were done.

Since the available information in a project team has a major influence on the extent of uncertainty, the categories of uncertainties have been extended by the concept of the known known, known unknown, unknown known and unknown unknown. This wording is from the Secretary of State Ronald Rumsfeld and it allows to distinguish the knowledge or competence of a project team.

A typical example is the unavailability of information on site-specific issues. Hydropower projects are often developed over several decades. The project team may change over such long periods with only part of the information being documented or otherwise available for the design team in a later design stage. This can lead to a gap between the theoretically available knowledge and the actually available knowledge in the project team and can be best described as the “unknown known”.

This may be an issue not only for projects with a long project development history. Projects with very limited resources can face similar issues. The limited engineering budget does not allow to incorporate all required technical disciplines and site investigation may be avoided, as is often the case at small hydropower projects. For example, an electrical engineer has to prepare the hydrological study which can lead to significant errors in the forecast, as he is not familiar with this discipline. The resulted uncertainties falls into the category of “unknown known”.

3.6 Conclusions

The main points described in this chapter are summarized as follows:

- As risk is typically associated with potential adverse effects in the hydropower community, the term of uncertainty is preferred over the term of risk.
- Uncertainty in this work covers both tails of the distributions around engineering projects (threat and opportunity) and is defined as *lack of certainty* (Ward and Chapman, 2003)
- Psychological and political-economic factors need to be taken into account for the analysis of inaccuracy forecasts in hydropower projects.
- For the characterization and assessment of the uncertainties of a specific hydropower project, it is necessary to consider the experience, knowledge and information available to

the project team, as they might not match with the state of knowledge in relevant disciplines of engineering.

Chapter 4 Uncertainties of Hydrology and Electricity Price

4.1 Introduction

Uncertainties in hydrology and electricity price are affecting several hydropower projects around the world. This chapter provides a description and outlines the possible magnitude of these uncertainties.

Climate change as one of the driving factors of hydrological uncertainties has been given a lot of attention during the last few decades of research. Therefore, this chapter includes a review and a retrospection on the accuracy of climate change forecasts.

The other factor described in this chapter is electricity price, regarding the current market situation and the main issues for deriving accurate forecasts. Retrospective analyses were carried out to indicate how accurate historical electricity price predictions have been.

4.2 Hydrological Uncertainty

In general, hydrological uncertainties affecting the performance of hydropower projects can be distinguished into the following categories:

- Flood damage during construction and operation phase
- Short-term variation of inflow
- Long-term variation of inflow

4.2.1 Flood Damage during Construction and Operation Phase

Flood damage during construction and operation phases can have a significant impact on the performance of a hydropower project. Delays during the construction phase are often related to problems with river diversion. In extreme cases, physical damage during the operation phase can even mean end of operations, i.e. end of asset lifetime. However, the management of these uncertainties is not related to global design parameter choices and thus is not considered in this study.

4.2.2 Short-term Variation of Inflow

The uncertainty of short-term inflow variation has typically two components: epistemic uncertainty and stochastic uncertainty. The epistemic uncertainty can be reduced by additional hydrometric measurements to prolong the available time series and thus improve the hydrological analysis or model. However, there will always remain the stochastic uncertainty, which is related to the stochastic and chaotic nature of rainfall-runoff process and weather phenomena.

The estimation of the short-term variation of inflow, including probabilities, can be integrated into the economic and financial analysis. Depending on the rate of return, it can have a significant impact on performance parameters, such as the NPV, by projecting occurrences of wet or dry periods after start of operation. The stochastic uncertainty and the impact can be estimated, but they cannot be reduced.

4.2.3 Long-term Variation of Inflow

Uncertainty of long-term hydrological forecast is the major source for the uncertainty of energy production forecast. Long-range planning hydrological forecasts for design purposes have typically been based on information from recent historical and observed data records (for example stream gauge evaporation pan, rainfall stations and so on). These assumptions are based on the premise that the range of observed supply variability is a reasonable proxy for future inflow possibilities.

In general, such hydrological forecasts include uncertainties that may stem from errors in the measured data, from interpretation of incomplete data, from errors and simplifications inherent in the hydrological model structure, and from errors and uncertainty due to the values of the model parameters (Refsgaard and Storm, 1990).

Another source of uncertainty is whether the climate of a reference period is still relevant at the time the hydropower plant is operated. This issue is getting more and more important in the light of climate change. The Intergovernmental Panel on Climate Change (2007) records that energy production and energy demand are especially sensitive to climate change.

Many research projects from all over the world have shown an effect of possible climate change on hydropower production. The following summary gives first examples from studies outside Switzerland, then followed by research in Switzerland.

The Hydklima research project prepared for Austria (Nachtnebel and Fuchs, 2001) describes a decrease in annual discharge, but lower seasonal fluctuation of discharge, which partly compensates for the lower inflow to hydropower plants. Atsushi (2007) indicates for three cases studied in India, Sri Lanka and Vietnam that the climate change will significantly change water inflow during dry years. As a consequence, it is proposed to increase the installed capacity and the storage capacity. In the US, a change in water availability and inflow fluctuations, particularly in snowmelt-dominated basins where impacts have already been reported, can be expected (Hamlet et al., 2002; California Energy Commission, 2005; Northwest Power Conservation Council, 2005). Hydropower production at facilities that are operated to meet multiple objectives (for example flood-risk reduction, irrigation, municipal and industrial water supply, navigation, in-stream flow augmentation and water quality) may be especially vulnerable to climate change (USGS et al., 2009).

The report prepared by Hänggi and Plattner (2009) summarizes the research on climate change and hydropower in Switzerland. The study highlights that the forecasted impact of the climate change on hydropower, especially in the Alps, is uncertain and has been frequently changed over the last few years. The forecasts of the year 2000 estimated an increase in precipitation in Switzerland due to climate change. For example, a 26% increase in energy production was simulated for the Grande Dixence hydropower plant for the period from 2031 to 2060 (Westaway, 2000). In 2002, the OcCC projected an increase in precipitation based on the third report of IPCC (2001). A trend towards lower precipitation during the summer and higher precipitation during the winter along with higher annual fluctuations was estimated. Simulations show an increase in annual precipitation by about 10% for the North part of the Alps and a decrease by about 10% for the South part for the year 2050. The impacts on the energy production of hydropower plants were controversially evaluated (ProClim, 2003). In 2004, new studies estimated a decrease in total precipitation for Switzerland (Frei, 2004). Those studies were based on a new generation of global and regional climate models (Christensen et al., 2002). As a consequence of the decrease of precipitation, forecasts predicted a decrease by around 7% of the mean discharge in the Alps for 2050 (Horton et al., 2005). Calculations projected a reduction of the energy output from hydropower (OcCC, 2007; BAFU and BFE, 2007). The significance of the forecasted reduction of energy production can be seen in the example of Mauvoisin. For the period from 2070 to 2099, a decrease in energy production by 36% was estimated (Schäfli et al., 2007).

A summary study presented in 2011 (SGHL and CHy) assesses a slight decrease in annual discharge in Ticino and in South Wallis until 2100, whereas no significant change of the discharge situation is estimated in the North Alps of Switzerland.

The above retrospection on forecasts of climate change and hydropower in Switzerland shows a shift from an increase to a decrease and finally to no significant changes of water availability within a research period of about 10 years.

Also, the comparison of different projections based on different climate scenarios underlines a high level of uncertainties. A summary is presented in Table 1.

The ranges of projection for most of the catchments are large. It should be noted that these uncertainties do not include uncertainties stemming from errors in the measured data, interpretation of incomplete data, errors and simplifications inherent in the model structure and errors and uncertainty due to the values of the model parameters. Taking also these uncertainties into account, it can be concluded that uncertainties can easily reach about 20%.

Whereas there is not a predominant cause for changes in hydrological regimes in Switzerland, the situation is different for certain international hydropower projects where changes in land-use practice can influence the hydrological regime. Population pressures can lead to more settlements, deforestation, change in agricultural practice, which can finally affect the runoff of a catchment. A long-term assessment of land-use changes is typically highly uncertain.

Table 1: Range of projection of annual discharge for various catchments in Switzerland simulated with various climate scenarios and models.

Study	River	Change of Annual Discharge	Range of Projections
Hänggi et al., 2011a	Löntsch	0% to +6%	6%
Hänggi et al., 2011b	Dischmabach-Davos, Kriegsmatte	-5% to +4%	9%
Hänggi et al., 2011b	Landquart-Klosters, Auelti	+4% to +12%	8%
Hänggi et al., 2011b	Mönchalpbach-Trittwald	-4% to +3%	7%
Hänggi et al., 2011b	Stützbach-Davos	-19% to -4%	15%
Hänggi et al., 2011b	Taschinasbach-Grüsch	-14% to -1%	13%
WSL and SLF, 2011	HPP Göscheneralp	-2% to +23%	25%
WSL, 2011a	HPP Gougra	+4% to +12%	8%
WSL, 2011c	HPPs Oberhasli	0% to +6%	6%
WSL, 2011b	HPP Mattmark	+1% to +11%	10%

4.2.4 Climatic Changes in the Last Decades

Hänggi and Weingartner (2012) discuss the climatic variation over the last century and its impact on the water available for hydropower production in Switzerland. Flow duration curves (FDC) of various runoff regimes and record periods were analyzed. Based on virtual intakes located all over Switzerland, the study shows that the warming and the increase in winter precipitation over the last century have influenced the available water volumes for hydropower production. The highest variations in discharge volumes were found in glaciated catchments of the Swiss Alps. The study comes to the general conclusion that the climatic changes have given rise to more balanced discharge regimes, resulting in higher energy production.

For most run-of hydropower schemes, the design discharge is selected on the basis of the FDC. As mentioned for run-of schemes in Chapter 2.2.1, the installed capacity is typically optimized for a discharge exceeding the duration curve between 10% (Q_{10}) and 40% (Q_{40}).

The data presented by Hänggi et al. show a significant uncertainty for the selection of a design discharge. Depending on the catchment and the period of record, Q_{10} and Q_{40} are differing significantly (Q_{10} ±30%, Q_{40} ±30%) compared with the reference period 1995-2009.

The study also shows a significant variation of the available water volume for hydropower generation depending on the period of record.

4.2.5 Conclusions

The main findings of this literature review are as follows:

- Uncertainties in hydrology have different sources such as measured data, interpretation of incomplete data, hydrological model structure, or climate change.

- The retrospection on past climate change projections in Switzerland underlines the generally high uncertainties of long-term hydrological estimates.
- Previous impact studies of climate change for hydropower plants in Switzerland indicate a range of climate projection up to about 25% of the annual discharge (see Chapter 4.2.3).
- Also, in the last decades, the available water volume for hydropower generation showed significant variation in some of the Swiss catchments (see Chapter 4.2.4).

4.3 Electricity Price

Electricity prices have a direct impact on the performance parameters and are therefore the basis for design and investment decisions. The time frame generally covers the entire economic lifetime of a hydropower plant, which ranges between 25 and 80 years.

Compared with other industries, the turnover of hydropower projects is very slow. Starting from a conceptual design, it can take years or even decades until the power plant finally starts to operate. That means that major decisions have to be based on long-term forecasts, not only because of the long economic lifetime, but also because of the long pre-construction phase. This increases the uncertainties of forecasts significantly.

Decisions on the active storage capacity and the installed capacity depend mainly on the forecast of peak and off-peak energy. In addition, hydropower plants are also designed to contribute to the stability of the grid. This aspect is getting more and more important in order to compensate the highly fluctuating production rates from renewables such as wind and solar.

Long-term electricity price forecasts differ from medium or short-term forecasts. Medium-term forecasts have a time horizon from a few days to a few months ahead and are often used for balance sheet calculations, risk management and derivatives pricing. Short-term electricity price modes are generally focused on short periods from a few minutes up to a few days ahead and thus are of importance in day-to-day market operations (Weron, 2014). As short and medium-term forecasts are not relevant for design decisions regarding global design parameters, these groups of models are not further discussed.

Craig et al. (2002) categorize the most-used long-term forecasting methodologies into six groups: trend projections, econometric projections, end-use analysis, combined approaches, systems dynamics, and scenario analysis.

However, regardless of which type of long-term forecast model is applied, the main questions for the design of hydropower projects are: How wrong are electricity price forecasts? What is the consequence if the forecast is wrong, or, in other words, how does it influence the design decisions?

Smil (2005) discusses various forecasts of energy affairs over a period of more than 100 years and concludes that they are "*a manifest record of failure*" and that "*we should abandon all detailed quantitative point forecasts*".

Also, other authors have tested the accuracy of energy forecasts. O'Neill and Desai (2005) assessed the accuracy of predictions of US energy consumptions produced by the Energy Information

Administration (EIA) over the period 1982-2000. For a projection horizon of 10-13 years, the average error is about 4%. Also, Winebrake and Sakva (2006) explore the forecast accuracy of predictions of the energy consumption based on the data from EIA covering the period between 1982 and 2003. For 10-year forecasts of energy consumption, they highlight a mean percentage error of 4.86%. The errors vary significantly over the analyzed energy sectors (commercial, industrial, residential, and transportation).

4.3.1 Liberalized Market

Deregulation of the electricity industry came on the political agenda in many countries around the world in the late 1980s and early 1990s. In Switzerland, partial liberalization started in 2009. Customers that consume more than 100'000 kWh/year have the option either to choose their supplier or to remain within the scope of the basic provision mandate. Full liberalization of the electricity market is planned for 2018, subject to a referendum by the Swiss population.

Due to the liberalization of the electricity market, electricity suppliers are faced with an increasingly complex situation marked by increased uncertainties.

Before liberalization of the energy market, the relative security in the market outlets and the price stability made it possible to make decisions with fuel price and demand level as sole uncertainties. Liberalization of the markets has increased the sources of uncertainty (see Figure 8). In particular, when making their investment choices, electricity suppliers face market uncertainties (future demand, supply and prices) and regulatory uncertainties (lack of visibility on the future legal environment controlling the electricity generation activity). All factors that affect supply and demand have an immediate impact on the electricity price. A major influence factor on the supply side is fuel prices (coal, gas, oil).

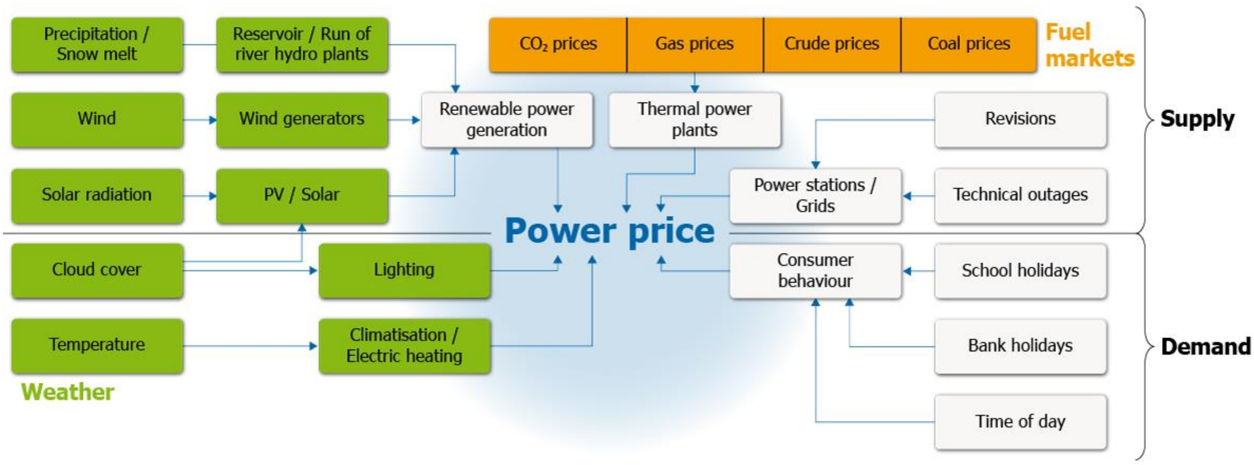

Figure 8: Factors influencing the electricity price (Source RWE, 2015)

Long-term electricity price models generally assume a gradual variation in process relationships. However, the real world is rife with discontinuities and disruptive events, and the longer the frame of the forecast, the more likely it is that pivotal events will change the underlying economic and relationships that all models attempt to replicate (Craig et al. 2002).

Smil (2005) provides a long list of examples of unpredictable events capable to influence significantly the energy market. Some examples from the recent history in Switzerland can be added. The impacts of the Fukushima nuclear accident on European energy policy, the substitution politics for wind and solar, or the development of Swiss energy market liberalization were difficult or impossible to predict.

4.3.2 Retrospective Electricity Price Forecasts – AEO, US

The following section shows a review of long-run forecasts of electricity prices for the US market. The analysis gives some evidence on the forecast error of electricity price prediction.

The U.S. Energy Information Administration (EIA) prepares forecasts of electricity price, energy production and energy consumption each year and presents the results in the Annual Energy Outlook (AEO). In addition, a review report is issued each year to show the relationship between past reference case projections and actual energy indicators. Figure 9 shows the actual electricity price and the projected values from 1993 until 2013. The electricity prices were almost always underestimated from 1998 on. The report gives an underestimation of pre-2009 natural gas prices and of coal prices as the main reasons for the underestimation of the electricity price (EIA, 2015).

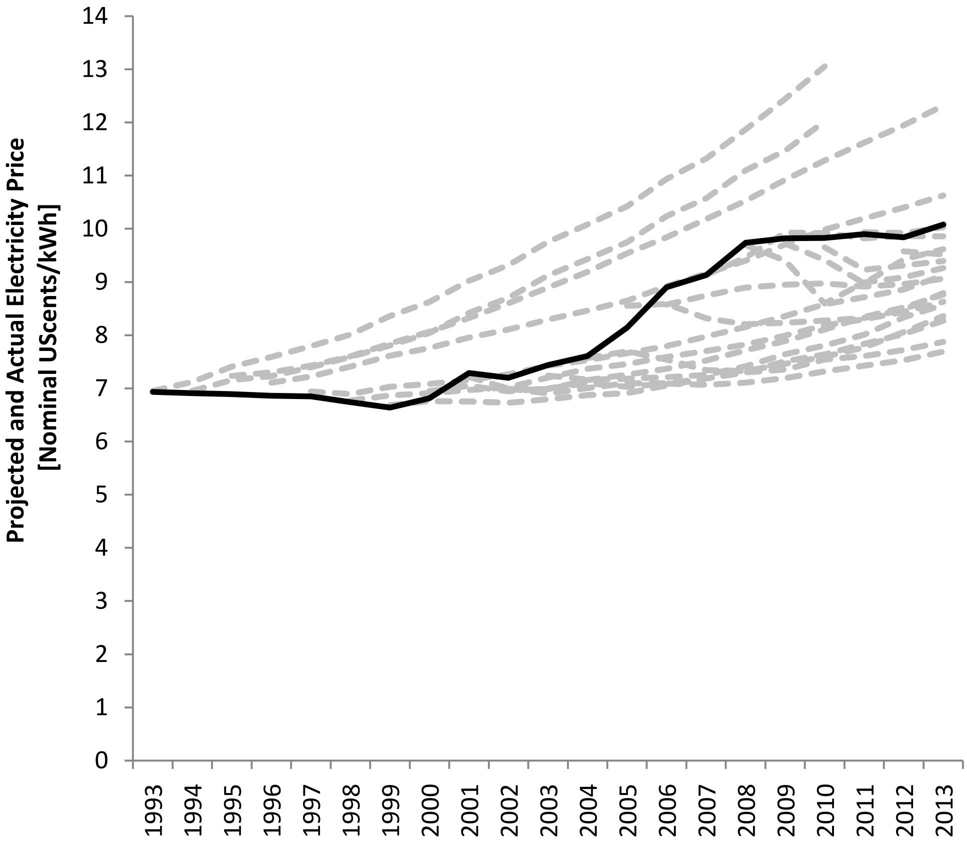

Figure 9: Projected (dashed line) and actual electricity price (continues line), data published by EIA, 2015

The works by O'Neill and Desai (2005) as well as by Winebrake and Sakva (2005) have focused on the errors of energy consumption predictions, whereas our interest lies in the accuracy of electricity price forecasts. Similar to above quoted studies, we applied an error decomposition technique to analyze the electricity price predictions. The difference between the projected electricity price and the actual electricity price was analyzed and characterized by the mean percentage error (MPE) and mean absolute percentage error (MAPE). The definitions and formulas applied in our work are based on the work of Winebrake and Sakva (2005) and are as follows:

Mean percentage error (MPE) is an average error of all electricity price forecasts of a given forecast horizon. MPE is given by the function:

$$MPE_{\tau} = \frac{\sum_t \frac{(\hat{Y}_{t,\tau} - Y_{t,\tau})}{Y_{t,\tau}}}{n_{\tau}} \quad (7)$$

Where τ is the forecast horizon (1 year, 2years … x years); t is the year in which the forecast was published; $\hat{Y}_{t,\tau}$ is the predicted electricity price for period τ published in the year t; $Y_{t,\tau}$ is the actual value of the electricity price for period τ and year of AEO publication t; and n_{τ} is the number of predictions with the time horizon τ.

An MPE greater than 0 means that the electricity price was overestimated. If MPE < 0, then the predicted electricity price was less than the actual value. However, a figure close to 0 does not necessarily indicate that the forecast is highly confident over the complete period. It might be caused by a combination of a period with overestimation and a period of underestimation. To avoid such misinterpretations, also the mean absolute percentage error (MAPE) has been calculated, given by the following function:

$$MAPE_{\tau} = \frac{\left| \sum_t \frac{(\hat{Y}_{t,\tau} - Y_{t,\tau})}{Y_{t,\tau}} \right|}{n_{\tau}} \quad (8)$$

where the variables and indices are the same as defined for the MPE.

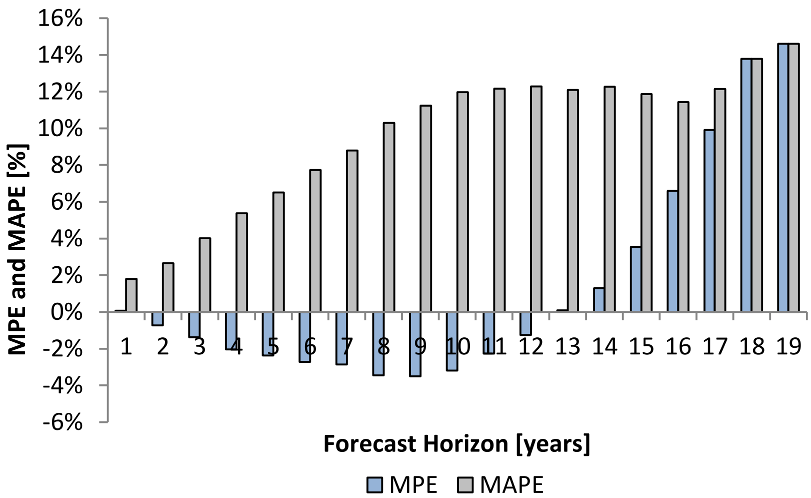

Figure 10: Mean percentage error (MPE) and mean absolute percentage error (MAPE), AEO U.S.

Table 2: Mean percentage error (MPE) and mean absolute percentage error (MAPE) for forecast horizons up to 19 years

Forecast horizon (years)	1	2	3	4	5	6	7	8	9	10
Number of observations	21	20	19	18	17	16	15	14	13	12
MPE	0.1%	-0.7%	-1.4%	-2.0%	-2.4%	-2.7%	-2.9%	-3.5%	-3.5%	-3.2%
MAPE	1.8%	2.7%	4.0%	5.4%	6.5%	7.7%	8.8%	10.3%	11.2%	12.0%

Forecast horizon (years)	11	12	13	14	15	16	17	18	19
Number of observations	11	10	9	8	7	6	5	3	1
MPE	-2.3%	-1.2%	0.1%	1.3%	3.5%	6.6%	9.9%	13.8%	14.6%
MAPE	12.2%	12.3%	12.1%	12.3%	11.9%	11.4%	12.1%	13.8%	14.6%

The MPE and MAPE of the electricity price forecasts show the range of forecast error up to a time horizon of 19 years. For forecast horizons up to 15 years, the MPE was below 5%. However, the MAPE shows already a strong increase up to about 12%.

For the forecasts with a time horizon of more than 15 years, the MPE increases significantly to about 14.6%. Is has to be noted, however, that because of the limited number of observations, confidence is low.

4.3.3 Electricity Price Forecasts in Switzerland

In Switzerland, there are no periodically published long-term electricity price predictions, as for example for the US market. The focus of publicly available energy predictions over the last few decades has been on *explorative* scenarios rather than on forecasts (see also Dolecek, 2004). An explorative scenario investigates the question: What can happen? Explorative scenarios can be distinguished into external scenarios and strategic scenarios. External scenarios are driven by external factors, which cannot be influenced. Strategic scenarios are based mainly on internal factors, answering the question: What can happen if we act in a certain way? The aim of explorative scenarios is to explore developments that are regarded as possible to happen. Typically, a set of scenarios is elaborated, covering a wide scope of plausible developments. Explorative scenarios are focusing on the long time horizon and can allow profound system changes (Börjeson et al., 2006).

The working group “Energie Trialog” summarized various scenarios. Figure 11 illustrates the explorative scenarios of energy consumptions developed before 2007. The comparison of the energy consumption scenarios shows a high variability ranging from a significant decrease (Greenpeace et al. 2006) to a significant increase (Axpo Hoch).

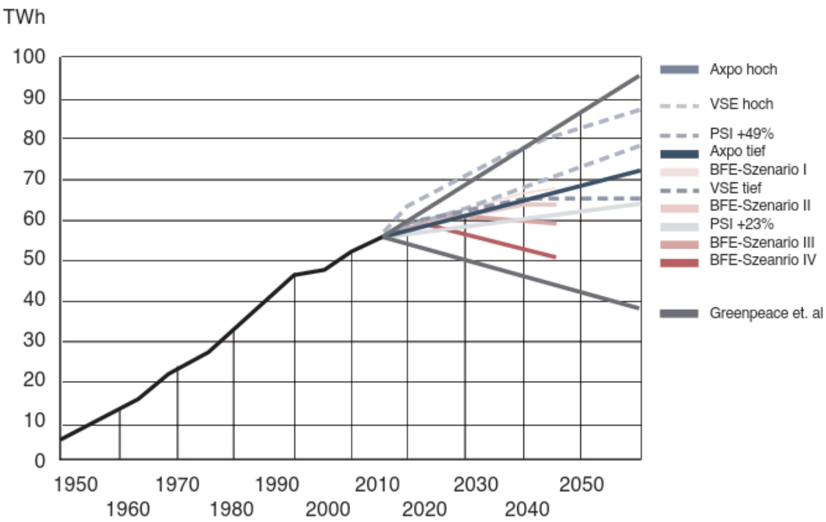

Figure 11: Overview on energy consumption scenarios in Switzerland until 2050 (Sources energy consumption scenarios: BFE 2007c, PSI 2007, Axpo 2005, VSE 2006, Greenpeace et al., 2006) (Source of Plot: Energie Trialog Schweiz, 2009)

Also other summary studies (e.g. Dolecek, 2004) show that energy scenarios for Switzerland cover a very wide range and highlight the high uncertainty.

4.3.4 Long-term Electricity Price Scenarios for Switzerland – An Example

An example of a long-term energy scenario covering the period between 2015 and 2050 can be found in Pöyry (2012). The study aims to analyze three questions: (i) the need of flexible energy production capacity, (ii) the interdependence of demand and supply of flexible energy and security of energy supply, (iii) the influence flexibility has on the electricity prices. The study includes three main scenarios, which make different assumptions in terms of energy demand and development of renewable energy capacity.

Figure 12 shows the actual electricity price and the projected values for each scenario. The year the prediction was made was 2012. For the year 2015, the actual electricity price was overestimated between 46% and 54%, depending on the scenarios.

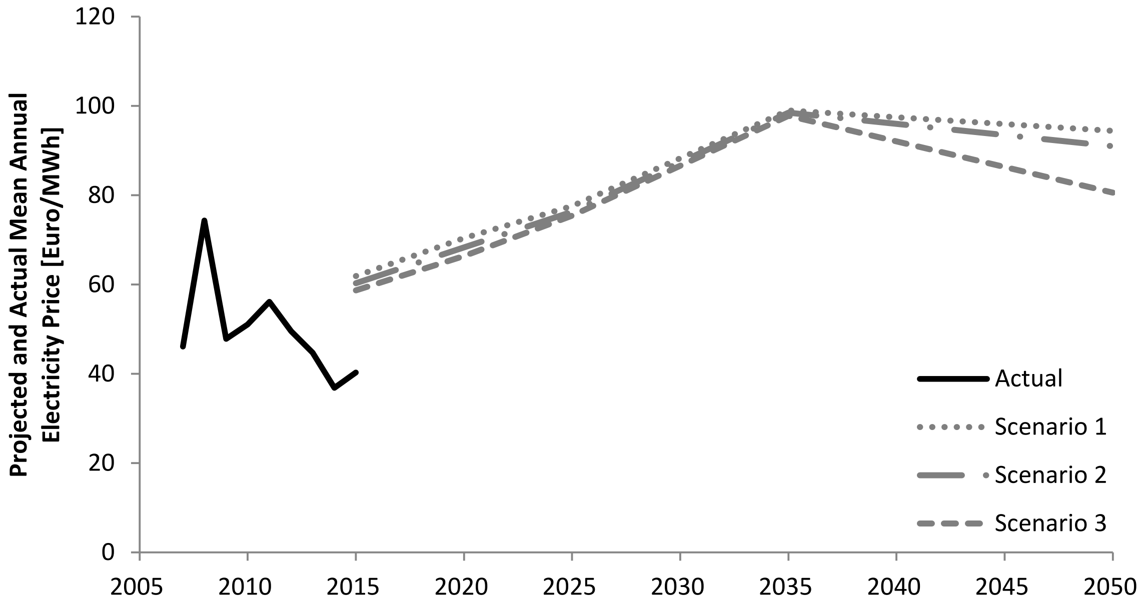

Figure 12: Projected (dashed line) and actual spot market electricity price (black line), Switzerland, data source Pöyry (2012)

4.3.5 Retrospective Electricity Price Forecasts – Switzerland

For the design of larger hydropower projects, electricity price forecasts are typically specifically prepared. In most projects a forecast is prepared during the feasibility stage.

To provide an indication of the forecast error of such electricity price prediction in Switzerland, historical electricity price forecasts until 2015 had been collected and analyzed. The data was provided by a major Swiss energy utility. The source of data is confidential, as major business decisions have been based on this information.

Figure 9 shows the actual electricity price and the projected values from 2010 until 2015. Annual forecasts, excluding 2012, were prepared. The development of the electricity prices was always significantly overestimated.

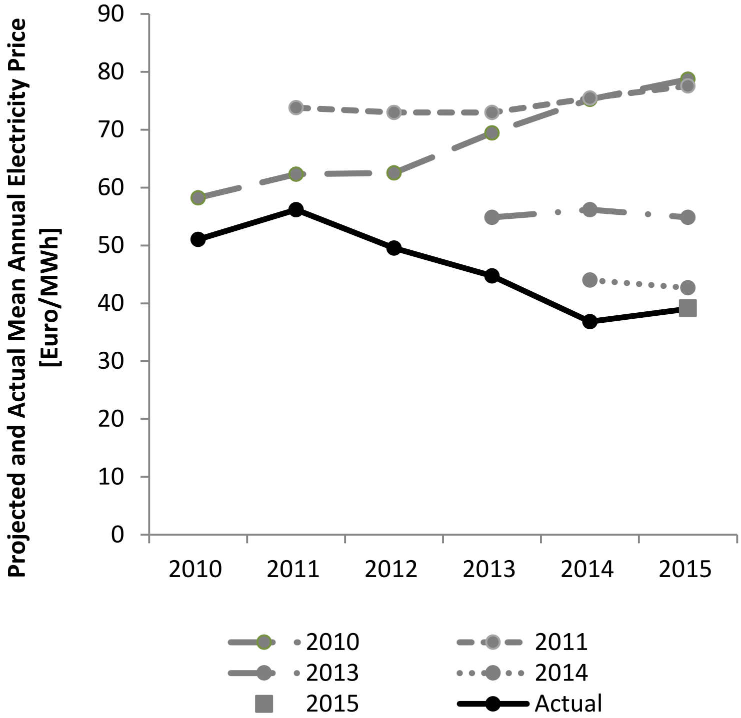

Figure 13: Projected (dashed line) and actual spot market electricity price (black line), Switzerland, data source: confidential

The MPE and MAPE were calculated based on equations (7) and (8), respectively (see Table 3).

The MPE and MAPE of the electricity price forecasts show the range of forecast error for a time horizon of up to 6 years. The MPE was about 60% for said time horizon and equal to the MAPE over the complete period.

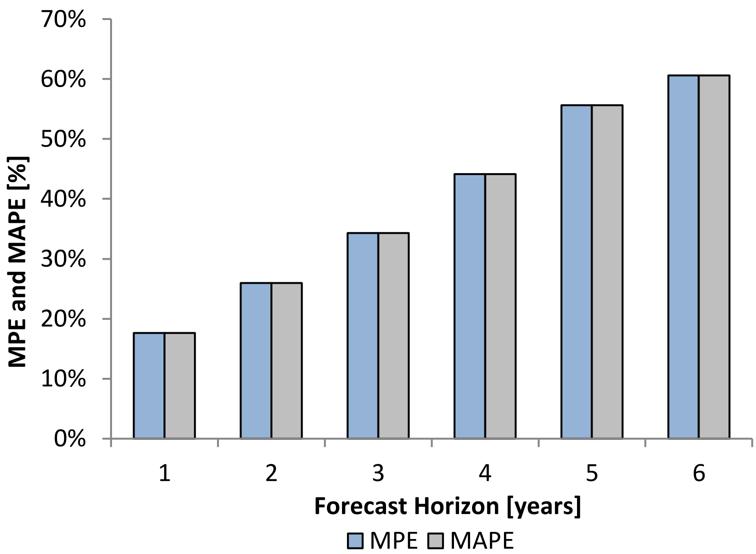

Figure 14: Mean percentage error (MPE) and mean absolute percentage error (MAPE)

Table 3: Mean percentage error (MPE) and mean absolute percentage error (MAPE)for forecast horizons up to 6 years

Forecast horizon (years)	1	2	3	4	5	6
Number of observations	5	4	3	2	2	2
MPE	17.6%	26.0%	34.3%	44.2%	55.7%	60.6%
MAPE	17.6%	26.0%	34.3%	44.2%	55.7%	60.6%

Confidence is limited by the low number of observation. Also, it has to be noted that the time period (2010-2015) followed an electricity price peak in 2008. The analysis of the range of error of long-term electricity price forecasts could be supported by taking into account additional forecasts from different institutes and covering a longer time horizon. However, this data could not be made available for this research work.

4.3.6 Conclusions

In the complex context of a liberalized market, not only the forecasts are becoming less reliable, but there are also limited management possibilities to compensate wrong or non-optimal decisions. A design error or a wrong investment decision in a liberalized market can have much greater impact on a company's electricity trading business than in a monopoly. In the case of a monopolistic situation, an unpredictable situation could be compensated by an increase in rates to match real costs, while in a competitive environment, this would result in a loss that would endanger the durability of the company, or at least reduce the cost effectiveness of a project (Gollier et al., 2005).

In terms of electricity price forecasts, the following conclusions are made:

- Hydropower design requires forecasts covering a time period in a range from 25 to 80 years.
- The most sensitive time period for performance parameters (NPV) are the first years of operation, even when assuming relatively low discount rates. However, as the sole pre-construction period can cover several years, also the predictions for this periods are subject to large errors.
- For hydropower design, it is necessary to have forecasts of peak, off-peak or even reserve energy prices to make decisions on active storage and installed capacity.
- There is increased uncertainty in a liberalized market. Unpredictable events can have major impacts on the electricity price.
- The analysis of the AEO forecasts indicates that the MPE for a forecast horizon of about 20 years is about 15%.
- Electricity price scenarios are typically explorative scenarios and are published without information on likelihood and probability.
- The analysis of forecasts for Switzerland indicates an MPE of 60% for a mid-term forecast horizon of 6 years.

Chapter 5 Uncertainties of Small and Large Hydropower Projects in Switzerland

5.1 Introduction

Recent publications have shown a dramatic cost overrun in large hydropower schemes (e.g. Ansar et al., 2014; Sovacool et al., 2014). These unexpected high cost overruns support the current trend of preferring small hydropower plants over large-scale schemes. A general assumption is that the risk associated with small plants is much lower compared with large hydropower projects. Policy makers, developers and especially NGOs and various other environmental organizations are often following the principle of “small is beautiful”.

In addition, various publications from research groups give support to this assumption. Ansar et al. (2014) argue that more numerous small hydropower projects are more prudent than large or megaprojects from the perspective of risk management. Dursun and Gokcol (2011) assume that large dams have become much riskier investments, while there still remains much unexploited potential for small hydro projects around the world. Sovacool et al. (2014) argue that smaller, decentralized, modular, scalable systems have less cost overruns in terms of frequency and magnitude. Flyvbjerg et al. (2004) summarize that research literature and media occasionally claim that the track record for infrastructure projects is poorer for larger projects than for smaller ones and that cost overruns are higher and more frequent for large projects.

On the other hand, several countries have introduced incentive programs to stimulate an increase of electricity production from small hydropower plants. The introduction of such supporting systems has led to a revival of small hydropower plants, which are in general defined as plants with an installed capacity up to 10 MW, over the last decade.

Most European countries (CH, BG, CZ, DE, EE, ES, FR, GR, HU, IE, IT, LT, LU, LV, PT, SK, UK and AT until 2010) opted for the feed-in tariff as supporting system. The feed-in tariff guarantees the producer a certain energy price. The tariff is fixed over a long period of time, commonly 20 years, and therefore excludes the uncertainties of energy price fluctuations for the investors (see also ESHA, 2012). In general, the feed-in tariffs are significantly higher than the market price.

The effect of this supporting system is that currently about 46 TWh/year are produced by small hydropower plants in the EU-27. This is a share of about 8% in the renewable energy mix. Further expansion is foreseen in several European countries such as Austria, France, Italy, Spain, Portugal, Romania, Greece or Poland (ESHA, 2012).

Also in Switzerland the feed-in tariff was introduced to push small hydropower projects. Before the feed-in tariff was launched in 2008, about 1’000 small hydropower plants with a total annual production of about 3400 GWh were in operation (Hirschberg et al., 2005). The supporting system led to more new developments and increased rehabilitation of existing plants. Recent figures (2015) show that 401 small hydropower plants were commissioned after 2008. The total production of these schemes in 2015 was about 877 GWh, which is share of about 2% of the total hydropower production in Switzerland (2015: 39’486 GWh).

Small hydropower is intended to play a significant role for the future development of renewable energy sources in Switzerland. According to the Energy Strategy 2050 (BFE, 2012), it is planned to be one of the major sources of the additional renewable energy. The Energy Strategy 2050 identifies the increase of hydropower production: by 1.53 TWh/a under actual conditions and by 3.16 TWh/a under improved conditions. The largest portion is intended to be covered by small hydropower plants (1.29 TWh/a under actual conditions, 1.60 TWh/a under improved conditions).

Small hydropower projects have been intensively supported by feed-in tariffs in many countries over the last few years without any systematic analysis of uncertainties and with surprisingly little attention being paid to comparing the uncertainties of large and small hydropower schemes.

In addition, most previous studies focused on the performance of construction cost estimates only. The uncertainties of energy production were not included. As energy production, in addition to the costs of construction, is another main factor influencing the economic performance of a hydropower project, we included this factor as well in our analysis.

A focal point of this study is to analyze the uncertainties of small hydropower projects supported by feed-in tariffs in Switzerland and to compare them with uncertainties of large hydropower plants. The following issues have been analyzed:

- How high is the cost overrun for small hydropower plants?
- Do large Swiss hydropower projects face cost overruns similar to those of international projects?
- Is the cost overrun of small hydropower schemes lower than that of large hydropower plans, as generally assumed?
- How accurate were the energy forecasts of large and small hydropower projects?

The results on uncertainties of small and large hydropower plants will allow a more comprehensive political debate as to the current supporting system.

Finally, implications for the planning and design of hydropower projects are discussed.

5.2 Uncertainties of Construction Costs and Energy Production

5.2.1 Construction Costs

Several publications show that hydropower projects suffer significant cost overrun.

The article by Ansar et al. (2014) establishes highest cost overruns. A mean cost overrun of 96% was calculated, based on a sample size of 245 large dams. The results have led to a debate in the hydropower community on the performance of hydropower schemes and the study itself. No associated data has been published so far. This makes a cross-check on the basic data impossible.

Bacon and Besant-Jones (1998) analyzed power generation projects approved for financing by the World Bank and International Development Association between 1965 and 1986, and completed by 1994. The study focuses on the reliability of estimates for construction costs and schedules for thermal and hydropower projects. In addition, the paper shows how estimations can be improved by applying regression models. The database contains 71 hydropower projects in developing countries. The average cost overrun is 27% (S.D.= 38%).

Head (2000) summarizes the figures presented by Bacon et al. (1998) and mentions that the analyzed projects were all carried out in the public sector. He indicates that an improvement can reasonably be expected if projects are financed by the private sector. This statement is based on a comparison with thermal projects. However, this is questionable, as other studies on construction costs for large infrastructure projects within a much larger data sample could not distinguish between cost overruns in the private or public sector (Flyvbjerg et al., 2002; Flyvbjerg et al., 2004).

Additional data on cost overruns for hydropower projects have been published by WCD (2001). The sample consists of hydropower, irrigation and multipurpose projects. The average cost overrun is 56% (n=81).

Sovacool et al. (2014) investigate the frequency and magnitude of cost and time overruns during the construction of 401 electricity projects between 1936 and 2014. The study is focused on different types of technologies, including hydropower plants. The 61 hydro facilities in the data sample had an average cost overrun of 71%.

The following table summarizes the results of previous studies.

Table 4: Average cost overruns published in previous studies

	Bacon and Besant-Jones (1998)	WCD (2001)	Ansar et al. (2014)	Sovacool et al. (2014)
n	71	81	245	61
Average	27%	56%	96%	71%

According to our best knowledge, no study analyzing cost overruns of small hydropower projects with feed-in tariffs has been published so far.

5.2.2 Energy Production

WCD (2001) reports that large dams designed to deliver electric power have on average met expectations for power delivery but with considerable variability, much of it on the downside. Data of 63 large dams could be made available for this analysis. Almost half of the sample exceeded the targets set for power generation, with about 15% exceeding the targets by a significant amount. More than half of the sample fall short of their power generation target. About 20% of the projects achieve less than 75% of the production target. It is important to note, that the data base includes also projects where the installed capacity varies between feasibility and commissioning status. That means that the over or underestimations of the energy production are also influenced by design decisions and should not be handled as uncertain factors such as hydrology, climate change.

Other studies on the quality of energy production estimates of hydropower schemes based on evidenced data could not be found.

5.3 Research Methods

Inspired by the research work of Flyvbjerg and his colleagues (Flyvbjerg, 2008; Ansar et al., 2014), the outside view has been selected for the data analyses. The outside view is an evidence-based approach allowing decision makers to base their decisions for new projects on the experience gained in projects realized in the past. Taking an outside view on the outcomes of an alternative or project means to place it in the statistical distribution of the outcomes of comparable, already constructed projects.

5.3.1 Sample Collection

The sample was collected according to the following principles:

- The class of small hydropower plants contains only projects subsidized by the feed-in tariff in Switzerland. The average capacity must be equal or below 10 MW in order to have access to the subsidizing program.
- Large projects contain only projects without feed-in tariff and with an installed capacity of at least 10 MW.
- All projects are located in Switzerland.
- For all projects costs for transmission lines were excluded.

5.3.2 Focus on Project – Specific Uncertainties

Uncertainties of hydropower projects are influenced by many underlying uncertainties caused by a wide range of factors as described in Chapter 6.3. This is the case for construction costs and energy production. The uncertainties can be grouped into political, commercial and project-specific uncertainties.

The target was to prepare data samples for small and large hydropower projects having similar political and commercial uncertainties. Therefore, all projects are located in Switzerland, which is a market characterized by low commercial uncertainties and stable political conditions.

Uncertainties in the collected project samples leading to errors in cost and energy production estimations are mainly stemming from project-specific uncertainties.

The limitation to Swiss projects allows a more reliable comparison of the estimate performance of small and large hydropower projects, compared with all previous studies where no country specific approach was selected.

5.3.3 Data Source – Small Hydropower Plants

Data of small hydropower projects has been provided by the Federal Office of Energy in Switzerland (BFE). The latest available report is from November 2014 and the projects started operation between 2008 and 2013. The available parameters of each project are summarized in Table 5. To ensure confidentiality, no project name, owner or location of the projects was made available. Because of this limitation, it was not possible to also provide a project-specific assessment of the causes leading to cost overruns or production overestimations.

The total number of projects in our data base is 1417. Depending on the analyzed factors, various filter criteria have been applied to improve the reliability of the statistical analyses. These filter criteria are described in the sections 5.4.1 and 5.4.2.

Table 5: Available parameters of small hydropower plants

Parameters	Unit/Notes
Status of project	Planning phase or operation phase
Planned installed capacity	kW
Realized installed capacity	kW
Date of start of operation	dd/mm/yyyy
Date of registration	dd/mm/yyyy
Gross head	m
Type of plant	Diversion scheme, w/o diversion, waste water, compensation, drinking water
Type of project	Rehabilitation or greenfield project
Type of turbines	Pelton, Francis, Kaplan, Ossberger, others
Estimated annual energy production	kWh
Actual annual energy production	kWh
Estimated investment costs	CHF
Civil costs	CHF
Actual investment costs	CHF

For the analysis of long-term production data of small hydropower plants, additional data was collected from the publications “Wasser und Energiewirtschaft” (SWV, 1964-1974). These publications include energy production estimates for projects that were in the planning and construction stage. The actual energy production data was obtained from the statistics of hydropower plants in Switzerland (BFE, 1991 - 2016). Details on this data base are shown in Annex C.

5.3.4 Data Source – Large Hydropower Plants

Data on estimated construction costs of large hydropower projects was collected from the publication series on hydropower development in Switzerland published by "Eidgenössiches Amt für Wasserwirtschaft", a former Swiss public authority with focus on water management. The books were published periodically, in general annually, and summarize the key data of projects in the planning stage, under construction and starting operation in the respective years. Data from the annual publications between 1947 and 1969 was collected and analyzed.

It has to be noted that these periods were the booming years of large hydropower development in Switzerland, similar to the high activity in the small hydropower business after the introduction of the feed-in tariff system.

Actual construction costs were collected from different sources. A large portion of the data was collected from the dissertation of Balmer (2012). Specific references are given in the data protocol (Annex A).

The estimated production figures were collected from the publications of "Wasser und Energiewirtschaft" (SWV, 1964-1974).The actual energy production data was obtained from the statistics of hydropower plants in Switzerland (BFE, 1991 - 2016). Details on this data base are shown in Annex B.

5.4 Data Samples

5.4.1 Construction Costs

Small Hydropower Projects

The data sample established for the analysis of cost overruns in small hydropower projects contains facilities fulfilling the following criteria:

- Actual construction costs higher than CHF 10'000. Very small projects were excluded.
- Projects with an installed capacity variance of less than ±25% from estimate to actual. Several projects show significant changes even during the construction phase with an impact not only on construction costs but also on energy production. According to the rationale of this work, such decisions are not errors in estimates, but clear management decisions and thus are not categorized as uncertainties.
- The ratio of actual to estimated construction costs must be smaller than 10 and larger than 0.1 (one project was excluded from sample Planning Phase 2).

Estimated costs have been collected for different planning phases. Planning Phase 1 contains all projects with cost estimates from the registration request for the feed-in tariff. This early design stage typically corresponds to a conceptual design. The sample Planning Phase 2 contains all figures of the construction or concession projects. It has to be noted that results of Planning Phase 1 and Planning Phase 2 are not reported for all of the projects. The sample size for Planning Phase 1 is 85 and the data sample for Planning Phase 2 contains 30 projects.

Results of Planning Phase 2 have been considered for the comparison of cost overruns of small and large hydropower projects. This sample has a portfolio of CHF 208 million and the actual construction costs range between CHF 0.1 million and CHF 59 million.

The sample contains projects with a wide range of gross heads and installed capacities (see Figure 15). Apart from pure hydropower projects, the sample also includes multipurpose projects. 11 facilities out of 30 projects are multipurpose projects (drinking water (8), waste water (1), compensation flow (2)).

The greater part of the plants were greenfield projects. 8 projects were rehabilitation or extension projects.

Inflation was neglected in the analysis of the cost overrun of small hydropower projects. Like in the period between 2008 and 2013, the level of inflation in Switzerland was less than 1% (FSO, 2016).

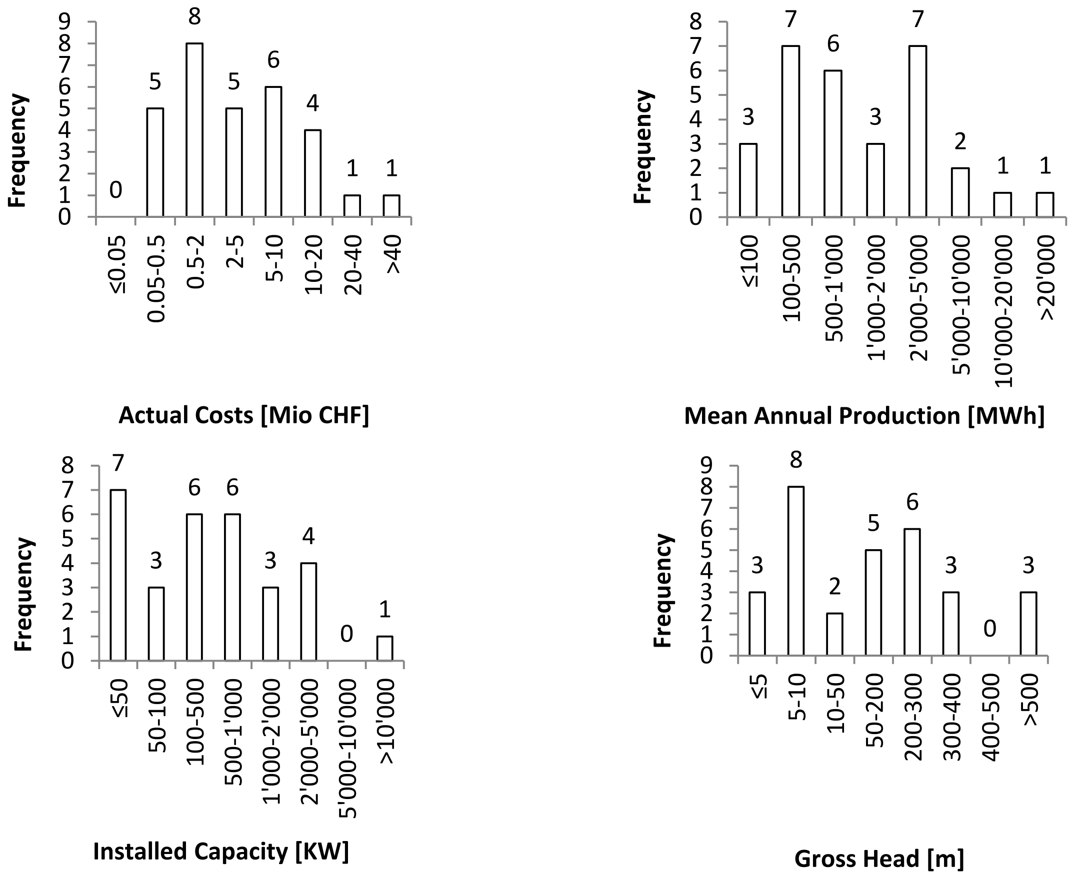

Figure 15: Small hydropower plants, data sample costs – Planning Phase 2, histograms of actual cost, mean annual production, installed capacity and gross head.

Large Hydropower Projects

The data sample contains medium to large hydropower projects with an installed capacity between 13 MW (Airolo-Piotta HPP) and 735 MW (Grande Dixence).

Because of the relatively long planning and construction times of large hydropower plants, the long-term inflation rate has been considered. For this purpose, the estimated and actual costs were adjusted according to the Swiss Consumer Price Index (CPI) published by the Federal Statistical Office (FSO, 2016).

The portfolio amounts to CHF 14’156 million adjusted for the CPI 2015.

The data sample and the key figures are shown in Annex A.

5.4.2 Energy Production

Small Hydropower Projects

Out of the 1417 projects, a representative sample of 264 plants was selected. About 73% of the projects were excluded as they were not constructed. The selected projects meet the following criteria:

- A minimum of one full calendar year of production data.
- The reported installed capacities of the corresponding year of estimated and actual energy production vary up to ± 25%.
- Actual and estimated annual energy figures must be equal or less than the theoretical maximum annual energy production (P_t) limited by the installed capacity (IC), calculated as follows:

$$P_t = IC \cdot 365 \cdot 24 \quad (9)$$

- Projects with a ratio of actual to estimated energy production equal or higher than 2 have been excluded (number of projects excluded: 2).

Based on above criteria, 264 projects have been selected covering both multipurpose projects and pure hydropower plants. An overview of the different plant types included in the data sample is shown in Figure 16. The projects cover a broad range of different characteristics of hydropower schemes in terms of head and installed capacity (see Figure 17).

Out of this sample, 163 plants are greenfield projects and 101 plants are rehabilitation or extension projects.

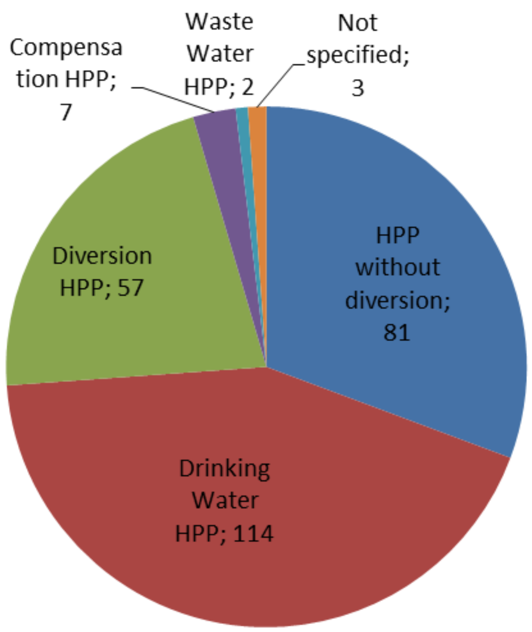

Figure 16: Small hydropower plants, data sample energy production, type of plants in the data sample

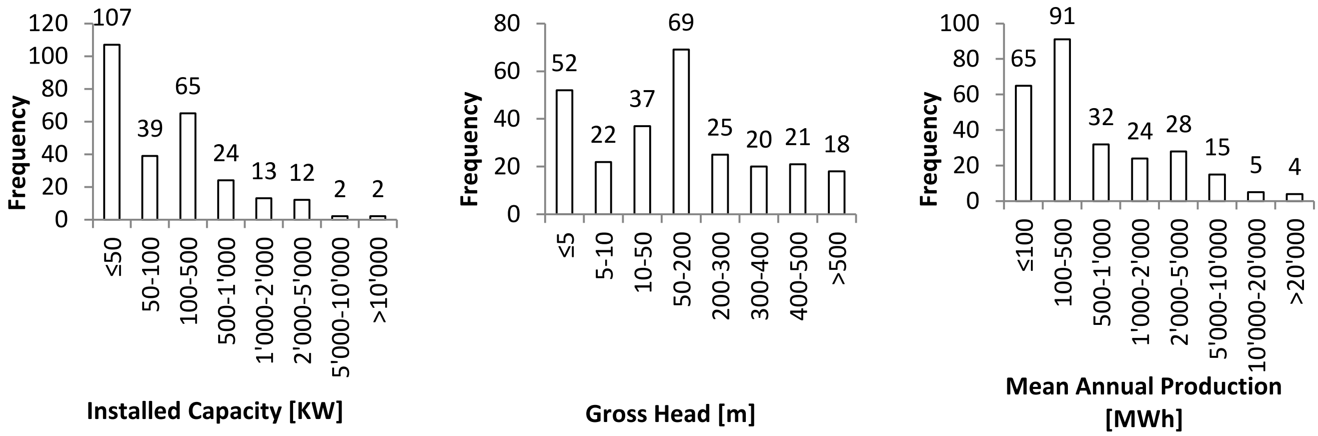

Figure 17: Small hydropower plants, data sample energy production; histograms of installed capacity, gross head and mean annual production

Small Hydropower Projects with Long-Term Production Data

This data group includes 15 projects with a total actual mean annual production of about 217 GWh. The actual installed capacities (at the generator) cover a range between 410 kW and 9.2 MW. The projects were commissioned between 1962 and 1973 and the actual production data records cover a period of at least 43 years. All projects are located in Switzerland.

Large Hydropower Projects with Long-Term Production Data

Actual and estimated production data of 24 projects was collected and integrated in the data sample. The actual mean annual production of these power plants is about 5’086 GWh, which is a share of about 13% in total Swiss hydropower production in 2015 (2015: 39’486 GWh).

The sizes of the power plants vary between an installed capacity (at generator) of 13 MW and 288 MW. The plants started operation in the years between 1962 and 1978. The production data covers a period from 21 to 54 years.

5.5 Results and Discussion on Cost Overruns

This section is structured as follows. The first subsection discusses cost overrun for small hydropower projects in Switzerland and includes a cost overrun analysis by planning stages. The second subsection covers the cost estimation performance in large hydropower projects and makes a comparison with results from previous studies. Finally, the qualities of cost estimates for small and large hydropower projects are compared.

5.5.1 Cost Overrun of Small Hydropower Plants

The analysis of the cost estimates for concession or construction projects (Planning Phase 2) and of the actual costs leads to following findings.

About 53% of the small hydropower projects suffer a cost overrun. The empirical distribution of cost overruns shows a very low median of 2%. This indicates a reliable estimation of the costs. The average cost overrun of 18% is strongly influenced by high cost overrun cases. About 24% of the projects suffered a cost overrun of more than 20%. 10% of the projects even had cost overruns of more than 50%. The fat tail of the density trace supports this finding.

The very high standard deviation of 42% indicates a very large variation in reliability of estimates for costs. These findings are summarized in Table 6 (Planning Phase 2 column).

Swiss standards (SIA, 2014) provide a target value for the accuracy of construction cost estimates. According to these standards, a construction or concession project should lead to an accuracy of construction cost estimation of ±20%. The major portion of the small hydropower projects (76%) meet this criterion. However, there is a clear trend towards underestimation of construction costs.

Cost Overrun and Planning Phases

Typically, the accuracy of cost estimates increases with the progress of the planning work, as data from site investigations or additional information get available, more detailed drawings for bills of quantities can be established, details of construction programs can be elaborated etc.

Beside this aspect, recent academic works argue that these technical reasons can only explain a minor portion of cost overestimation. Flyvbjerg documented in his work (2002) that large engineering projects have a significant lack of accuracy in forecasting costs, demand etc. Based on large data samples of projects, he argues that the main reasons for this inaccuracy are optimistic bias and strategic misrepresentation. It is argued that psychological and political-economic explanations much better account for inaccurate forecasts than technical explanations.

If strategic misrepresentation and optimistic bias are a main source for overestimating a project's performance, it could be expected that the underestimation of costs would be in a similar range or even tend to increase over the planning phases. In early planning phases, when projects have to be pushed to be continued, one could expect a similar or higher portion of strategic misrepresentation or optimistic bias than in later design stages. In such case, technical explanations would be of minor importance.

The dataset established for this work, allows the cost overrun to be analyzed based on cost estimates made at an early design stage, corresponding to the data provided for the registration of the feed-in tariff request, and on cost estimates elaborated for the construction or concession project.

The data is organized in two groups. Planning Phase 1 contains data from the registration of the feed-in tariff request, which corresponds typically to the conceptual design phase. Planning Phase 2 contains all cost estimates of construction or concession projects.

The average cost overrun based on the cost estimated in Planning Phase 1 is 28% with substantial variation around that mean value. Standard deviation (S.D.) is 55% and the density trace shows a fat tail (see Figure 18).

The accuracy of cost estimation increases over the planning stages. Cost estimates prepared for the construction or concession projects (Planning Phase 2) are on average 18% lower than the actual costs.

The likelihood that projects suffer a cost overrun decreases only slightly from 56% to 53% from Planning Phase 1 to Planning Phase 2. The Mann-Whitney U test indicates that there is not enough evidence to reject the null hypothesis that there is a positive shift in the median (p=0.6181, h=0).

However, the variation of the cost overrun is reduced along the design progress, as the statistical key data show: S.D. decreases from 55% to 42%; IQR decreases from 41% to 20% (see Table 6). In addition, extreme cost overruns leading to the fat tail and the number of outliers are reduced (see Figure 18 and Figure 19). This is also supported by key figures on extreme cost overruns. During Planning Phase 2, only 3% of the projects suffer a cost overrun of 100% or more, whereas in the case of cost estimates prepared in early design stages, the actual costs will double in 9% of the projects.

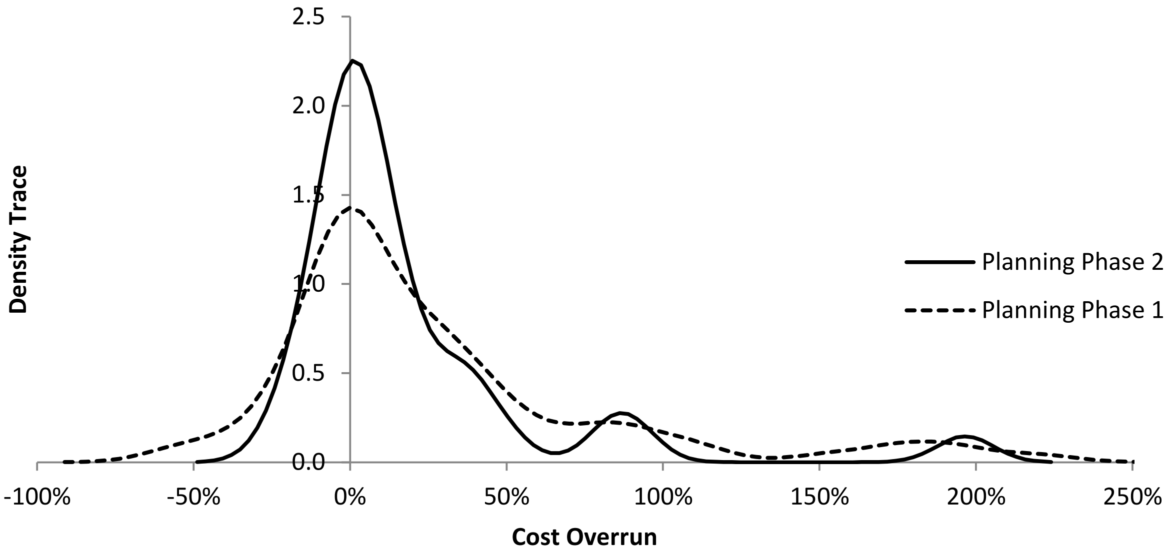

Figure 18: Density trace of cost overrun (actual/estimated) for small hydropower projects in Switzerland

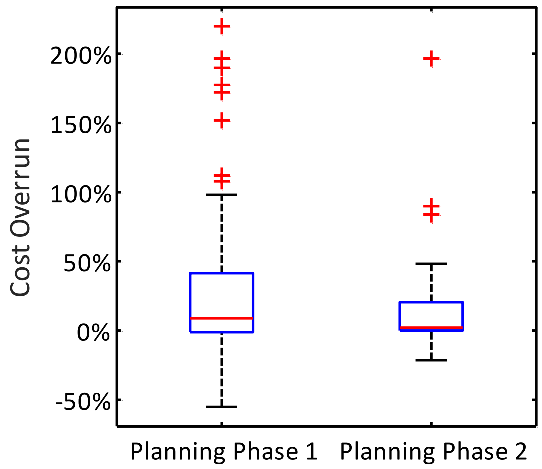

Figure 19: Box plots of cost overrun of small hydropower projects and two groups of planning phases; central mark indicates the median, bottom and top edges indicate the 25th and 75th percentiles, whiskers extend to the most extreme data points not considered outliers (Whisker corresponds to approximately ±2.7 S.D.), outliers are plotted as crosses.

Table 6: Small hydropower projects: Statistical key data of cost overrun, Planning Phases 1 and 2

	Planning Phase 1	Planning Phase 2
n	85	30
Portfolio [CHF million]	311	208
Max actual costs [CHF million]	25	58.7
Min actual costs [CHF million]	0.03	0.10
Max installed capacity [MW]	14.0	11.3
Min installed capacity [kW]	1.8	4.0
Average	28%	18%
Median	9%	2%
S.D.	55%	42%
Q1	-1%	0%
Q3	40%	20%
IQR	41%	20%
Cost overrun	56%	53%
More than 100%	9%	3%
More than 50%	19%	10%
More than 20%	41%	24%

The data of small hydropower projects indicates that cost overruns are mainly caused by technical reasons, as the continued underestimation of the costs of the progressing planning phases could not be detected. The following results of the comparison of cost overruns for Planning Phase 1 versus Planning Phase 2 support this finding:

- The median drops from 9% to 2%
- Average cost overrun decreases from 28% to 18%
- There is a decrease in high or extreme cost overruns
- Empirical distribution is getting narrower and skewness towards adverse outcomes is reduced.

5.5.2 Cost Overrun of Large Hydropower Projects

A major part of the large hydropower projects in Switzerland (67%) suffered a cost overrun. The average cost overrun is 15% with a high variation in values (S.D. 27%). The median and average cost overruns are very close to one another.

Empirical distribution of cost overruns typically shows a skewness towards adverse outcomes. However, the density trace of the analyzed data sample follows closely the shape of a normal distribution (see Figure 20).

38% of the projects suffered a cost overrun of more than 20%, 9% more than 50% and no project in the data sample shows a cost overrun higher than 100%.

The results of the analysis for large hydropower projects are given in Table 7.

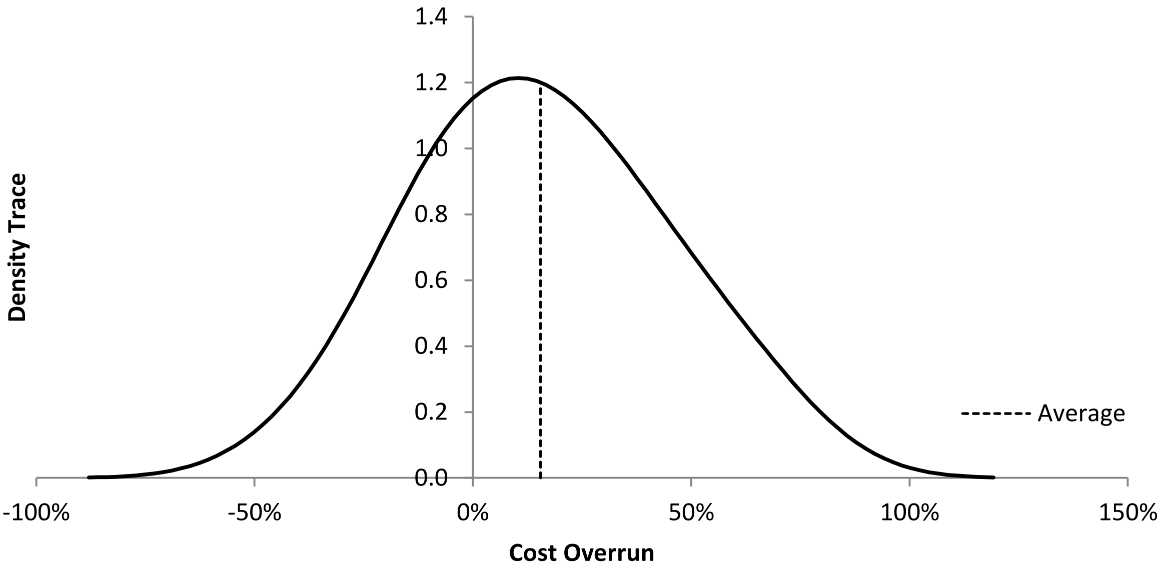

Figure 20: Density trace of cost overrun (actual/estimated) for large hydropower projects in Switzerland

Table 7: Large hydropower projects: Statistical key data of cost overrun

n	20
Portfolio [CHF_{2015} million]	14'114
Max actual costs [CHF_{2015} million]	5'118
Min actual costs [CHF_{2015} million]	39
Max installed capacity [MW]	735
Min installed capacity [MW]	13
Average	15%
Median	15%
S.D.	27%
Q1	-4%
Q3	35%
IQR	39%
Cost overrun	67%
More than 100%	0%
More than 50%	9%
More than 20%	38%

Inflation

Inflation can have a significant impact on the project costs. This is also the case in an economically and politically stable country such as Switzerland.

Due to the long duration of hydropower projects, especially when comparing figures from the planning phase against the actual costs reported after the commissioning date, inflation effects can lead to significant cost variation and are a source of economic uncertainty. Therefore, poor prediction of inflation is often an important component of cost overruns as mentioned by WCD (2001).

The comparison of cost overrun for large hydropower plants in current and constant price terms shows a shift from 31% to 15% for the average cost overrun.

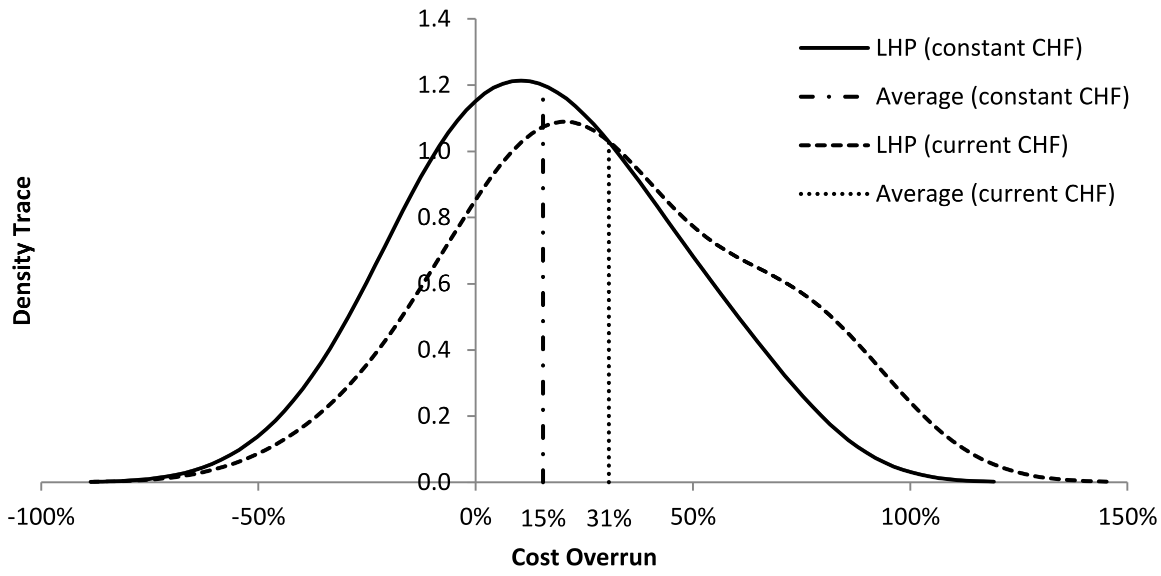

Figure 21: Density trace of cost overrun for large hydropower projects in current and constant Swiss Francs

Obviously the best way to reduce the risk of inflation is to select projects with short implementation schedules. In this respect, small hydropower projects show less exposure to inflation-induced cost overruns than large schemes.

However, the small and large hydropower projects in our data base were realized in different periods. Small hydropower plants in the data sample were constructed between 2008 and 2013 with almost no local inflation (CPI lower than 1%). The values of the large hydropower projects cover the period from 1947 until 1969. In this period, inflation rates were significantly higher than those during the analyzed period of small projects. Therefore, the cost analysis excludes the effect of inflation and the comparison of the values of small and large hydropower schemes were carried out in constant Swiss Francs.

Comparison with Other Studies

The results confirm the finding of previous studies that the main portion of large hydropower projects face cost overruns. The data sample of Swiss projects shows that 67% of the projects suffer cost overruns. This is very close to the figures presented by previous studies, which are all in the range of about 3 out of 4 projects.

However, the results clearly do not confirm the magnitude and variability of cost escalations shown in the previous studies.

A significant divergence of the mean values is observed, which can be explained by extreme figures, which skew the results significantly.

Ansar et al. (2014) found that the actual costs were on average 96% higher than the estimated costs. The density trace shows an extremely long tail to adverse outcomes and the data sample includes projects with extreme cost overruns of up to more than 5'000%.

Sovacool et al. (2014) present a mean cost overrun of 77% with extreme cost overruns reaching up to 513% (estimated for the project Sardar Sarovar Dam in India). No explanations are given on the specific cases leading to this magnitude of cost overrun.

The WCD (2001) shows a mean cost overrun of 56% with values up to 180%.

Bacon and Besant-Jones (1998) came to a mean cost overrun of 27%. It has to be noted that this study excluded outliers based on a statistical approach and the data sample included projects with a maximum cost overrun of up to approximately 122%.

Based on the comparison (see also Table 8), the following conclusions are made:

- A majority of the large hydropower projects face cost overruns. This is supported by the data of the Swiss projects as well as by previous studies.
- The established data sample for this study indicates that the average cost overrun is significantly below the figures shown by previous studies (e.g. Ansar et al., 2014; Sovacool et al., 2014).
- All studies show a large variability in cost overrun.
- A major difference exists in terms of extreme cost overruns. In the sample of Swiss large hydropower projects, the maximum cost overrun is 68%, whereas other studies report figures up to more than 5'000% (Ansar et al. 2014).

The large differences also highlight the importance and challenge to provide a representative data sample. The very high variability of the data samples indicate that a large sample size is required to come to meaningful conclusions.

In addition, it is unknown how other studies dealt with changes in project scope during the implementation phase. Such changes can have a significant impact on the project costs as well as on the benefits of a project. Cost overrun estimates should only include additional costs that do not lead to an increase in income from energy production. More specifically, it can be expected that projects undergoing major changes in installed capacity or active storage will produce higher benefits. In the data sample of Swiss projects, this aspect was taken into account. However, it is unknown how previous studies dealt with project changes linked to an increase in benefits.

Typically, no detailed cost breakdowns are available, as this information is in general confidential. This also limits the possibility to analyze cost escalations for specific salient features of a hydropower project, such as underground work for waterways, civil works at dam or powerhouse.

Table 8: Key data of studies analysing cost overruns of large hydropower projects

Study	n	Projects with cost overrun	Cost overrun				
			Average	Median	S.D.	Max.	Comments
Large hydropower plants - Switzerland	20	67%	15%	15%	27%	68%	- Limited to Swiss projects - Inflation-adjusted - Hydropower plants only - Not limited to schemes with large dams
Bacon and Besant-Jones (1998)	71	appr. 75% (estimated from frequency plot)	27%	-	38%	(appr. 122%)	- Global data base - Projects mainly in developing countries with loans from WB and IDA - Incl. inflation - Omission of projects with an actual to estimated cost ratio of more than 4 S.D. from the mean of the remaining points - Max cost overrun lies within 2.5 S.D. from the mean
WCD (2001)	81	appr. 75% (3 out of 4 dams)	56%	-	-	180%	- Global data base - Inflation-adjusted - Sample also includes non-hydropower dams
Ansar et al. (2014)	245	appr. 75% (3 out of 4 dams)	96%	27%	-	(appr. 5’000%)	- Global data base - Inflation-adjusted - Sample also includes non-hydropower projects - Limited to plants with a dam height > 15 m
Sovacool et al. (2014)	61	77%	71%	30%	112%	513%	- Global data base - Inflation-adjusted (all projects based on inflation from the Statistical Abstracts of the U.S.)

Another issue is the adjustment for inflation in the host country, or inflation in foreign countries if finance or resources are imported. This can have a major effect on cost escalations. Typically, inflation adjustments are based on publicly available consumer price indexes. However, inflation in the construction sector does not necessarily follow the inflation levels of other goods or services.

The method of data collection is basically driven by which data items are available. Private investors are in general sensitive to sharing project data with the public or academia. It has to be noted that construction cost estimates published by investors or project developers are linked to strategic considerations because of their potential impact on the tender process. Projects financed by the World Bank (WB) or other international development agencies (IDA) are often located in countries that face high political and market uncertainties. This raises the question how representative these projects are for all hydropower projects.

5.5.3 Comparison of Cost Overrun of Small and Large Hydropower Projects

The focal point of this chapter is comparing cost overruns between small and large hydropower projects.

The general assumption that small hydropower projects are less exposed to cost overruns than large hydropower projects is not supported by the data available to us. The average cost overruns of small and large projects are in a similar range. Large projects suffer a mean cost overrun of about 15%, whereas small hydropower projects face a cost escalation of about 18%.

However, major differences in empirical distributions can be observed. Whereas the density trace of small projects shows a narrow distribution around a median of 2% and a long tail to adverse outcomes, the density trace of large projects almost follows a normal distribution with a median of 15%.

The comparison leads to following main conclusions:

- Small projects tend to have more extreme cost overruns. The density trace of small plants shows a much longer tail to adverse outcomes.
- The chance for small projects to have a cost overrun is smaller than for large projects. The costs of small hydropower plants were underestimated for about 1 out of 2 projects. 67% of the large projects suffered cost overruns.
- For small hydropower plants, cost underestimation is almost as likely as cost overestimation. This is clearly not the case for large hydropower projects.
- The average cost overruns are in a similar range.

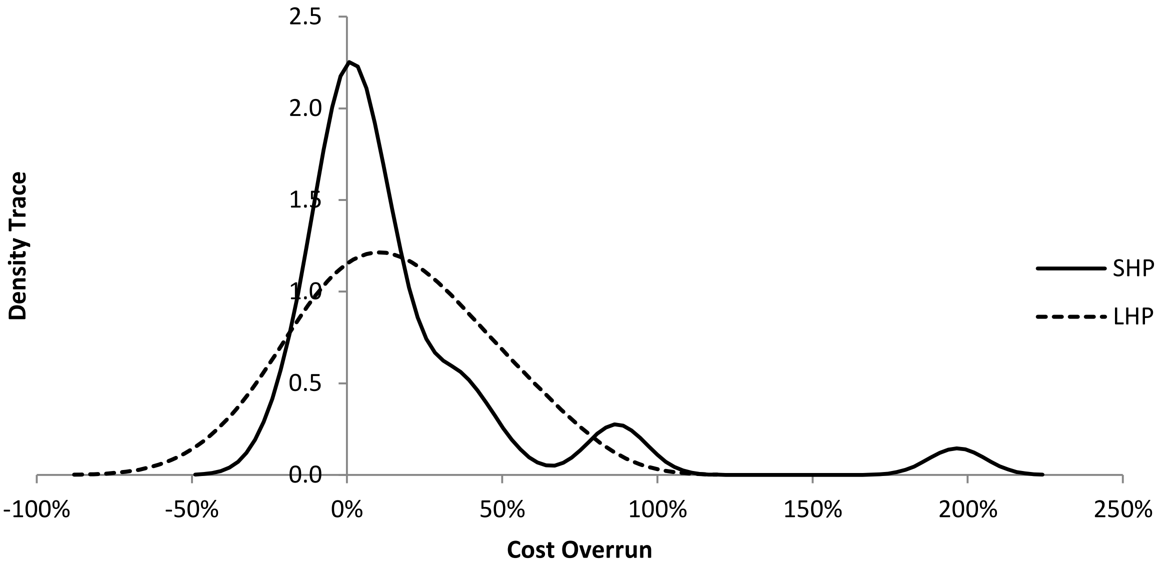

Figure 22: Density trace of cost overrun for small (SHP) and large hydropower projects (LHP)

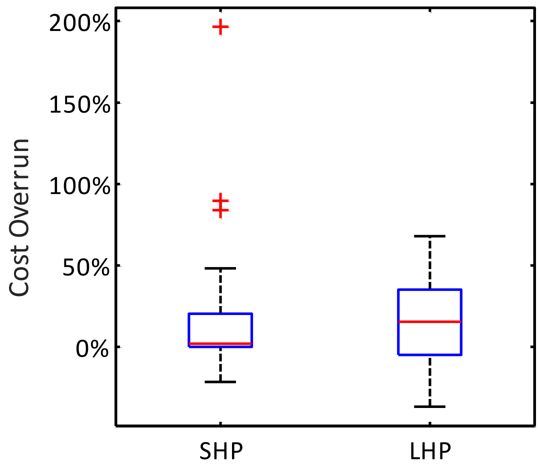

Figure 23: Box plot of cost overrun of small (SHP) and large hydropower projects (LHP) ; central mark indicates the median, bottom and top edges indicate the 25th and 75th percentiles, whiskers extend to the most extreme data points not considered outliers (Whisker corresponds to approximately ±2.7 S.D.), outliers are plotted as crosses.

5.6 Results and Discussion on Energy Production Forecasts

5.6.1 Introduction

The second main factor influencing significantly the overall performance of a hydropower plant beside construction costs is energy production. Energy production estimates are also subject to a number of uncertainties, some of which are caused by long-term hydrological uncertainties. Uncertainties in hydrological forecasts may stem from errors in the measured data, interpretation of incomplete data, errors and simplifications inherent in the hydrological model structure and errors and uncertainty due to the values of the model parameters (Refsgaard and Storm, 1990), or from potential climate change (see Chapter 4.2). Beside hydrological uncertainties, the hydraulic design and water management (incl. sediment management, hydraulic losses, operation pattern, release of compensation flow etc.) and the reliability of the hydro and electromechanical equipment can lead to overestimation of the production figures.

The performance of energy forecasts has been analyzed by comparison of actual versus estimated energy production. Production overestimation is expressed as the actual mean energy production minus the estimated mean energy production in per cent of the estimated mean energy production.

5.6.2 Energy Production Forecast of Small Hydropower Plants

The following chapter is structured as follows. The first subsection analyses the overall performance of the mean annual energy production estimates of small hydropower plants in Switzerland. The focal question is the level of accuracy of production estimates. In addition, the relation between the accuracy of estimates and the plant size of small hydropower schemes is investigated.

The second subsection compares energy production estimates for greenfield projects against those for rehabilitation or extension projects. A potential source of uncertainty is often the limited availability of hydrological data. Some of the small hydropower plants in Switzerland are planned in ungauged catchments. Therefore, it could be expected that rehabilitation projects have better estimates than greenfield projects because of the availability of operational data that can be used for the analysis of the historical inflow.

The third subsection compares the accuracy of production estimates for pure hydropower plants and for multipurpose schemes. Studies on the performance of international large hydro dams indicate that hydropower schemes tends to meet the target value more often than multipurpose schemes (WCD, 2001).

Finally, early-life failure of small hydropower plants is analyzed.

A limitation in the following analysis is that the operational data records cover only one to five years. Therefore, the analysis allows to identify some general trends only. Conclusions on long-term effects should be derived carefully because of the relatively short production periods.

Energy Production

The data shows a general high tendency for overestimating the energy production. In 7 out of 10 projects, the estimated energy production was below actual generation.

The data sample of small hydropower plants leads to a bell-shaped empirical distribution around an average production overestimation of 14% (see Figure 25). The key data are summarized in Table 9.

Table 9: Small hydropower projects: Statistical key data of production overestimation

n	264
Total estimated production [GWh]	572
Total actual production [GWh]	544
Average overestimation	14%
S.D.	27%
Median	13%
Projects with overestimation	69%
More than 20%	38%
More than 50%	10%

The comparison of the total actual and estimated production values shows low divergence (4%). This can be explained by the fact that larger projects with higher production figures had much better estimates. A comparison of the production overestimation by plant sizes supports this finding.

The installed capacity and the actual mean production have been selected as indicators for the plant size. Figure 24 shows production overestimation for different groups of installed capacities (Box Plot A) and different groups of actual mean annual production (Box Plot B).

Overestimation of production decreases significantly with increasing installed capacity (see Figure 24, Box Plot A). The data is categorized into four groups. Very small hydropower plants with an installed capacity of less than 100 kW (GR-IC 1) show an average production overestimation of 20% (median 18%). For projects with an installed capacity from 100 kW to 500 kW (GR-IC 2), the estimated production was on average 9% higher than actual generation (median 10%). Productions with an installed capacity of 500 kW to 1 MW (GR-IC 3) show only 6% (median 8%) and projects with an installed capacity higher than 1 MW (GR-IC 4) achieved the target production value (median -1%).

A similar strong increase in the accuracy of energy production estimation can be observed when plotting production overestimation versus actual mean annual production (P_A). Projects with an annual production less than 200 MWh (GR-Pr 1) suffered highest production overestimation. Mean production overestimation is 26% (median 26%). Projects with a mean annual production from 200 MWh to 1000 MWh then have a much better performance of energy forecast. Mean production overestimation drops to about 10%. Projects with an energy production of 1000 MWh or more have a similar mean production overestimation, GR-Pr 3 about 2% and GR-Pr 4 approximately 3%, but group 3 shows a higher variability.

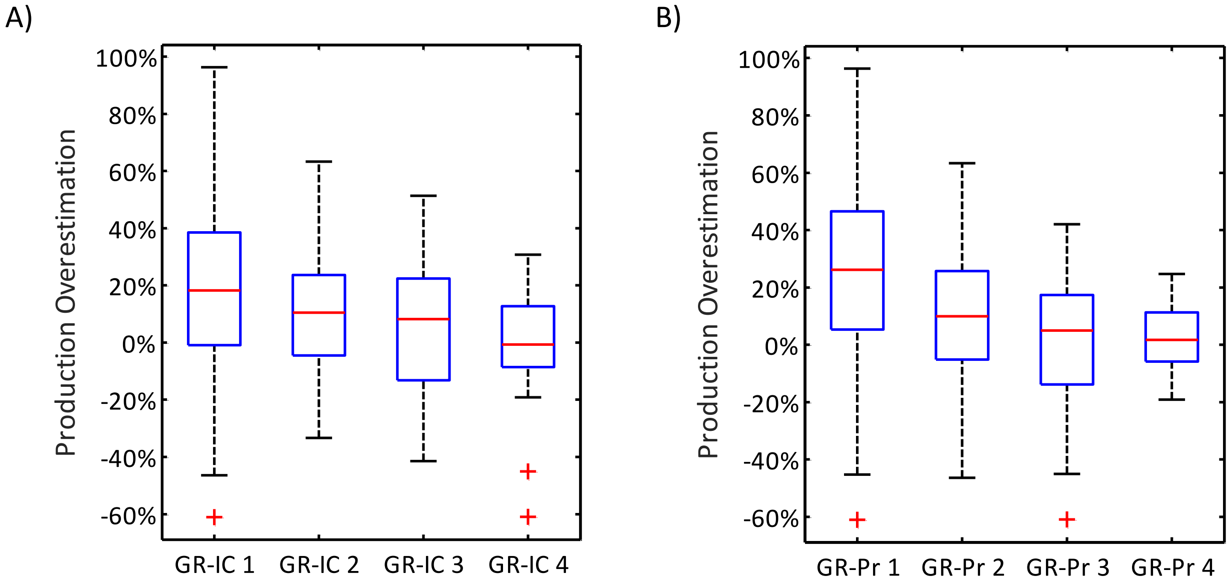

Figure 24: Box plots of production overestimation for different plant sizes; Box plot A) Plant size indicated by installed capacity categorized into four groups (GR) GR-IC 1: IC < 100 kW, GR-IC 2: 100 kW ≤ IC < 500 kW, GR-IC 3: 500 kW ≤ IC < 1000 kW, GR-IC 4: IC ≥ 1000 kW; Box plot B) Plant size indicated by actual mean annual production (P_A) categorized into four groups GR-Pr 1: P_A < 200 MWh, GR-Pr 2: 200 MWh ≤ P_A < 1000 MWh, GR-Pr 3: 1000 MWh ≤ P_A < 5000 MWh, GR-Pr 4: P_A ≥ 5000 MWh; central mark indicates the median, bottom and top edges indicate the 25th and 75th percentiles, whiskers extend to the most extreme data points not considered outliers (Whisker corresponds to approximately ±2.7 S.D.), outliers are plotted as crosses.

Energy Production of Rehabilitation and Greenfield Projects

It can be expected that rehabilitation projects have better estimates than greenfield projects as operational data can be used for the analysis of the historical inflow. Therefore, the performances of production estimates for rehabilitation and greenfield projects have been compared.

Figure 25 shows the comparison of the density trace of all projects in the data sample, both rehabilitation and greenfield plants. No significant changes can be observed. Average values lie between 12% (greenfield projects) and 17% (rehabilitation projects) and there is no major difference as to median values (median of greenfield projects 10%, median of rehabilitation projects 16%).

The available data do not support the hypothesis that rehabilitation projects have significantly better estimates than greenfield projects and this is also supported by the results obtained in the Mann-Whitney U test (p=0.187, h=0).

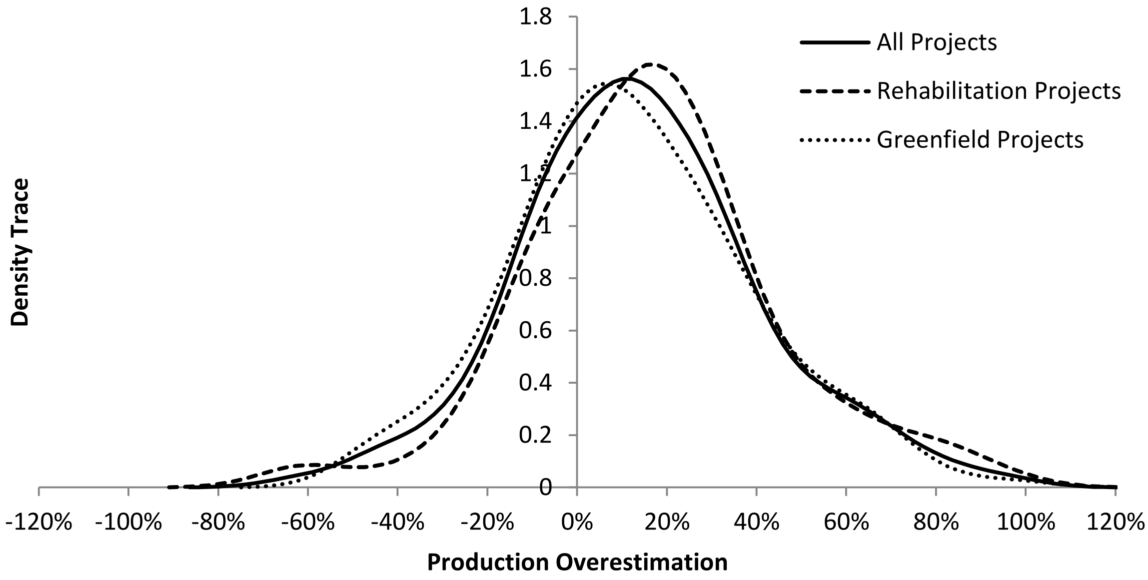

Figure 25: Density trace of production overestimation for all projects in the data sample, rehabilitation and greenfield projects

Energy Production of Singlepurpose Hydropower and Multipurpose Projects

The study of WCD (2001) describes that large dams constructed for pure energy production tend to meet generation targets more often than multipurpose projects. This trend has been checked for small hydropower plants in Switzerland.

Figure 26 shows the density trace of hydropower and multipurpose plants. Projects designed for pure energy production have a mean production overestimation of 18% (median 17%). In contrast to hydropower projects, the estimation performance of multipurpose schemes was on average closer to target (average 12%, median 5%). However, the Mann-Whitney U test indicates that there is not enough evidence to reject the null hypothesis that there is a positive shift in the median (p=0.379, h=0).

About 75% of the hydropower plants in the sample (n = 85) did not achieve the estimated energy production, whereas 8 out of in total 13 multipurpose projects in the sample were below target (62%).

The trend found for large dams according to which hydropower projects tend to have production figures closer to target than multipurpose projects cannot be observed in the data sample of small hydropower plants. On the contrary, the data indicates a trend towards less production overestimation for multipurpose projects.

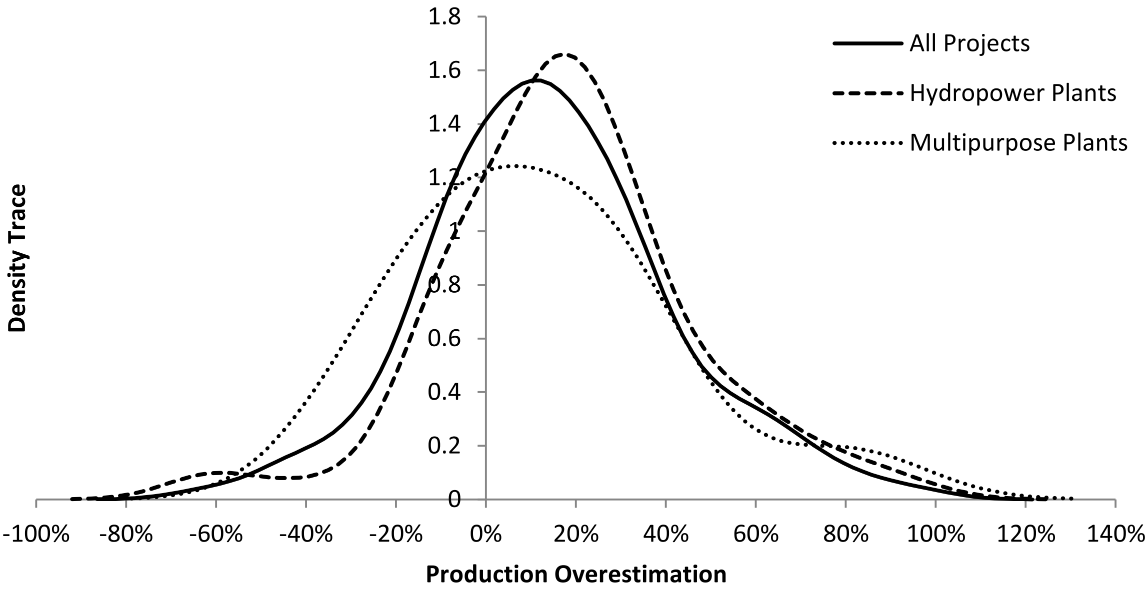

Figure 26: Density trace of production overestimation for all projects in the data sample, hydropower and multipurpose plants

Hydrological Production Potential during the Period 2010 to 2014

Energy production estimates for hydropower plants are typically covering a forecast period of 25 to 80 years. In contrast, the data sample analyzed in this study covers only production periods up to a maximum of 5 years (2010 to 2014).

Hydrological variation over the period from 2010 until 2014 can influence the analysis of production overestimation. The index of potential production published annually by the Swiss electricity statistics (BFE, 2011 - 2015) was used as a reference of the mid-term hydrological variation for this period. As small hydropower plants typically have no significant storage capacity and the main portion of energy production is generated during summer months, the index of potential production for the summer periods (IPP_S) was selected.

The IPPs for the period 2010 to 2014 was very close to 1 (mean IPPs 2010 to 2014: 1.02), meaning that this period was close to the long-term average hydrological period in Switzerland.

Figure 27 shows the index of potential production and the ratio of estimated to actual annual energy production in the relevant years. Production overestimation can be observed in all years, also in years with an IPPs above 1 (i.e. 2010, 2012, 2013, 2014). Thus, even in years with a hydrological production potential greater than the long-term reference, the estimated energy production could not be reached on average. The ratio of the actual to estimated energy follows the yearly fluctuation of the IPPs.

The conclusion is that the hydrological inflow for the period 2010-2014 was very close to the long-term average and consequently there is no evidence that production overestimation is caused by a below-average discharge period.

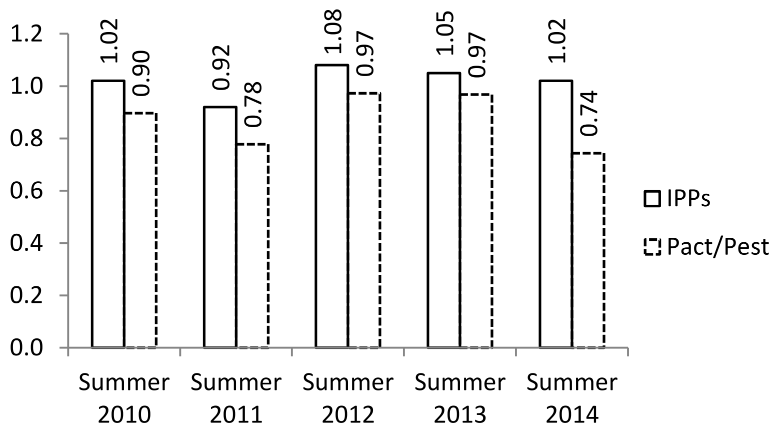

Figure 27: Comparison between the Index of Potential Production for summer periods (IPPs) and the ratio of actual to estimated average annual energy (P_{act}/P_{est})

Early-Life Failure and Energy Production

Figure 28 shows production overestimation as a function of the number of years in operation. Values summarized in group 1Y refer to the first year of operation, values categorized in 2Y are production overestimations for the first and second operation years, and so on.

As shown in the chart, the production values in the first year of operation are significantly below the target value, and power plants with a longer operation period tend to be closer to the targets. In the first year of operation, energy production was on average 29% below the long-term estimates. After the second production year, the values are closer to the estimated generation targets with production overestimation ranging between 8% and 13%.

A possible explanation for such relatively poor performance in the first production years is early-life failure. Early-life failures are most probably related to the electromechanical and hydromechanical equipment and maybe also to inadequate operation shortly after commissioning. Most probably, poor hydraulic design or inadequate construction is less relevant as it can be expected that such issues would affect the production figures over a period of more than 1-2 years.

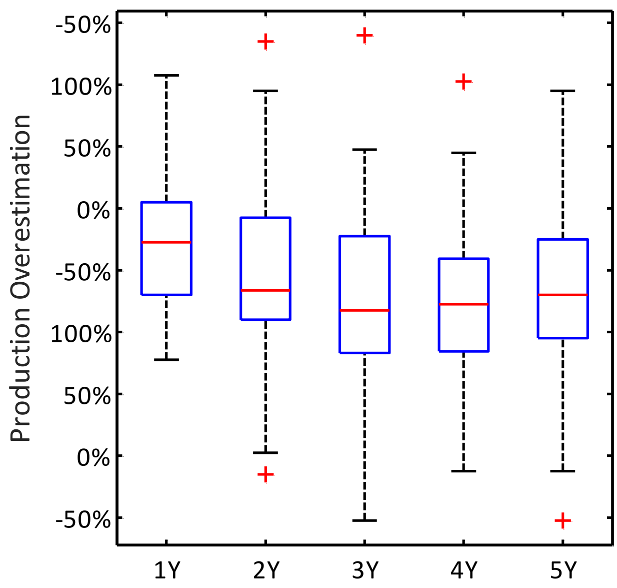

Figure 28: Box plot of production overestimation as a function of the number of years in operation; 1Y = energy production of 1st production year, 2Y= average of energy production of 1st and 2nd production years,…,5Y= average of energy production from 1st up to 5th production years; central mark indicates the median, bottom and top edges indicate the 25th and 75th percentiles, whiskers extend to the most extreme data points not considered outliers (Whisker corresponds to approximately ±2.7 S.D.), outliers are plotted as crosses.

Comparison with Long-Term Production Data

The data for small hydropower schemes shows an overestimation of energy production in the mid-term. However, the time horizon is clearly limited and allows no conclusions on the long-term performance of estimates. That is because the data covers a production period of up to 5 years only and because actual production especially in the first production year was significantly below the estimate.

To provide an indication of the quality of long-term forecasts for small hydropower plants, an additional data sample was established. All plants included in the sample had an installed capacity between 420 kW and 9.2 MW and the production period covered at least 43 years.

Table 10 summarizes the statistical key data. Almost half of the projects in the data group exceeded the targets set for power production. But the production was slightly overestimated also in the long term. Production overestimation was 5% on average, and about 20% of the projects in the sample achieved less than 80% of the estimated long-term production.

It has to be noted that the sample size was relatively small (n= 15). In addition, it was not possible to obtain long-term production data for power plants with an installed capacity below 300 kW. The analysis of the production figures for a mid-term period shows that especially such small hydropower plants are subject to higher production overestimation than larger projects.

However, with account being taken of these limitations, a tendency for overestimating the production can be observed, which supports the findings obtained with the sample that includes projects with mid-term production data.

Table 10: Small hydropower projects: Statistical key data of long-term production overestimation

n	15
Total estimated production [GWh]	228
Total actual production [GWh]	217
Average production overestimation	5%
S.D.	14%
Median	0%
Projects with overestimation	47%
More than 20%	20%
More than 50%	0%

5.6.3 Energy Production Forecasts of Large Hydropower Plants

Large hydropower plants in Switzerland in our sample (n=24) have on average exceeded the production estimates. For about 4 out of 5 projects, actual production was higher than the estimated values published before commissioning. The estimated or target figures were exceeded by about 8% on average.

Table 11: Large hydropower projects: Statistical key data of long-term production overestimation

n	24
Total estimated production [GWh]	4'699
Total actual production [GWh]	5'086
Average production overestimation	-8%
S.D.	10%
Median	-6%
Projects with overestimation	21%
More than 20%	0%

In contrast to the study by WCD (2001), the sample of the Swiss large hydropower plants show a higher performance in energy forecasts in terms of frequency of exceedance of the power generation target, average production overestimation, and variability of the results.

In contrast to the samples of small hydropower plants, there has been no downward bias in energy production estimates. The Mann-Whitney U test indicates a rejection of the null hypothesis of equal medians (p=0.0072, h=1) and supports the finding that there is a positive shift of production overestimation for large and small hydropower projects.

A majority of large hydropower schemes exceeded the production targets by 8% on average. In contrast, about half of the projects in the sample of small hydropower plants reached the production targets and the mid-term and long-term production data show an average production overestimation of 14%, or 5%, respectively.

5.7 Conclusions

The first objective of this study was to analyze the extent of cost overruns typically suffered by small hydropower projects.

The analysis of cost overruns of small hydropower projects show that there has been a large downward bias in the estimation of construction costs. Cost overrun is about 18%. The median shortfall of cost estimates was only 2%. However, the results show a very high variability. About 24% of the projects suffered a cost overrun of more than 20%, and 10% of the facilities had a cost overrun of even more than 50%. In addition, almost half of the projects had lower actual costs than estimated.

The second main objective was to analyze whether large Swiss hydropower projects face cost overruns similar to those of international projects.

The established data base of Swiss projects confirms the finding of previous international research studies as far as the trend of chance of cost overrun is concerned (Bacon and Besant-Jones, 1998; WCD, 2001; Ansar et al., 2014; Sovacool et al., 2014). In about 67% of the projects the actual costs exceeded the estimates.

The average cost overrun is however significantly below the figures derived from global databases. The data sample of Swiss projects shows an average cost overrun of 15%, whereas previous studies presented figures in the range of 27% up to 96%.

The main reason for the difference is most probably that the present study analyses Swiss projects only. Hydropower projects in Switzerland face much lower commercial and political uncertainties, compared with some of the other countries. Uncertainties in Swiss projects are mainly stemming from project-specific uncertainties. That is not the case for all other studies, which included projects from all over the world with a wide range of different political and commercial uncertainties. It has to be noted that part of the projects included in the previous studies were financed by the World Bank or other international development agencies. Such projects are often located in countries that face high political and market uncertainties.

Another crucial aim of this study was to investigate the assumption that the cost overrun of small hydropower schemes is generally lower than that of large hydropower plans.

The comparison of large and small hydropower projects leads to the following main findings:

- Average cost overruns in small and large projects are quite similar. The average cost underestimation of small hydropower projects was 18%, and for large hydropower plants the average cost overrun was 15%.
- Small projects tend to have more extreme cost overruns than large facilities. The density trace of small plants shows a much longer tail to adverse outcomes. Compared with large hydropower plants, the variability of cost overrun was much higher.

- The chance for a small project to suffer a cost overrun is much smaller than for large projects. Costs for small hydropower plants were underestimated for about 1 out of 2 projects. 67% of the large projects suffered a cost overrun.

It is concluded that the cost estimations have been overoptimistic for small as well as large hydropower projects. However, a major difference can be observed in the empirical distributions of the cost overruns. Small projects show a higher variability of cost overrun compared with large projects. A possible explanation for this high variability of the performance of construction cost estimates are the limited engineering resources typically involved in the planning and execution phases of small hydropower plants.

In hydropower, the size of the scheme is not necessarily linked to complexity. Small hydropower schemes require the same technical disciplines as large schemes such as geology, hydrology, hydraulics, civil engineering, electro and hydromechanical engineering, and similar interfaces have to be taken into account. Since the available budget is usually limited, the number of engineers is often reduced, leading to the effect that engineers in charge have to also cover disciplines outside their core competencies. Large projects on the contrary can rely on a team of relevant specialists and experts and also on a completely different setup to ensure a high level of quality control is typically established. The engagement of the different parties, including contractors, owners and lenders' engineers leads to much higher engineering standards compared with small projects.

The final objective of this study was to analyze the performance of energy forecasts for small and large hydropower projects. For this purpose, the actual versus the estimated energy production was compared.

The data of small hydropower plants covering a production period up to 5 years shows a generally high tendency for overestimating the energy production. In 7 out of 10 projects, estimated energy production was above actual generation and average production overestimation was 14%.

Small hydropower projects were suffering a slight production overestimation also in the long term. The production of large hydropower projects, on the contrary, was on average 8% higher than the estimated figures. About 80% of the projects reached or exceeded the production targets.

In addition, production overestimation shows a relationship to plant size. Larger projects in the group of small hydropower plants tend to have more accurate energy forecasts than smaller projects. Especially very small projects with an installed capacity in the range of 100 kW, or projects with an annual production lower than 200 MWh, tend to lead to overestimation of the energy production.

There is no technical reason why production estimates for small hydropower projects would lead to lower accuracy, compared with estimates elaborated for large projects. For both types of hydropower projects, uncertainties in the hydrological forecasts may originate from errors in the measured data, interpretation of incomplete data, errors and simplifications inherent in the hydrological model structure and errors and uncertainty due to the values of the model parameters or inadequate consideration of climatic changes. Also, the quality of the hydraulic design and of the water management study (incl. sediment management, operation pattern, release of compensation flow etc.), or the performance of hydro and electromechanical equipment can affect the production estimates for both large and small hydropower plants.

The question is whether the above listed potential causes are dealt with at a same level of detail. Hydrological studies of large hydropower plants are typically based on long-term hydrometric measurements and comprehensive hydrological studies. In contrast, small hydropower plants tend to be more often placed in ungauged catchments and to have limited resources available to establish a comprehensive hydrological study. Besides that, additional errors can be caused by the project team's limited experience in hydraulic design or water management. Finally, poor construction can't be excluded either.

5.7.1 Policy Implications

The methods for estimating the construction costs and energy production of small hydropower projects in Switzerland have been overoptimistic. Cost overruns of small hydropower plants show a large variability, and a tendency for energy production overestimation can be observed. From this perspective it can be concluded that "small hydropower projects are not always beautiful".

If cost overrun is formulated as specific cost overrun per installed capacity, it becomes apparent that small hydropower projects have a higher specific cost overrun than large hydropower projects (see Table 12).

Table 12: Specific cost overrun of large and small hydropower projects

	Small hydropower projects	Large hydropower projects
n	30	20
Portfolio [CHF million]	208	14'114
Total installed capacity [MW]	33	2'432
Specific construction costs [CHF million/MW]	6.3	5.8
Average cost overrun	18%	15%
Specific average cost overrun [CHF million/MW]	1.2	0.9

The difference is mainly due to the lower specific construction costs of large hydropower projects (5.8 million CHF/MW) compared to small hydropower projects (6.3 million CHF/MW); in other words, as the average construction costs per installed capacity of larger schemes are lower than for small hydropower projects, less cost overrun per installed capacity is to be expected.

The analysis of cost overruns of the small hydropower plants reported in this study indicates potential for improvement, especially in terms of the methods applied for estimating the construction costs, including the quality of design, and in terms of appropriate approaches to control actual construction costs.

From a technical perspective, no reason can be given why very high cost overruns leading to a long tail to adverse outcomes were avoided for large projects but not for small facilities. Most probably, this is related to lower risk awareness or maybe to higher risk acceptance of the project teams in charge of small hydropower projects.

In a first step, risk awareness should be increased in small projects. Beside the classical method of communication of risks affecting small hydropower plants to the relevant authorities and project developers, it would be beneficial to foresee a project-specific assessment of small power plants with cost overruns exceeding a certain benchmark. A cost overrun benchmark of 20% could be applied as target value of the accuracy of construction cost estimates according to the Swiss standards (SIA 103, 2014). It is expected that most causes are related to inadequate engineering and not to unpredictable site conditions.

In a second step, the possibilities to improve the overall quality of the design and construction works of small hydropower projects should be evaluated. One option could be to establish a supporting system including measures to ensure adequate quality of both project design and execution. That could be achieved by providing an adequate engineering budget.

Another crucial finding of this study is that the Swiss power plants in our sample have faced significantly less cost overrun than projects from previous international studies. When taking into account the fact that the actual production rates of most of the hydropower plants were above targets, the assumption that large hydropower schemes are typically highly risky structures must be questioned.

5.7.2 Implication for Design and Planning

The following sections describe possible ways to incorporate uncertainties of construction cost and energy production forecasts into the evaluation of a project.

Adjustment Factors

The analysis shows that the methods of estimating construction costs tend to be overoptimistic. For a majority of the hydropower projects, the unforeseen additional construction costs could not be covered with the contingencies. A common approach is to estimate hydropower project cost contingency on the basis of predetermined guidelines. Often, single contingency or float values for different cost items are applied. The projects in the data base show that the foreseen contingencies on average were too low.

One possibility is to increase contingencies. On the assumption that future projects will be similar to the projects in the data base, adjustment factors could be proposed. However, the large variability of cost overruns, especially for small hydropower projects, clearly shows the disadvantage of such an approach.

In order to take the large variability of the results into account, the reference class forecast (RCF) technique can be applied. The RCF technique is part of the “outside view”. This method provides that decision makers apply an uplift or downlift to the estimated figures (“inside view”) in order to generate a de-biased “outside view” forecast, depending on the acceptable chance of not reaching the target figure (Flyvbjerg, 2008; Ansar et al., 2014).

A predictor for construction costs and energy production was derived from the findings of the investigations on small and large Swiss hydropower projects (see Figure 29 and Figure 30). The objective of this predictor is to adjust the biased construction cost or energy forecasts. It can be used as a basis for the creation of uncertainty profiles.

Small and large hydropower projects are handled as reference classes. If a planner is willing to accept a 10% cost overrun chance, the required uplift will be 83% for a small hydropower project and 61% for a large hydropower project.

Similar to the predictor for construction costs, adjustment factors were derived from the established data bases. If a chance of production overestimation of 25% is acceptable for small hydropower projects in the mid-term, the estimated energy production figures have to be multiplied by an adjustment factor of 0.7; for long-term estimates an adjustment factor of about 0.85 has to be chosen. For large hydropower projects, an adjustment factor of 1.0 corresponds to a 25% chance of production overestimation. However, adjustment factors for long-term energy production forecasts have to be interpreted carefully, as the data sample is relatively small.

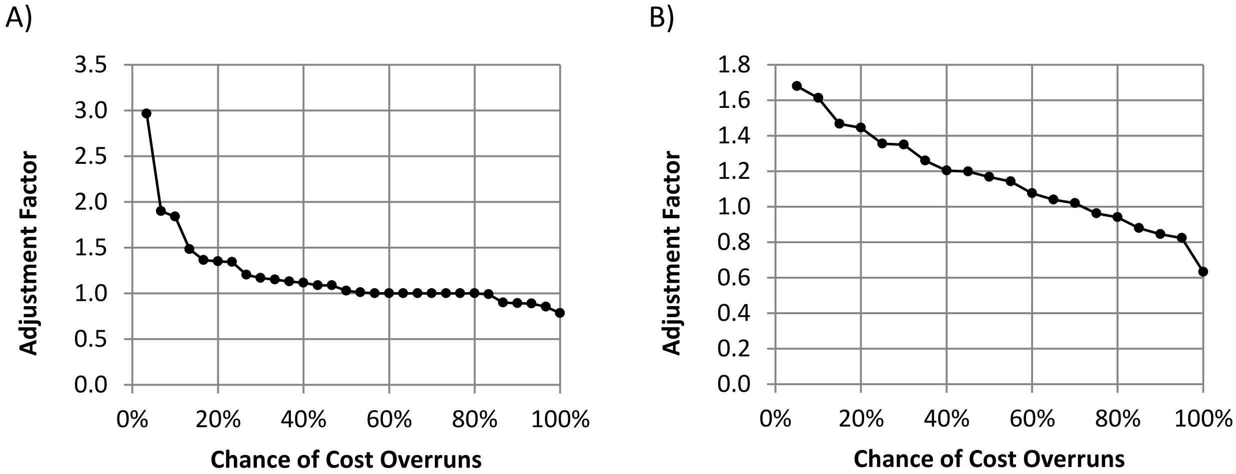

Figure 29: Adjustment factors for construction costs as a function of the acceptable level of chance of cost overruns. A) Small hydropower projects (n=30), B) Large hydropower projects (n=20).

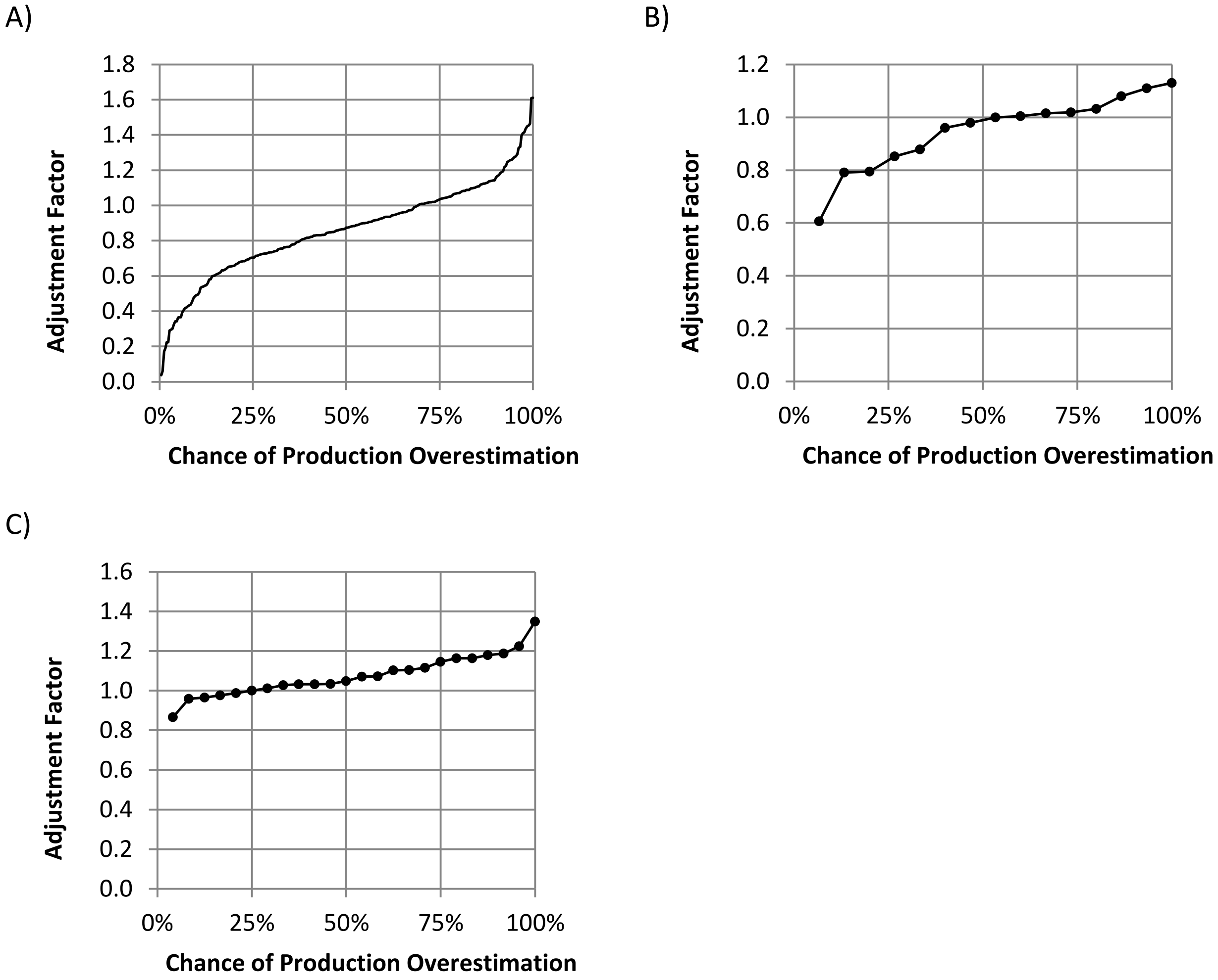

Figure 30: Adjustment factors for energy production forecasts as a function of the acceptable level of chance of production overestimation. A) Small hydropower projects, mid-term (n=264), B) Small hydropower projects, long-term (n=15), C) Large hydropower projects, long-term (n=24),

Expected Net Present Value, Value at Gain and Value at Risk

A more comprehensive project evaluation can be captured by the criteria of Expected Net Present Value (ENPV), Value at Risk (VaR) and Value at Gain (VaG) instead of the Net Present Value (see also Mun, 2006).

VaR is defined as the maximum expected loss over a target horizon with a given level of confidence (Jorion, 1997). In contrast, VaG quantifies the performance in the upside scenarios.

The basic procedure to produce project risk profiles (Monte Carlo Simulation) was proposed decades ago by Hertz (1964).

In general, the following three-step approach can be applied:

1. Development of probabilities for uncertain parameters
2. Monte Carlo simulations to generate a set of input data for the economic model
3. Evaluation and comparison of alternatives under the criteria of ENPV, VaR and VaG

However, criteria such as ENPV, VaG and VaR have been rarely applied for hydropower projects because of the strong assumptions they impose on the underlying probability distributions.

The datasets elaborated for this study allow the definition of probabilities based on empirical data. Table 13 gives the probability distributions fitted to the different samples of large and small hydropower projects in Switzerland.

Table 13: Definition of probabilities of construction costs and energy production of small and large Swiss hydropower projects

Factor	Probability distribution	Parameter
Small hydropower projects		
Construction costs	Generalized Extreme Value	shape parameter = 0.311717 scale parameter = 0.169882 location parameter = 1.00562
Mid-term energy production	Weibull	scale parameter = 0.951203 shape parameter = 3.51844
Long-term energy production	Weibull	scale parameter = 1.00559 shape parameter = 9.28587
Large hydropower projects		
Construction costs	Generalized Extreme Value	shape parameter = -0.265507 scale parameter = 0.260957 location parameter = 1.05859
Long-term energy production	Generalized Extreme Value	shape parameter = -0.140319 scale parameter = 0.091807 location parameter = 1.03486

Illustrative Example of Application

A typical case has been developed in order to test the probabilistic evaluation of a project. The case represents a high-head run-of hydropower scheme in the Swiss Alps (see Chapter 8).

The objective is to provide an evaluation of the economic performance by considering the uncertainties of construction costs and energy production forecasts. The key data of the hydropower plant and the calculated NPV based on the classical deterministic approach are given in Table 14.

Table 14: Key data of case study

Parameter	Unit	
Design discharge (*Qd*)	[m^3/s]	4
Max. generation discharge	[m^3/s]	5.4
Gross head	[m]	522
Net head (H_n)	[m]	511.3
Specific hydraulic loss coefficient	[-]	0.667
E&M equipment efficiency (η)	[-]	0.88
Installed capacity (*IC*)	[MW]	18
Construction costs	[CHF million]	47.1
Annual energy production (P_A)	[GWh]	64.83
NPV-deterministic	[CHF million]	13.66

It is assumed that the project developer is accepting a chance of 20% for both cost overrun and production overestimation: adjustment factors of 1.44 for construction costs and 0.99 for energy production were defined on the basis of the predictors shown in Figure 29 B) and Figure 30 C). Applying these factors gives adjusted construction costs of CHF 67.82 million and adjusted annual energy production of 64.18 GWh. Based on these figures, a DCF calculation was made, resulting in a negative NPV of about CHF -11 million.

The other approach relies on the probability distributions fitted to our sample of large hydropower plants. General Extreme Value distributions as defined in Table 13 were applied to construction costs and energy production.

Based on these distributions, 1000 runs consisting of construction costs and energy production were generated using the Monte Carlo method.

Subsequently to the generation of the wide range of runs, the NPVr is calculated for each run. It is assumed that each of the runs has the same probability, which here is 1/1000 (pr). The following equation is used to calculate the ENPV.

$$ENPV = \sum_{n=1}^{1000} p_r \cdot NPV_r \qquad (10)$$

Table 15 combines the results of the deterministic approach and those of the probabilistic evaluation. The deterministic NPV is only slightly above the ENPV. The chance that the realized NPV exceeds the deterministic NPV is in the range of 50%. The VaR (P 10%) leads to CHF -8.9 million and the VaG (P 90%) suggests that this project can be economically very promising. As shown in Figure 31, the chance that the project will lead to a negative NPV is about 23%.

Table 15: Economic results for project evaluation

Economic parameter	Unit	
NPV - deterministic	[CHF million]	13.7
ENPV	[CHF million]	11.7
VaR (P 10%)	[CHF million]	-8.9
VaG (P 90%)	[CHF million]	31.3

Compared with the estimation based on the predictor, which is a single-point estimation, a decision on whether or not further planning steps should be taken for this project will most likely turn out to be completely different. If the decision is based on the results derived from the adjustment factors, the project will be most probably stopped. The project will on the contrary most probably continue if the decision is made on the basis of the more comprehensive figures derived by Monte Carlo simulations.

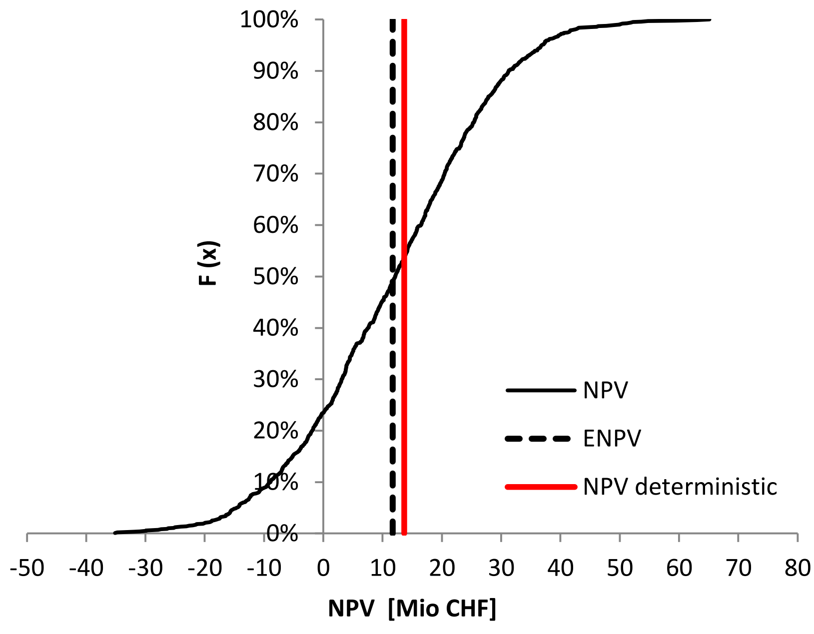

Figure 31: Cumulative distribution of NPV, Expected Net Present Value (ENPV) and deterministic NPV

Discussion

Adjustment factors derived from the reference class forecast provides valuable information for the evaluation of the whole group of projects. In addition, it is a simple approach which can be easily applied by a project team. On the other hand, as it is a one-point estimation, it can lead to misleading conclusions.

The criteria of ENPV, VaG and VaR allow for a more comprehensive evaluation of projects and project alternatives. The elaborated probability distribution provides an efficient and transparent way to incorporate uncertainties of construction costs and energy production into the evaluation process.

It has to be noted that the distributions are based on historical data and that an application of these methods implies the assumption that future uncertainties will be similar to the uncertainties represented in the sample. This is especially crucial for energy production forecasts, as it is questionable whether the climate of the historical period will still be relevant for the operation time of new hydropower plant. This issue is getting more important in the light of the climate change.

Another limitation of these approaches is that they cannot address project-specific uncertainties. If a decision needs to be made as to which design alternative should be used, a project-specific assessment will be required. This approach is described in the next chapter.

Chapter 6 Project-Specific Assessment of Uncertainties – Establishment of a Register of Uncertainties

6.1 Introduction

Uncertainties and especially downside risks of hydropower projects have for decades been the subject of discussion, typically a risk discussion. There are various academic studies and applied project reports dealing with this topic and mentioning project-specific risks. However, with a view to incorporate uncertainties into the design process, the following issues have been identified:

- Uncertainties are discussed on a general level for large engineering projects, and specific hydropower issues are not mentioned explicitly.
- The analysis is directed to specific sources of uncertainty only (such as uncertainties of hydrology associated with climate change).
- Uncertainties of hydropower projects are discussed for specific project phases only, in most cases for the construction phase.
- Uncertainties are limited to the negative effects.
- Uncertainties are not linked to performance parameters.
- Only uncertainties that can be quantified (incl. likelihoods or probabilities) have been considered.

Based on literature research and brainstorming, uncertainties affecting hydropower projects were collected and combined in a register. The register gives an overview on the wide field of uncertainties affecting hydropower projects, from political uncertainties to site-specific uncertainties. The performance-oriented register of uncertainties shows the linkage between the uncertainties and the input factors of an economic evaluation of a project. The register can be used as a basis for the preparation of project-specific assessments of uncertainties.

6.2 Literature Review

Perry and Hayes (1985)

Perry and Hayes have identified primary sources of risks in projects. These are physical, environmental, design, logistics, financial, legal, political, construction and operational risks. The authors argue that each of these primary sources of risks needs to be thoroughly considered in order to draw up a comprehensive project-specific list before the risk analysis and response can be elaborated.

Cooper et al. (1985)

The paper by Cooper et al. (1985) discusses a risk analysis of a construction cost estimate for a large hydroelectric project. The aim of the study was to provide a check on the reliability of the cost estimate and the adequacy of the contingency allowance. The sources of risk were basically structured according to the line items of the cost estimate of each structure. The risks that affect specific line item costs were grouped into quantity risks, unit cost risks, schedule risks and global risks. The latter comprise labour rates, contractors' profit margins and taxes. The effect of a risk on each item was assessed via distribution of proportional variations on the base-cost estimate for the item. However, the study focuses only on risks that might be considered as "normal" variations for projects. The common feature of "normal" risks is that they cannot cause long delays to the project. Abnormal or catastrophic risks were not considered, such as:

- Major design changes
- Site changes
- Water charges
- Labour problems
- Land acquisition
- Major floods
- Jurisdictional and regulatory processes

Goldsmith (1993)

Goldsmith's book on the economic and financial analysis of hydropower projects (1993) mentions general risks of infrastructure projects. The following four groups of risks are described:

- Technical risks: malfunction, unduly early obsolescence due to becoming outdated by technical progress and unduly rapid deterioration of the facilities. The latter can be due to failure to meet their expected performance or to stand up to the conditions they are exposed to.
- Operational risks: unexpected, or unpredicted, changes in the parameters on which the design was originally based (hydrology, site conditions, power market response)
- Financial risks: construction cost overruns, delays in completion or unpredictable changes in costs and revenues throughout the lifetime of the asset, including the effects of inflation and currency movements
- Commercial risks: failure to meet predetermined financial targets

Brenner et al. (1997)

Brenner et al. (1997) present a general classification of the most common risks with relevance to hydropower projects. The risks were linked to the design phase, construction phase, operation phase and finally to the project's performance. Brenner et al. argue that the most significant risk periods are the construction and operation phases. However, one of the most significant risks for hydropower plants, namely energy price, is not listed.

Kelman et al. (1997)

Kelman and his colleagues give a list of typical risk issues related to dam projects to be addressed by the financiers and the concession company. The risk issues are categorized into the following three groups:

- Physical: damage to the works, and/or construction plant, machinery or equipment
- Political: company risks, legal proceedings, change in legislation, people risks, contract risks, taxation
- Financial: inflation, foreign exchange, credit risks, interest rates and availability of finance.

Typical project risk issues in addition to the above-mentioned three main groups are presented along the time line of the project phases.

Head (2000)

The study elaborated by Head (2000) describes issues and challenges related to the private financing of hydropower projects in developing countries and highlights construction, hydrological and environmental risks. According to this study, construction risks arise in principal from geological conditions, which can have a major influence on the construction schedule as well as on the final costs. Other sources of construction risks are linked to the construction sites, which are often located in remote areas vulnerable to flooding and logistical problems. In respect to hydrological risks, the study describes the following main types:

- Flood damage: during construction phase or during operation phase
- Short-term duration deficits: dry period with an inflow below the long-term average
- Sustained production deficits: causes can be either an incorrect original hydrological assessment of the long-term inflow or subsequent changes in the hydrological regime.

Another main risk for hydropower projects is environmental risk. Environmental clearance can be a time-consuming and expensive business, especially if the project has to meet local environmental permitting requirements as well as acceptable international standards as defined by organizations such as the World Bank. The required studies vary substantially between projects and can be complex.

Miller and Lessard (2001)

Miller's and Lessard's work on large engineering projects distinguishes between the following risks:

- Market-related risks
    - Demand risks
    - Financial risks
    - Supply risks
- Completion risks
    - Technical risks
    - Construction risks
    - Operational risks
- Institutional risks

    - Regulatory risks
    - Social acceptability risks
    - Sovereign risks

According to Miller and Lessard, many risks are linked to the life cycle of the project. For example, regulatory risks diminish very soon after permits are obtained, or technical risks drop as engineering experiments are performed.

Head (2006)

Head distinguishes between political, commercial and project risks and provides examples for each of the three groups.

Palmieri (2015)

Palmieri mentions the same three main types of risks as Head (2006): political (country), commercial (market, defaulting offtaker) and project (site-specific) risks. Beside these general main types of risks, special attention is given to geotechnical risks in the form of unforeseen geological conditions. According to this publication, geological risk is a key factor in cost and schedule control on all major civil engineering projects and is a major contributor to cost and schedule overruns.

Malovic et al. (2015)

Malovic et al. prepared a guide for IFC to discuss each step of hydropower project development (site selection, plant design, permitting/licensing, financing, contracting and commissioning) while explaining key issues and typical responses. The guide also lists risks associated with hydropower projects and mentions typically applied mitigation measures. The following groups of risks are mentioned:

- Political risks
- Economic and financial risks
- Technical risks
- Social risks
- Environmental risks

6.3 Performance-Oriented Register of Uncertainties

The three main uncertainties for the evaluation of hydropower projects are costs, benefits and time framing. These factors are affected by underlying uncertainties such as CAPEX, energy price or construction time, which in turn stem from a wide range of political, commercial or project-specific uncertainties. Obviously, some of the causes can affect more than just one main uncertainty and interact with one another, such as CAPEX and construction time.

This structure reflects the input to economic evaluation and allows for direct incorporation of the uncertainty assessment into the economic assessment (see Figure 32)

Each hydropower plant is a unique structure and therefore requires a project-specific uncertainty assessment. The performance-oriented register of uncertainties can be used as a starting point and extended where and as required.

The causes, or uncertainties listed on the lowest level, have been categorized into the following three groups (see also Head 2006):

- Political uncertainties (see Table 16): This group includes the failure of the host government to fulfil its obligations under the project agreements. As well as the political uncertainties, all country uncertainties are included. Typically, this group affects the complete hydropower sector in a country.
- Commercial uncertainties (see Table 17): This category summarizes risks that affect revenues despite the fact that the host government is honouring its agreements and that the power plant is operating as planned. Examples are enforced changes in tariffs, or payment default of the offtaker. Typically, this group of uncertainties affect the complete hydropower sector providing the same services (energy production, flood control, etc.) for the same market. They are equal to market uncertainties.
- Project uncertainties (see Table 18 and Table 19): This group includes all site-specific risks that can occur during implementation and in the operation stages, such as cost and construction time overrun, hydrological risk (power production lower than the estimated one), environmental and social risks.

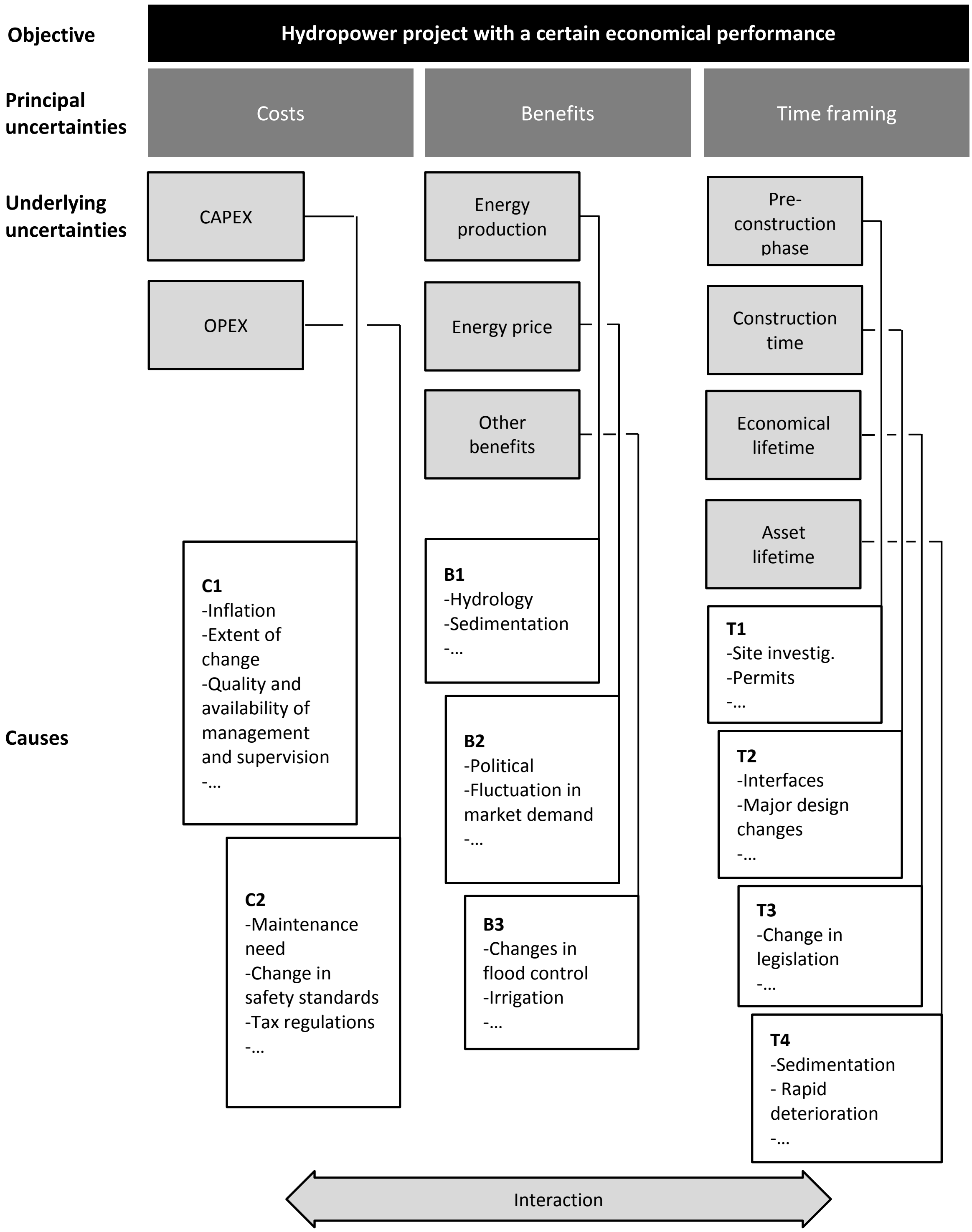

Figure 32: Concept map, structure of uncertainties and links to economic performance parameter

Table 16: Political uncertainties

No	Category	Cause	C1	C2	B1	B2	B3	T1	T2	T3	T4
Po1	Political uncertainties	Political change or instability (revolution, war)	x	x	x	x	x	x	x	x	x
Po2	Political uncertainties	Corruption	x	x				x	x		
Po3	Political uncertainties	Import embargoes	x	x					x		
Po4	Political uncertainties	Threat by terrorists or political organisations	x	x	x	x	x	x	x	x	x
Po5	Political uncertainties	Strikes or labour disputes involving: workforce, suppliers, unions	x	x	x		x		x		
Po6	Political uncertainties	Tax regulation	x	x							
Po7	Political uncertainties	International objections on social, environmental or cultural grounds (incl. NGOs)	x					x	x		
Po8	Political uncertainties	Expropriation, Failure to provide the site or access	x								
Po9	Political uncertainties	Public enquiry	x	x				x			
Po10	Political uncertainties	Local law, legal differences between home country and home countries of suppliers, contactors, designers	x						x		
Po11	Political uncertainties	Jurisdictional and regulatory processes	x	x				x	x		
Po12	Political uncertainties	Changes in legislation	x	x	x		x	x	x	x	
Po13	Political uncertainties	Changes in dam safety regulations	x	x							
Po14	Political uncertainties	Changes in regulations on flood water control		x	x		x				
Po15	Political uncertainties	Changes in water charges		x							
Po16	Political uncertainties	Changes in regulations on fish migrations			x		x				
Po17	Political uncertainties	Changes in regulations on compensation flow			x		x				
Po18	Political uncertainties	Changes in fees for use of transmission lines etc.		x							
Po19	Political uncertainties	Failure to recompensed the project company for any adverse changes in legislation	x	x							
Po20	Political uncertainties	Permits			x		x	x			x
Po21	Political uncertainties	Transboundary issues			x		x	x			
Po22	Political uncertainties	Sequestration of the assets			x		x			x	
Po23	Political uncertainties	Currency restrictions				x					
Po24	Political uncertainties	Change in energy tariff systems or subsidize systems				x					
Po25	Political uncertainties	Change of type of energy market (liberalization)				x					
Po26	Political uncertainties	CO_2 market				x					
Po27	Political uncertainties	Project cancellation						x	x		
Po28	Political uncertainties	Concession agreements						x			
Po29	Political uncertainties	Land acquisition						x			
Po30	Political uncertainties	Right of way						x			

Table 17: Commercial uncertainties

No	Category	Cause	C1	C2	B1	B2	B3	T1	T2	T3	T4
C1	Commercial uncertainties	Exchange rate fluctuations, inflation	x			x					
C2	Commercial uncertainties	Currency restriction	x	x							
C3	Commercial uncertainties	Credit risks	x								
C4	Commercial uncertainties	Availability of specialized resources-expertise, designers, contractors, supplies, scarce construction skills, materials	x					x	x		
C5	Commercial uncertainties	Market conditions - Contractors and suppliers (low bids, labour rates, contractors profit margins)	x								
C6	Commercial uncertainties	Limited marked for equipment (maintenance and rehab)		x							
C7	Commercial uncertainties	Fluctuations in market demand for product or service			x	x	x				
C8	Commercial uncertainties	Lack of a market for the services provided				x	x				
C9	Commercial uncertainties	Enforced change in tariffs				x					
C10	Commercial uncertainties	Default of the offtaker in respect of his payment obligations				x	x				

Table 18: Project uncertainties

No	Category	Cause	C1	C2	B1	B2	B3	T1	T2	T3	T4
Pr1	Project uncertainties	Availability of funds, adequacy of insurance	x	x				x	x		
Pr2	Project uncertainties	Financing packages	x					x			
Pr3	Project uncertainties	Adequate provision of cash flow	x					x	x		
Pr4	Project uncertainties	Losses due to default of contractors, suppliers	x								
Pr5	Project uncertainties	Liability for acts of others, direct liabilities	x								
Pr6	Project uncertainties	Physical loss or damage by fire, earthquake, accident, landslip	x	x	x		x	x	x	x	x
Pr7	Project uncertainties	Flood damage during construction phase	x						x		
Pr8	Project uncertainties	Flood damage during operation phase		x	x		x	x		x	x
Pr9	Project uncertainties	Climate conditions (Snow, avalanges, rain periods etc.)	x	x				x	x		
Pr10	Project uncertainties	Remote areas vulnerable to logistical problems	x					x	x		
Pr11	Project uncertainties	Insufficient data from site investigations (geology, topography, hydrology)	x								
Pr12	Project uncertainties	Geological conditions	x						x		
Pr13	Project uncertainties	Construction material at site	x						x		
Pr14	Project uncertainties	Design adequacy	x	x					x		
Pr15	Project uncertainties	New technology & innovative applications	x	x				x	x		
Pr16	Project uncertainties	Detail, precision and appropriateness of specifications	x						x		
Pr17	Project uncertainties	Major design changes	x					x	x		
Pr18	Project uncertainties	Contractors and suppliers interfaces, schedule risks	x								
Pr19	Project uncertainties	Quality and availability of management and supervision	x					x	x		
Pr20	Project uncertainties	Contractor’s experience	x						x		
Pr21	Project uncertainties	Delay due to customers/suppliers downtime	x						x		
Pr22	Project uncertainties	Loss or damage in the transportation of materials and equipment	x								
Pr23	Project uncertainties	Ecological damage, pollution, waste treatment, nuisance	x						x		
Pr24	Project uncertainties	Land and water use conflicts	x		x		x	x			
Pr25	Project uncertainties	Resettlement and social unrest	x					x			
Pr26	Project uncertainties	Public health and safety risks	x					x			
Pr27	Project uncertainties	Cultural heritage issues	x					x			
Pr28	Project uncertainties	Wetlands protection	x								
Pr29	Project uncertainties	Requirements of fish migration facilities	x								
Pr30	Project uncertainties	Damage payable in respect of legal liability		x							
Pr31	Project uncertainties	Injury to public/third party property		x			x				
Pr32	Project uncertainties	Change in labor costs for operation		x							
Pr33	Project uncertainties	Sedimentation		x	x		x				x
Pr34	Project uncertainties	Unsuitability of equipment or failure to perform intended function, malfunction		x							x
Pr35	Project uncertainties	Structural adjustments: Change in operation proceedings for water release or flood control		x							
Pr36	Project uncertainties	Changes in upstream/downstream flow regime			x		x				
Pr37	Project uncertainties	Short-term duration variation: Dry period with an inflow below the long-term average			x		x				
Pr38	Project uncertainties	Long-term variation: Incorrect original hydrological assessment, change in hydrological regime			x		x				
Pr39	Project uncertainties	Plant availability “Firm power” delivery			x						
Pr40	Project uncertainties	Performance shortfalls due to design or construction problems			x		x				

Table 19: Project uncertainties (continue)

No	Category	Cause	C1	C2	B1	B2	B3	T1	T2	T3	T4
Pr41	Project uncertainties	Electro-mechanical equipment performance			x						
Pr42	Project uncertainties	Hydraulic net head			x						
Pr43	Project uncertainties	Unduly rapid deterioration of the facilities		x	x		x				x
Pr44	Project uncertainties	Fitness for purpose (unsuitability of equipment or failure to perform intended function)			x		x				
Pr45	Project uncertainties	Latent defects			x		x				
Pr46	Project uncertainties	Maintenance needs		x	x		x				
Pr47	Project uncertainties	Safety of operation			x		x			x	x
Pr48	Project uncertainties	Organizational interfaces					x	x	x		
Pr49	Project uncertainties	Detail risks arising from survey, investigations						x			
Pr50	Project uncertainties	Site changes						x			
Pr51	Project uncertainties	Project delay or cancellation or stop of production for environmental or social reasons						x	x	x	x
Pr52	Project uncertainties	Unduly early obsolescence due to becoming outdated by technical progress									x
Pr53	Project uncertainties	Experience of owner (decisionmakers)	x	x	x	x	x	x	x		

6.4 Conclusions and Recommendations for the Application

The concept map shows the breakdown of the uncertainties and their relationship with the main objective, a certain economic performance parameter, such as NPV or IRR. This structure reflects an input to economic evaluation and allows the uncertainty assessment to be directly incorporated into the performance evaluation.

A register of commercial, political and project uncertainties was established, which can be used as a basis for the development of a project-specific register.

In addition, the register reflects the wide range of potential uncertainties that can have an impact on the performance of a hydropower project.

For a project-specific assessment, the following working steps are recommended (see also ICE, 2014):

- Preparation of a discounted cash-flow model and calculation of the economic performance parameter (such as the NPV) of the baseline scenario.
- Elaboration of a project-specific register of uncertainties based on the list provided in Table 16, Table 17, Table 18 and Table 19.
- Preliminary impact assessment of each uncertainty listed in the project-specific register. A first attempt to evaluate the significance of each uncertainty can be made on the basis of the following categorizations: (i) clearly significant, (ii) possibly significant and (iii) probably insignificant.
- In-depth studies on uncertainties with significant impact.
- Estimating the chances of occurrence of an uncertain event during the economic lifetime.
- Estimating the impact or consequence of an uncertain event.
- Calculation of risk-adjusted economic performance parameter (such as risk-adjusted NPV).

Chapter 7 Management of Uncertainty – The Proposed Framework

7.1 Introduction

In this study "management of uncertainty" is understood as an active response to uncertainty.

Whereas the approaches described in Chapter 5 and Chapter 6 focus on the assessment of uncertainties affecting a hydropower project, the methods presented in this chapter make one step further. They are seeking ways to actively avoid threats or exploit opportunities by design choices.

A wide range of methods have been proposed by previous studies, but most of them have never been applied on real ongoing projects. One of the problems is that there is no available framework for the various methods to be applied to hydropower projects with a view to provide guidance for the selection of appropriate design methods.

The following chapter firstly summarizes the current praxis of managing uncertainties in hydropower projects and, secondly, gives an overview on relevant research studies. Finally, the framework for hydropower projects is described.

7.2 Current Praxis

The four classical ways of mitigating threats to infrastructure projects are described in RAMP (ICE, 2015). Other authors (Malovic et al., 2015; Head, 2006) explain the threats to hydropower projects and give typical examples for mitigation measures. These four classical ways of mitigating threats at hydropower plants can be summarized as follows:

- Reduced or eliminated
  One possibility to reduce or eliminate threats is to adjust the design. This way of managing threats can be found in several hydropower projects, especially in early project stages. A proper hydropower design takes construction risks (such as availability of construction material, geological risks of foundation and waterway alignments, construction flood risks) into account and reduces or eliminates them by design adjustments. Also, design approaches to safety-relevant risks (such as flood safety, seismic hazard, terrorist attacks etc.) fall into this category. Other typical examples are the selection of experienced engineers and contractors, or a proper management setup.

- Transferred to another party
  From a theoretical point of view, the risk should be borne by the party best able to control it. So the threats are allocated to the employer, contractor, engineer or insurance companies, depending on the overall project strategy. According to Head (2006), political threats are typically insurable under guarantees, commercial threats are partly insurable, whereas project threats are normally not insurable. The allocation of project threats (in this

context typically known as project risks) is a major point in the contractual setup for the tender and construction phases. Finally, threats can be also shared with external parties. This category comprises projects with feed-in tariffs or projects with risks shared with external investors.

- Avoided
  The threats in question are not involved in the project at all. Typical examples in hydropower projects are the avoidance of resettlements of villages by selecting a different dam location.
- Absorbed
  Threats that cannot technically or economically be eliminated, transferred or avoided must be absorbed. Contingency for cost estimations fall into this group.

It has to be noted that these classical approaches are clearly focused on threats without taking exploration of opportunities into account. Therefore, the classical approaches can be improved by adding weight to the upside opportunities associated with uncertainty.

In addition, a significant level of uncertainty is related to long-term forecasts. There are numerous hydropower projects where the long-term forecasts were not matching the effective values and finally the plants did not reach the expected performance targets. Therefore, hydropower is strongly affected by uncertainties, which make many developers skeptical about hydropower. This is a major reason why some hydropower projects are not constructed and cannot contribute to sustainable energy supply.

Especially, the uncertainties related to climate change and the large energy price fluctuations have created a demand for methods that consider the uncertainties of long-term forecasts in the selection of design parameters for hydropower projects.

7.3 Research Studies

The following section gives an overview on reports discussing methods of managing uncertainties for hydropower projects or for the water resource sector. These studies can be categorized into two groups. The first group focuses on single methods. The second group of papers does not focus on one specific method only, but gives an overview of various promising approaches for the water sector.

7.3.1 Methods to Manage Uncertainties

Various reservoir sizing models for deterministic and stochastic environments have been developed for the design of hydropower plants (e.g. Stedinger et al., 1983; Lall and Miller, 1988; Sinha and Bischof, 1998). Labadie (1997) presents a review of reservoir system optimization models with stochastic dynamic programming approaches.

Michailidis and Mattas (2007) apply the real-option approach to an irrigation dam in Greece. The analyzed option is delay of investment. One of the main findings is that new advanced methodologies could significantly diminish the weaknesses of the discounted cash flow techniques.

Bockman et al. (2008) present a real options-based method to define investment timing and optimal capacity choice for small hydropower projects. Additionally, an optimal trigger price for initiating an investment is estimated. The method is illustrated at the example of three small hydropower projects in Norway.

Wang (2008) provides a comprehensive overview on real options applied in river basins. His work shows that the application of real options allows the net benefit to be increased and/or the downside risk to be reduced.

Nassopoulos et al. (2012) apply the regret approach to dam dimensioning in the water management sector. The study focuses on the choice of a reservoir volume and considers different climate scenarios. Finally, a reservoir volume that leads to the lowest regret is selected.

Elverhøi et al. (2010) present a decision support framework for hydropower producers with production facilities due for rehabilitation. Real Option Analysis was used to evaluate the investment opportunities.

Fertig et al. (2014) analyzed optimal investment timing and capacity choice for a pumped hydropower storage scheme in Norway. In total five capacity alternatives of the hydropower scheme with arbitrage in the German spot market are analyzed. Real Option Analysis was used to value the investment opportunity in order to account for uncertainty of the electricity market and intertemporal choice.

Arsenault et al. (2013) highlight the value of adaptive management of the operation rules. The study compares the possibilities of adding an additional turbine to an existing power plant and adapting the operation rules of this power plant for a wide range of climate change projections.

Cervigni et al. (2015) evaluate the impacts of climate change on hydropower and irrigation expansion plans in Africa's main river basins (Congo, Niger, Nile, Orange, Senegal, Volta, and Zambezi), as well as the effects on the electricity sector across four power pools (Western, Eastern, Central, and Southern power pools). Based on a single consistent methodology, a wide range of state-of-the-art future climate scenarios were analyzed. Illustrative assessments of hydropower projects were made within the scope of this study. A key finding is that applying the approach to adaptation under climate uncertainty can cut in half or reduce even more the maximum climate change impact (loss of revenue or missed opportunity to increase it) that would be faced in case of inaction. The decision method used was the Robust Decision Making approach.

7.3.2 Overview on Various Methods Applicable in the Water Sector

The Morgan et al. (2009) summarizes the topic of climate change and water resources and discusses several possibilities to respond to climate changes, which are operational, demand management, and infrastructure changes. Three principal strategies for making decisions in the face of uncertainties are presented. The report describes the classical decision analysis that seeks "optimal strategies", "resilient strategies" that work reasonably well across a range of possible outcomes, and "adaptive" strategies that can be modified to achieve better performance as the future unfolds.

Hallegatte (2009) summarizes and examines five methods applicable to long-term investments and climate uncertainty. The following five methods are evaluated: (i) selecting ‘‘no-regret’’ strategies that yield benefits even in the absence of climate change; (ii) favoring reversible and flexible options; (iii) buying ‘‘safety margins’’ in new investments; (iv) promoting soft adaptation strategies, including long-term prospective; and (v) reducing decision time horizons. The study highlights that it is essential to consider both negative and positive side-effects and externalities of adaptation measures.

The Water Utility Climate Alliance (Means et al., 2010) describes new planning techniques for water utilities to prepare for a large range of possible climate change impacts. This report describes the following five Decision Support Planning Methods (DSPM): Classic decision analysis, traditional scenario analysis, robust decision making, real-option analysis and portfolio planning. These methods were selected because of their relevance to the water industry. The report contains a comprehensive evaluation including 21 evaluation criteria. Based on these criteria, a DSPM method can be chosen for a specific planning need and taking into account available capabilities.

Ray and Brown (2015) outline a process for risk assessment of water resources projects that can serve as a decision support tool to assist project planning under uncertainty. This report provides guidance on the application of proven techniques for climate change risk assessment and advanced tools for risk management. The proposed procedure consist of four successive phases: Phase 1: Project Screening, Phase 2: Initial Analysis, Phase 3: Climate Stress Test, and Phase 4: Climate Risk Management. Importance is given to the stress test, which allows an identification of system vulnerabilities. It also allows an identification of design modifications leading to a reduction of the system’s vulnerability. The report summarizes the following four tools for decision making under uncertainty: information gap decision theory, robust decision making, dynamic adaptive policy pathways, stochastic and robust optimization (including real-option analysis). The study includes an example of the application of the proposed procedure. A run-of river hydropower project in Sub-Saharan Africa was analyzed with the objective to select the installed capacity of the scheme. The evaluation is based on regret criteria and a design case in the middle range is favored. However, no final design choice is given in the example.

7.4 The Proposed Framework

As described in the previous chapter, several promising methods have been proposed for the design of hydropower projects under uncertainties (e.g. Wang, 2008; Bockman et al., 2008; Cervigni et al. 2015; Arsenault et al., 2013; Schleiss and Oberrauch, 2014). The studies show that applying these methods allows uncertainties to be managed and threats to be finally reduced, and some of the methods also allow exploitation of opportunities. However, for their application to hydropower projects some guidance is needed as to which of the design methods is best suited.

The elaborated framework proposed in this section is specifically designed for hydropower projects. It provides guidance for the selection of potential design objectives that quantify or at least characterize its interaction with uncertainties and define the type of management of the uncertainties. Various design objectives are proposed based on the work by McManus and Hastings (2005).

These objectives are summarized in Table 20.

Table 20: Design objectives and descriptions

Design objective	Description
Robustness	Ability of the hydropower scheme to provide its originally defined services over a wide range of alternative futures, without any structural or operational adjustments
Versatility	Ability of the hydropower scheme to provide additional services not originally included to this extent in the requirements definition, with operational adjustments and without any structural adjustments
Flexibility	Ability of the hydropower scheme to be structurally adjusted to provide additional services not included in the original requirements definition, or to increase the services originally defined
Interoperability	Upstream storage schemes: Ability of the system to control water flow which can increase the energy production and energy value of existing or potential new downstream hydropower plants. Downstream and diversion schemes: Ability of the scheme to make use of potential upstream hydropower projects.

Figure 33 shows the framework including the design objectives. As it can be seen in this figure, a crucial criterion for the selection of a design objective is whether or not the strategy of managing uncertainty requires structural adjustments. From the perspective of a project team developing a new hydropower plant or a rehabilitation project, this is a critical issue.

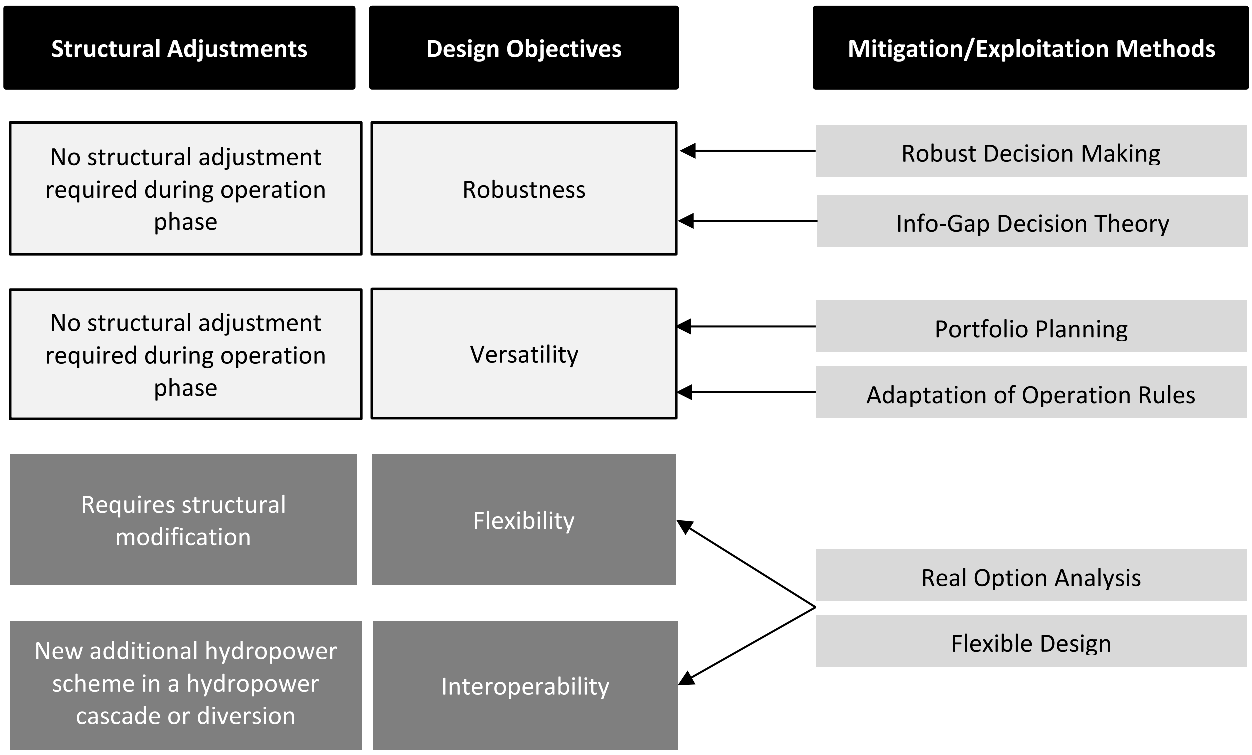

Figure 33: Concept of the framework

Whereas it is often assumed in research papers (e.g. Wang, 2008) that a hydropower project can be adjusted to given physical constraints, practical experience shows that environmental and non-power operation constraints are often the dominant limitations.

For hydropower plants, several of these constraints, such as full supply level, minimum operation level, maximum discharge capacity, minimum discharge requirements, or limitation to do hydropeaking, are typically defined in the concession contracts.

A change in such legal constraints often is a long long-lasting process and leads to additional threats. If a design change includes the assumption that a hydropower plant can be adjusted during the operation phase, it is necessary to consider the downside risk that permissions for structural adjustments might be withheld or granted after several years of delay only.

As to the criterion whether a project is a greenfield plant or an existing plant, the question to be answered by the project team is whether or not structural adjustment are a possible option.

If structural adjustments are considered not to be an option, robustness or versatility can be selected. These design objectives are focused on the services that can be provided with the schemes as built or designed. The robustness of a scheme is set during the planning stage and cannot be influenced during the operation phase. Therefore, versatility is the only design objective that can be investigated for existing hydropower schemes where no structural adjustments are to be considered.

Compared with the design objective robustness, versatility focuses on additional services not originally foreseen in the design requirements.

Services to be provided are defined in the planning phase and are based on the needs and opportunities of a hydropower scheme. Typically, requirement definitions of the services describe the type of energy to be provided: base load, peak energy and/or reserve energy. In case of a multipurpose scheme, the requirement definitions include also the design criteria for other purposes such as flood control, irrigation or water supply. Versatility aims to improve the performance by integrating additional purposes such as flood control, or by providing additional energy production services such as reserve energy instead of peak energy.

Flexibility and interoperability require structural modification or major extension. Interoperability is only relevant if a new hydropower scheme will possibly be constructed in the river basin.

Flexibility foresees a reconstruction or upgrading of an existing power plant in order to better match the observed conditions and the forecasted scenarios for the next decades. A shift in the electric supply market, hydrology, sedimentation, or ecological preferences can change the definition of what effective designs are, and the original design criteria elaborated for the construction of the power plants would have to be adjusted and structural modification to be undertaken. Flexibility includes options such as increase in storage capacity by dam heightening, installation of an additional turbine make, or extension of the scheme by constructing an additional diversion scheme.

Interoperability focuses on river basin development and not on standalone hydropower plants.

Depending on the design objectives, different mitigation or exploitation methods can be applied. Robustness can be achieved by applying the Robust Decision Making (RDM) method or the Info-Gap Decision Theory (IGDT). Adaptation of the Operation Rules or Portfolio Planning can be used where versatility is the selected design objective. Real-Option Analysis or the more general concept of Flexible Design allows a design for flexibility or interoperability.

The design objectives also differ with regard to the implementation phase. Measures to achieve high robustness are planned and implemented during the planning phase. In other words, this is an active process during the planning phase and a passive process during the operation phase. Measures focused on versatility, flexibility or interoperability can be designed during the planning phase, but the decision whether or not they will be implemented will be made during the operation phase, depending on the potentially changing operation conditions. Compared with robustness, these management measures are active processes during the operation phase.

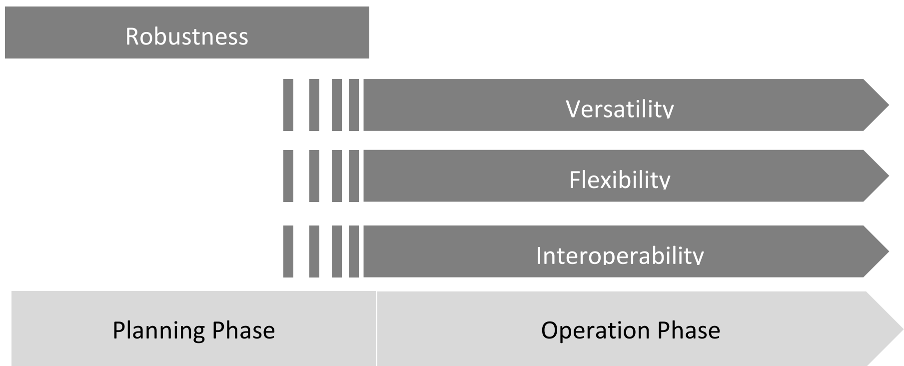

Figure 34: Phase of implementation of the measures depending on the design objectives

7.5 Conclusions

A simple framework for hydropower projects was developed, allowing a straightforward selection of the design objective and the required design method. It includes methods that have to be carried out during the planning phase as well as methods that are more suitable for power plants in operation.

Importance is given to the question whether or not structural adjustments are required, as this can be a critical item for a project team's decision whether or not to follow up on certain possibilities.

Details on the proposed design objectives and their application are given in the following chapters.

Chapter 8 Case Study – Description of Analyzed Hydropower Project

8.1 Introduction

A real-world hydropower project in the Swiss Alps was selected for a case study in order to test and illustrate the application of the different methods.

In order to promote the different new design methods, a simple case has been selected, which represents a typical design problem. An adequate plant size needs to be selected based on the design discharge. But the energy price forecasts are highly uncertain and there also is some uncertainty about anticipated inflows. Inflow is expected to increase in the future as the catchment area is partly covered by glacier. Therefore, the classical approach, which would be to select the design discharge on the basis of the highest NPV without taking uncertainties into account, may not lead to an optimum result in terms of design discharge selection.

The present chapter provides a description of the project selected for the case study for which the design objectives of robustness and flexibility have been analyzed. For the description and discussion of the application of the new design methods to this real project, reference is made to Chapter 9.3.3 for Info-Gap Decision Theory, to Chapter 9.4.3 for Robust Decision Making, and to Chapter 11.4 for Flexible Design.

The technical design was developed by an engineering company and is described in the feasibility study by Pöyry Energy (2007). Chapter 8.2 gives a brief overview and the construction costs of the various design alternatives.

Chapter 8.3 describes the hydrological study for this research project. As some of the applications require climate change projection, a hydrological model was elaborated and inflow time series for a wide range of climate change scenarios were simulated.

All energy simulations were carried out with a production model in daily time steps. The developed model and the used input parameters are described in Chapter 8.4.

Chapter 8.5 gives the assumed input parameters for the calculation of economic performance parameters.

8.2 Project Description

The project is a high-head run-of hydropower scheme in the Swiss Alps. The headworks consists of a weir equipped with a main gate and a flushing gate, and a two-chamber sand trap. The waterway is designed as an underground structure with a 1.8 km long low pressure reservoir tunnel and a 1.2 km long inclined tunnel which will be equipped with a penstock. Two Pelton units with equal installed capacity are foreseen.

The plant size is determined by the installed capacity, which depends on the design discharge. Active storage is not foreseen. Five different design discharge rates within a range between 2.0 m^3/s and 6.0 m^3/s are considered. The estimated construction costs are summarized in Table 21.

Table 21: Salient features of design alternatives

		Alternatives				
Parameter	Unit	Qd2	Qd3	Qd4	Qd5	Qd6
Design discharge (Q_d)	[m^3/s]	2.0	3.0	4.0	5.0	6.0
Max. generation discharge (Q_{max})	[m^3/s]	2.7	4.0	5.4	6.7	8.0
Gross head(H_g)	[m]	522.0	522.0	522.0	522.0	522.0
Net head (H_n) at Q_d	[m]	507.3	510.2	511.3	511.7	511.4
Specific hydraulic loss coefficient	[-]	3.678	1.316	0.667	0.414	0.295
Efficiency of E&M equipment (η)	[-]	0.88	0.88	0.88	0.88	0.88
Installed capacity (IC)	[MW]	9	13	18	22	26
CAPEX	[CHF million]	40.2	43.7	47.1	50.1	52.7

8.3 Hydrology

8.3.1 Introduction

The purpose of the hydrological model was to analyze the climate impact on the design choice for various installed capacities of a hydropower project. Therefore, a hydrological model was applied to simulate various climate change scenarios. The discharge series of the different climate change scenarios were simulated at daily time steps and then used for energy production simulations.

8.3.2 Catchment

The catchment of the hydropower project covers an area of 25 km^2. The catchment is partly glacierized (22%) and its steep alpine topography covers elevations between the altitude of the intake of 999 m asl and 3119 m asl.

A gauging station (Alpbach-Erstfeld) with long-term records (start of records in 1961, ongoing) is located in the catchment and covers about 82% of the catchment area of the planned hydropower plant. The discharge recorded at the gauging station is characterized by strong seasonal fluctuations due to snowmelt and glacier melt in late summer.

The records from this reference station were used for the calibration and validation of the rainfall-runoff model. In addition, records from the period 1961 to 2013 were selected as reference inflow. The inflow at the intake was calculated based on the ratio of the catchment areas of the gauging station and at the intake location.

Climate change studies require long-term meteorological records. As there are no meteorological stations in the catchment area, stations in the close vicinity were selected according to their distances from the catchment area and their elevations. Table 22 is a list of meteorological stations selected for this study.

As reported by Kobierska et al. (2013), meteorology in this region is highly affected by altitudinal gradients so that the data requires pre-processing. An adjustment factor was determined on the basis of the long-term specific runoff in order to obtain the catchment rainfall from the point measurements of the observed data.

Table 22: List of meteorological stations

Elevation Band (EB)	Parameter	Meteorological stations used
EB - Glacier	Precipitation	Altdorf, Engelberg, Gütsch
EB - High Altitude	Precipitation	Altdorf, Engelberg, Gütsch
EB - Medium Altitude	Precipitation	Altdorf, Engelberg, Gütsch
EB - Glacier	Air temperature	Gütsch, Titlis
EB - High Altitude	Air temperature	Gütsch
EB - Medium Altitude	Air temperature	Engelberg, Gütsch

8.3.3 Hydrological Model

The hydrological model "Routing System" developed at the Laboratory of Hydraulic Constructions (LCH) of Ecole Polytechnique Fédérale de Lausanne (EPFL) was selected for the simulation of the mountainous catchment of the case study. This model was developed and tested for hydrological-hydraulic modelling tool studies in high-mountainous catchment areas (Dubois, 2005; García Hernández et al., 2007; Bieri, 2013). The hydrological forecasting process is based on the semi-distributed conceptual approach, and spatial precipitation and temperature distributions can be taken into account for simulating the dominant hydrological processes, such as glacier melt, snowpack constitution and melt, soil infiltration and runoff. For details on the model, reference is made to García Hernández et al. (2007).

The catchment area was discretized in three elevation bands. Each elevation band is characterized by a dominant hydrological process. The elevation band between 2'727 m asl and 3'119 m asl is mainly covered by glaciers. The middle and lower elevation bands have no permanent ice cover, but, due to their different elevations, the major difference between them lies in the seasonal evolution (melt and accumulation) of snowpack. Table 23 gives the elevation bands and their areas.

Table 23: Discretization of catchment

Elevation Band	Catchment area km^2	Min. elevation m asl	Max. elevation m asl	Mean elevation m asl
EB - Glacier	5.50	2’313	3’119	2’727
EB - High Altitude	12.85	1’803	3’040	2’225
EB - Medium Altitude	6.93	999	1’803	1’462
Total Catchment	25.27	999	3’119	2’094

8.3.4 Calibration and Validation

The purpose of the hydrological study is to simulate energy production of a run-of scheme using different design alternatives corresponding to different design discharges. Therefore, the ratio of the simulated and observed design volumes (r_{Qmax}) was used for calibration. The design volume (V_{Qmax}) determines the potential energy production of a run-of hydropower scheme. It expresses the mean volume of water that can be expected to be available for energy production for a specific maximum generation discharge (Q_{max}). For run-of river plants, V_{Qmax} is typically derived from flow duration curves. For further information on how to calculate V_{Qmax}, see Hänggi and Weingartner (2012).

r_{Qmax} is defined as follows:

$$r_{Qmax} = \frac{V_{Qmax}^{sim}}{V_{Qmax}^{obs}} \tag{11}$$

where V_{Qmax}^{sim} = simulated volume for a specific maximum generation discharge; V_{Qmax}^{obs} = observed volume for a specific maximum generation discharge.

The model was calibrated for the time period from 01.01.1983 to 31.12.1996 and validated for the following 13-year period until 31.12.2009.

The calibration shows good agreement between the measured and simulated runoffs and tends to be on a conservative side. For the comparison of the project alternatives it is important that no significant variation of the different r_{Qmax} is observed.

The results of the validation period indicate for the simulated annual volume an accuracy in the range of about ±8%, which was found to be adequate for the purpose of this study.

Table 24: r_{Qmax} for calibration and validation periods

Max. generation discharge	[m^3/s]	2.7	4	5.4	6.7	8
Calibration Period (01.01.1983-31.12.1996)						
r_{Qmax}	[-]	0.96	0.93	0.93	0.94	0.95
Validation Period (01.01.1997-31.12.2009)						
r_{Qmax}	[-]	1.03	1.02	1.04	1.06	1.08

8.3.5 Climate Change Scenarios

In total 10 climate change scenarios were considered. The climate change scenarios are based on the data elaborated for the extensive research project "Swiss Climate Change Scenarios CH2011" (CH2011, 2011; Bosshard et al. 2011). This report and the corresponding data provide a detailed basis for climate impact studies. The data is based on 30-year mean temperature and precipitation changes and is generally suitable for analyses of mean annual cycles. The precipitation and temperature datasets were derived from regional climate model data provided by the ENSEMBLES project (Linden and Mitchell, 2009). In total 10 model chains, each consisting of one general circulation model (GCM) driving one regional model (RCM), were studied. All model chains are based on the A1B emission scenario so that the differences between the 10 model chains represent modelling uncertainty. The A1B emission scenario is characterized by balance across fossil-intensive and non-fossil energy sources, describing a future world of very rapid economic growth with a global population that peaks in mid-century and declines thereafter. In addition, it assumes a rapid introduction of new and more efficient technologies (CH2011, 2011).

The 10 different model chains considered in this study are given in Table 23.

Table 25: Climate change – Model chains

Institute	GCM	RCM
ETHZ	HadCM3Q0	CLM
HC	HadCM3Q0	HadCM3Q0
SMHI	HadCM3Q3	RCA
DMI	ECHAM5	HIRHAM
KNMI	ECHAM5	RACMO
ICTP	ECHAM5	REGCM
MPI	ECHAM5	REMO
SMHI	ECHAM5	RCA
CNRM	ARPEGE	ALADIN
SMHI	BCM	RCA

The dataset provides changes relative to the reference period from 1980 until 2009 for the scenario periods 2021-2050 (referenced as 2035), 2045-2074 (referenced as 2060), 2070-2099 (referenced as 2085). The changes of temperature and precipitation for the 10 models chains are available for various meteorological stations in Switzerland.

8.3.6 Results

Figure 35 presents the mean annual inflow volume of projections from near (2035) to far future (2085). In the near future all 10 model chains indicate a relatively low increase of the annual runoff (<10%). In the long future 5 out of 10 model chains lead to a moderate increase of the annual runoff in the range from 15% to 20%.

Figure 36 shows the monthly average discharges of the 10 model chains over a simulation period of 27 years. In terms of seasonal pattern, the simulation leads to similar results.

Discharge increases during spring and early summer. The peak flow shifts from July towards June and will be more pronounced. The discharges of July and August fall below the long-term records. In addition, simulation results predict higher winter discharge.

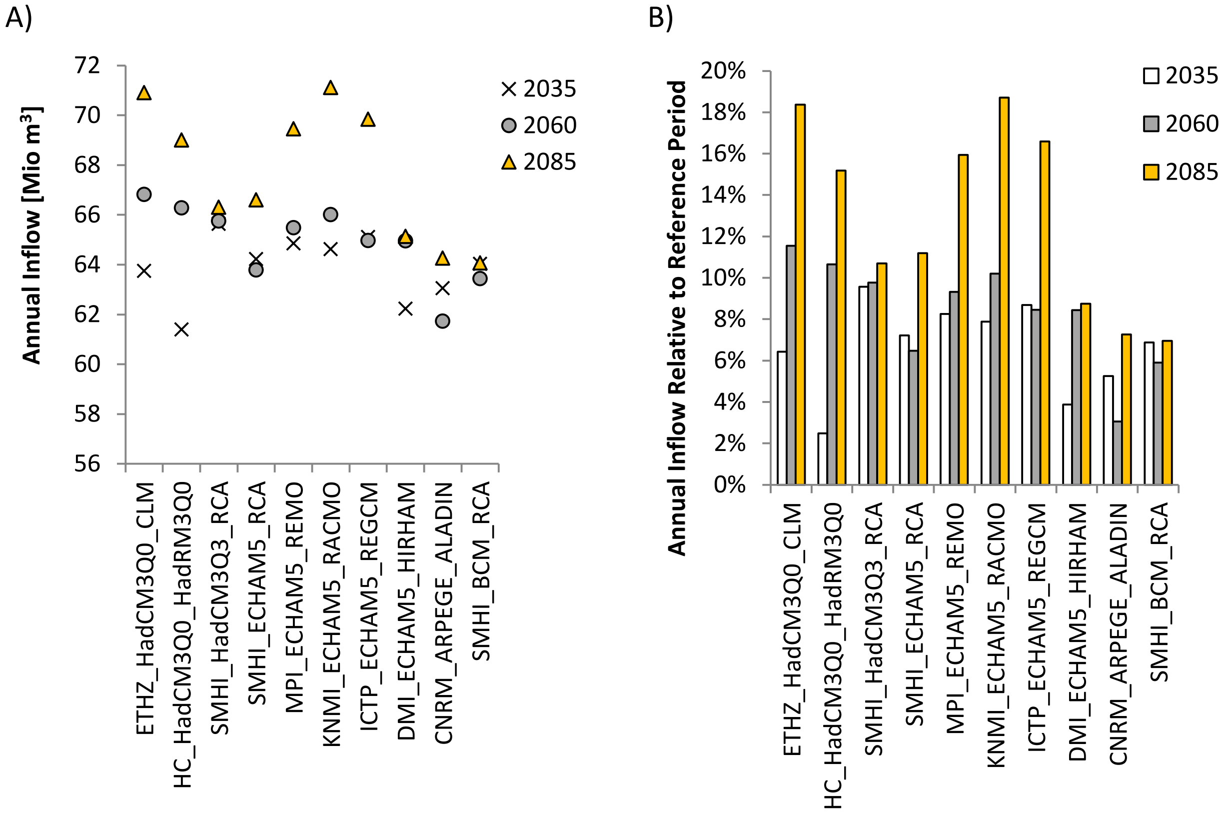

Figure 35: Annual inflow of the simulated model chains for different climate change projections A) shows the calculated annual inflow, B) presents the changes relative to the reference discharge

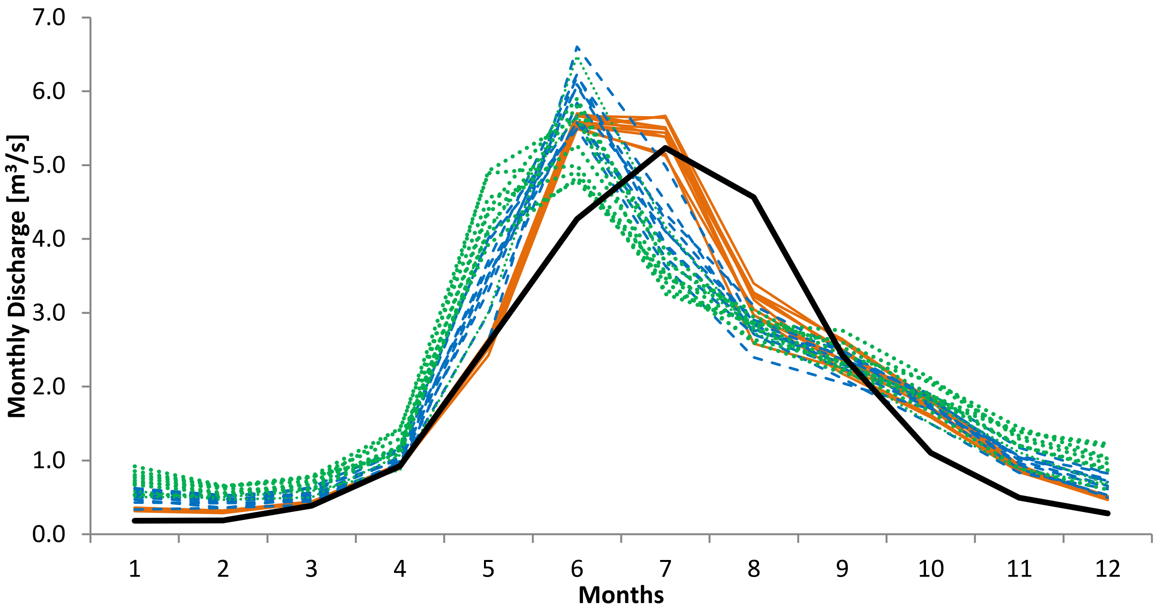

Figure 36: Monthly discharge of different climate change projections and the reference discharge (black line); discharge projections for the periods 2035 (orange lines), 2060 (blue lines) and 2085 (green lines)

8.4 Energy Model

An energy production model applicable for a high-head run-of river power plant was elaborated. The spreadsheet model simulates daily energy production of a stand-alone hydropower plant for periods up to 50 years. The model needs long-term daily inflow and the required environmental flow, on the one hand, and the technical parameters of the analyzed design alternative on the other (see Table 21).

8.5 Economic Evaluation

A DCF model is used for the calculation of economic performance parameters. Input parameters for the DCF model are listed in Table 26.

Table 26: Input for economic model

Parameter	
CAPEX	Depending on design alternative
OPEX	1% of CAPEX, plus CHF 50‘000/year (fixed costs)
Re-investment in E&M equipment	(35 years after start of operation)
WACC	3%
Construction period	3 years
First year of operation	4^{th} year
Economic lifetime	50 years
Water royalties	CHF 110 /kW gross capacity

Table 27 gives the NPVs for the analyzed design alternatives based on the assumption of a long-term energy price of 65 CHF/MW. A design discharge of 4 m^3/s, which corresponds to an installed capacity of 22 MW, has the highest NPV (Alternative Qd4), followed by design alternative Qd5.

Table 27: NPV of alternatives

		Alternatives				
	Unit	Qd2	Qd3	Qd4	Qd5	Qd6
NPV	[CHF million]	1.32	10.36	13.66	13.30	11.37

8.6 Conclusions

An actual hydropower project has been selected for the application of the different new design methods. The selected case represents a typical design problem, namely the choice of a design discharge. The conventional approach would lead to a design discharge of 4 m^3/s (Design alternative Qd4).

The climate change projections indicate an increase in long-term inflow in comparison with the historical discharge data. However, the climate change projections cover a wide range of future states. In addition, the long-term energy price is considered to be a major source of uncertainty with a potential impact on the design discharge to be chosen for this power plant.

Therefore, new promising design methods have been applied. For the description and discussion of the application of the new design methods to this real project, reference is made to Chapter 9.3.3 for Info-Gap Decision Theory, to Chapter 9.4.3 for Robust Decision Making, and to Chapter 11.4 for Flexible Design.

Chapter 9 Robustness

9.1 Introduction

No uniform definition of robustness exists. Morgan et al. (2009) gives on overview on the various definitions and concepts. Two promising approaches in hydropower design are Robust Decision Making (RDM) (Lempert et al., 2003) and the Info-Gap Decision Theory (IGDT) (Ben-Haim, 2006).

Lempert et al. (2003) define robust strategy as one that performs well over a very wide range of alternative futures – in comparison with its alternatives.

Based on the robustness definition used in the info-gap approach developed by Ben-Haim (2006), a robust strategy sacrifices a small amount of optimal performance in order to obtain less sensitivity to broken assumptions.

In recent years, a strong focus has been put on the development of robust decision methods, especially under the pressure of climate change. In this context, robustness is often defined as keeping options open. Adaptive decision strategies or system flexibility make part of these concepts (IPCC, 2001; Rosenhead, 2001). However, this work distinguishes between design objectives according to whether or not they require structural modification. The concept of flexibility takes into account that the structure of a hydropower scheme can be adjusted during its life cycle, whereas the concept of robustness assumes that no structural changes (other than maintenance or rehabilitation) will be carried out during the operation period.

9.2 Application Potential

The methods have the potential to guide the project team to define robust plant size parameters, e.g. design discharge and active storage, without agreeing on the potential futures.

Especially for hydropower plants, where there is no possibility of extension of services or structural modification, robust design is the preferred measure.

Examples of manageable factors under severe uncertainty include:

- Electricity price
- Inflow (including climate change)
- Compensation flow
- Water supply
- Irrigation water

9.3 Info-Gap Decision Theory

9.3.1 Description of Method

The Info-Gap Decision Theory (IGDT) is a methodology developed by Ben-Haim for supporting model-based decisions under severe uncertainty. According to Ben-Haim (2010), an info-gap is defined as follows:

An info-gap is a disparity between what is known and what needs to be known in order to make a comprehensive and reliable decision.

For the design of a hydropower plant we often have an info-gap on the energy price. We know very little about how the energy price will develop in the long run, but we need this information to make a comprehensive and reliable decision on the design parameters.

An info-gap is also included in the inflow forecast. Uncertainties related to the measured data, interpretation of incomplete data, simplifications inherent in the hydrological model structure, model parameters (Refsgaard and Storm, 1990) or, more generally, climate change lead to a certain info gap.

Further aspects can also be treated as info gaps, depending on a given project, such as water supply, which may change over the long term with a growing population, irrigation water depending on agricultural development and/or climate change, or compensation flow, which may change due to changes in legislation.

The info-gap analysis is based on the following three elements:

- **Info-gap model of uncertainty**: This is a non-probability quantification of uncertainty, such as the mean annual energy price over the economic lifetime or the mean inflow volume
- **System model**: The system model in the context of hydropower design is typically structured in several sub-models (energy price forecast model, hydrological model, energy production model, construction cost estimation and economic model), which leads finally to the performance parameter.
- **Performance requirements**: This can be a set of values that define the outcomes to be achieved, which can be a certain NPV or annual energy production, the reliability of the energy production, or the definition of various types of energy (peak, base or reserve energy), or a combination of these requirements.

Two decision functions are formulated based on the analysis of the info-gap including the components uncertainty model, system model and performance requirements. The following decision functions support the selection of a reliable design concept:

- **Robustness function:** The robustness function assesses the greatest tolerable horizon of uncertainty by satisfying the performance requirements. In other words, how wrong can our assumptions or forecasts be while still providing an acceptable performance of the hydropower plant.

- **Opportuneness function**: The opportuneness function assesses the lowest horizon of uncertainty possible for an outcome better than anticipated. However, this is about potential, not guarantee. Some design parameters may bring great “windfalls”, such as additional installed capacity allowing additional energy to be generated in case of unexpected flow from climate change-induced glacier melt.

The robustness and opportuneness functions do not necessarily lead to the same preferred design parameters. The *robust-satisficing* decision strategy selects the more robust option, whereas the *opportune-windfalling* decision strategy chooses the concept that can lead to a better performance than expected.

9.3.2 Application to Hydropower Design

According to our best knowledge, the IGDT approach has never been used in hydropower projects so far, whereas various research work has been done in water infrastructure.

A comparison of both methods for water system planning was prepared by Matrosov et al. (2013). RDM and IGDT were applied in an expansion project for London’s water supply system to identify the most robust alternative out of 20 water supply infrastructures. Uncertainty of future hydrological inflows, water demands and energy prices were considered. For the identification of the most robust system, multiple criteria of system performance were into account. The study concludes that the methods are complementary and can be beneficially used together to better understand results.

9.3.3 Case Study

Description of Case

The application of the IGDT has been tested for the high-head run-of hydropower plant described in Chapter 8.

Uncertainty Model

It was assumed that the long-term annual energy price ($\tilde{u}_1$) would be 65 CHF/MWh. The hydrological studies estimated an average inflow volume of 64.51 million m^3/a based on records of the period 1961-2013 ($\tilde{u}_2$).

The energy price (u_1) and the inflow volume (u_2) are both highly uncertain and influence the NPV. No probability on the energy price and inflow forecasts can be given, or is agreed on, by the project team.

The energy price might decrease to about 30 CHF/MWh or increase to about 120 CHF/MWh. The hydrological study estimates a range between 59.91 million m^3 (historical long-term average, 1961-2013) and 71.12 million m^3 of annual inflow. All inflow series that take climate change into account lead to an increase of the inflow volume.

These ranges of estimates are integrated in an uncertainty model to form upper and lower boundaries, i.e. σ_l (lower boundaries) and σ_r (upper boundaries). The scaling factors are ω_l for the left-hand side and ω_r for the right-hand side. The uncertain parameters (energy price and inflow volume) are scaled by h for each "horizon" or increment of uncertainty.

The info-gap model becomes:

$$U(h,\tilde{u}) = \{u : max[\sigma_l,(1-\omega_l h)\tilde{u}_i] \leq u_i \leq min[\sigma_r,(1+\omega_r h)\tilde{u}_i]\},$$
$$h \geq 0, i = 1,2 \qquad (12)$$

The available information and assumptions are summarized in the following table.

Table 28: Input to the IGDT model

	Convention	Value
Estimated energy price	$\tilde{u}_1$	65
Estimated inflow volume	$\tilde{u}_2$	59.91
Lower boundaries	σ_l	σ_l = [30, 59.91]
Upper boundaries	σ_r	σ_r = [120, 71.12]
Scaling factor, left-hand side	ω_l	ω_l = [0.538, 0.000]
Scaling factor, right-hand side	ω_r	ω_r = [0.846, 0.187]

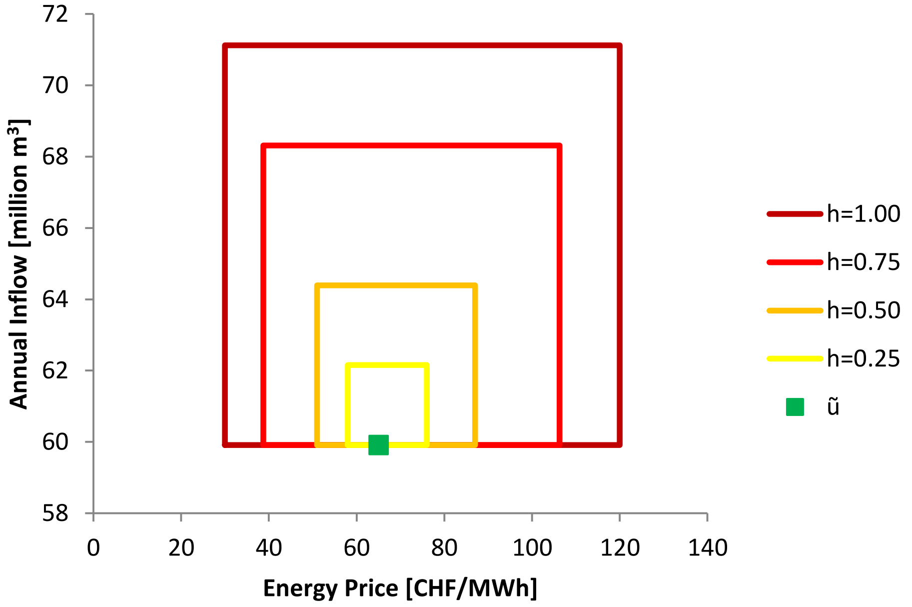

Figure 37: Info-Gap uncertainty model showing the uncertainties from a best estimate ($\tilde{u}$) of the energy price and the annual inflow of each horizon (h).

System Model

The system model is composed of an energy production model and an economic model. For the simulation of energy production, a model with daily simulation time steps was selected. For details, reference is made to Chapter 8.4 and Chapter 8.5.

Performance Requirement

A $NPVc$ = 0 was selected. That means that the NPV will be always positive under the consideration of the estimated uncertainties.

Robustness and Opportuneness Functions

The actual net present value of each design alternative (NPV_d) is unknown, as the actual energy price and actual inflow volume are unknown. The robustness to uncertainty of the design alternative is the greatest horizon of uncertainty up to which the NPV_d of that design is not worse than a critical NPV_c. The robustness function for each design alternative (*d*) is defined as follow:

$$\hat{h}\,(d) = max\left\{h\colon \min_{u_i \in U(h)} NPV_d\,(u_i, d)\ \geq NPV_c\right\} \tag{13}$$

The opportuneness from uncertainty of the various design alternatives is the lowest horizon of uncertainty at which the NPV can be as high as the NPV_w:

$$\hat{\beta}\,(d) = min\left\{h\colon \min_{u_i \in U(h)} NPV_d\,(u_i, d) \geq NPV_w\right\} \tag{14}$$

Results

The design alternative Qd4 is the most robust solution, tolerating a 14% decrease of the energy price and using the historical inflow, which corresponds to the lowest estimate. (Level of robustness is 0.26). An annual inflow of about 59.91 million m^3/year and a mean energy price of about 56 CHF/MWh will lead to an NPV equal or higher than zero. For NPVs larger than the critical NPV, the design alternative Qd4 is always the preferred design alternative.

Qd5 is the next most robust design alternative, able to maintain an acceptable level of performance with an energy price 13% lower than the best estimate (level of robustness of 0.24).

The slopes of the robustness curves equal the increments of robustness that can be obtained by reducing the performance by one unit. A steep slope means that the robustness can be increased with only small loss of performance. In the analyzed case, design alternatives with a smaller design discharge have larger slopes. This leads to a crossing of Qd3 and Qd6 at a robustness level of about 0.13.

The opportuneness curves show the performances of each of the design alternatives that can be achieved in more benign futures (see Figure 40). The focus is on the lowest opportuneness curves with a shallow gradient, which indicate a high increase in performance for small increments of uncertainty. The higher the design discharge is, the smaller the slopes of the opportuneness curves are. Should the inflow and the energy price turn out to be higher than expected, a larger plant size can provide for a higher increase of the NPV.

The opportuneness curves show a crossing of Qd5 and Qd4 at an increment level of about 0.10. In other words, if the inflow volume increases to more than about 61.03 million m^3 and if the energy price exceeds 69 CHF/MWh, Qd5 will result in a higher NPV. Qd6 crosses Qd4 at a horizon of 0.15 (inflow volume of 61.59 million m^3, energy price of 70 CHF/MWh).

In a more benign future, Qd5 and Qd6 will lead to similar results, if the uncertain parameters (inflow volume and energy price) are both scaled together. That means that energy price and inflow volume will increase proportionally.

For an analysis of each uncertain parameter, the value of the other parameter is set at the best estimate (see Figure 41 and Figure 43). If only one of the two uncertain parameters is considered, i.e. either the energy price or the inflow volume, it can be observed that the opportuneness curves of Qd6 and Qd5 do not cross and Qd5 will always be the preferred design alternative. Only if both the energy price and the inflow increase, Qd6 could turn out to be the best solution.

Should the project team be risk-averse, Qd4 would be the preferred solution. This design alternative leads to a positive NPV also under harsher futures. If more attention is given to opportuneness, either Qd5 or Qd6 could be selected; Qd6, however, is found to be attractive only if there is an increase in energy price and inflow.

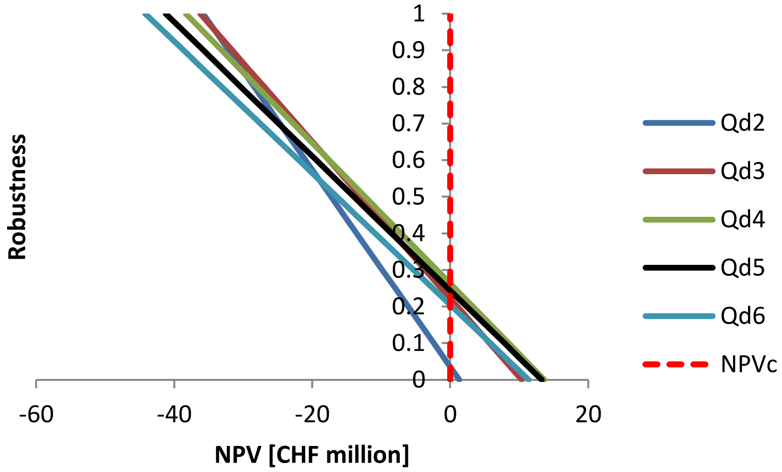

Figure 38: Robustness curves for different design alternatives (Qd2 to Qd6). Qd2 is the design alternative with a design discharge of 2 m^3/s, Qd3 has a design discharge of 3 m^3/s…Qd6 has a design discharge of 6 m^3/s. *NPVc* is the performance requirement (*NPVc* = 0).

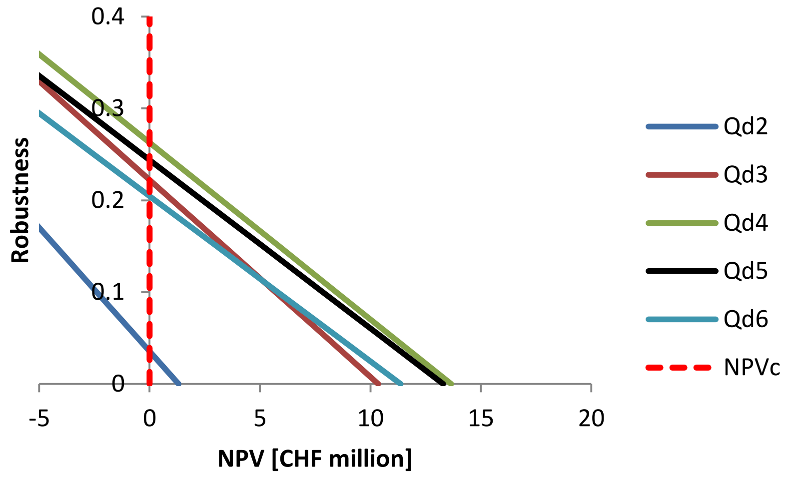

Figure 39: Detail view of Figure 38: Robustness curves for different design alternatives (Qd2 to Qd6). Qd4 is the most robust design alternative.

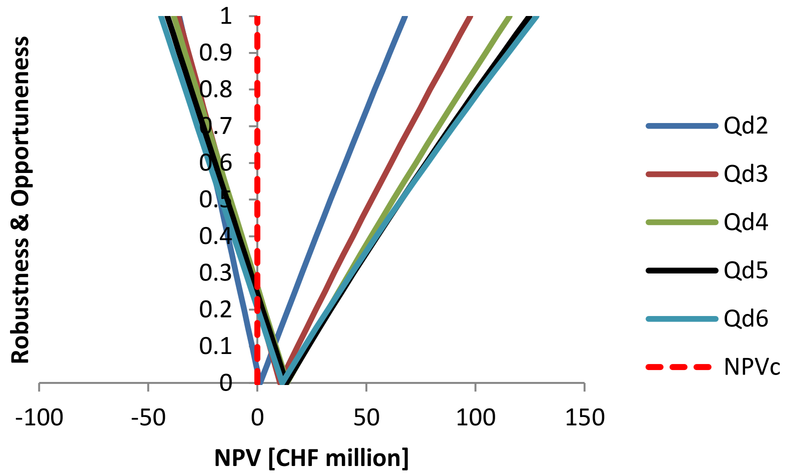

Figure 40: Robustness and opportuneness curves for different design alternatives (Qd2 to Qd6). *NPVc* is the performance requirement (*NPVc* = 0).

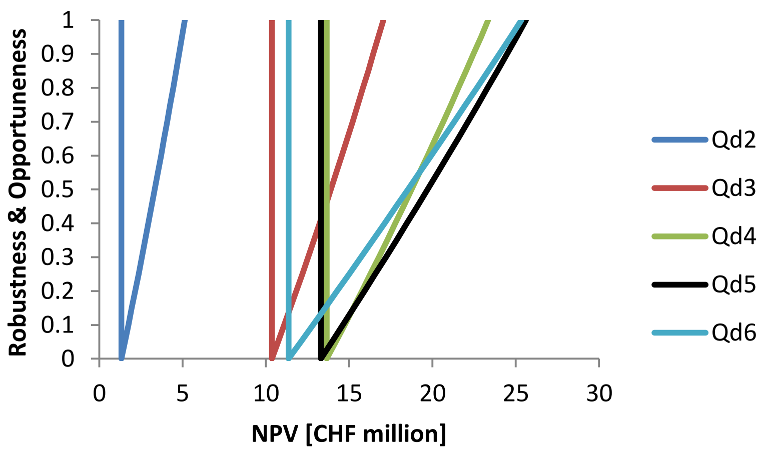

Figure 41: Robustness and opportuneness curves for different design alternatives (Qd2 to Qd6) based on inflow uncertainty only

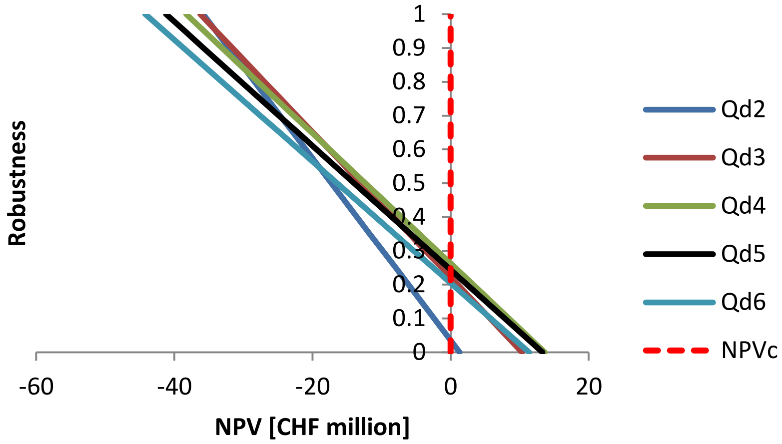

Figure 42: Robustness curves for different design alternatives (Qd2 to Qd6) based on energy price uncertainty only. *NPVc* is the performance requirement (*NPVc* = 0).

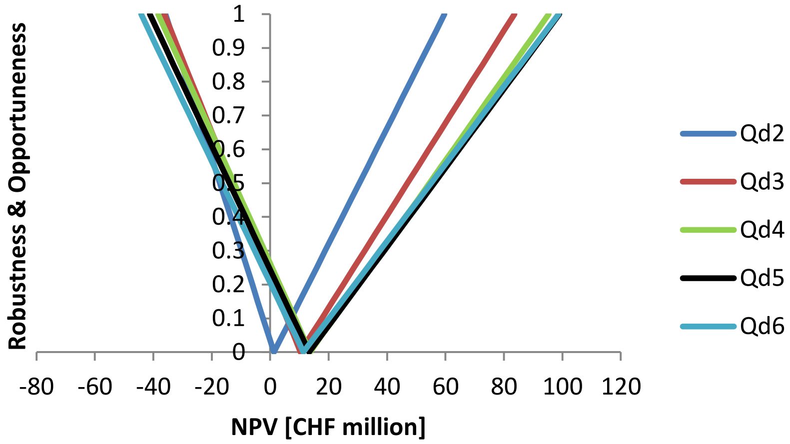

Figure 43: Robustness and opportuneness curves for different design alternatives (Qd2 to Qd6) based on energy price uncertainty only

9.3.4 Discussion

The Info-Gap Decision Theory (IGDT) offers a structured framework to analyze a hydropower scheme in highly uncertain situations. In the reported example, energy price and inflow were considered as the uncertain parameters. However, the method can be easily extended to include other factors, such as weighted average cost of capital (WACC).

On the one hand, the method allows the most robust design for harsher futures to be identified, but, on the other, it also shows clearly the opportuneness of design alternatives.

The robustness and opportuneness curves are providing valuable information for a comprehensive decision, and an especially advantageous feature of this approach is that the continuous robustness and opportunities curves allow for the identification of the uncertainty level at which a different design concept would lead to better results.

In addition, the method can be applied without assigning any probabilities to any of the uncertain factors and it can be used on the basis of best estimates and lower and upper boundaries. Best estimates of inflow, energy price or construction costs are part of any design study of hydropower projects, and can be directly integrated into the IGDT.

Another advantage of this method is that both the concept and the results can be easily communicated also to decision-makers not familiar with design methods considering uncertainties.

The definition of the uncertainty model can be challenging, especially if the uncertain parameters are to be handled as time series (such as hydrological inflow series based on climate change scenarios).

A clear limitation of this approach is the lack of examples of the application of IGDT for hydropower projects. According to our best knowledge, the above-reported case study is the very first attempt to apply this approach to hydropower projects. Further guidance for engineers would be needed to implement it in practice.

9.4 Robust Decision Making

9.4.1 Description of Method

Robust Decision Making (RDM) is a set of methods and tools designed to support decision-making under deep or severe uncertainty. The method describes uncertainty by considering the performance over a wider range of futures. For the selection of a design alternative, preference is given to robustness over optimality.

The decision framework combines features of both classic decision analysis and scenario planning. Morgan et al. (2009) characterize classic decision analysis as a method that describes uncertainty with well characterized probabilities, recommends optimal strategies, and uses tools such as decision trees or influence diagrams to illustrate planning options. Robust decision differs from classic decision analysis in two aspects. Firstly, it evaluates robust strategies or design concepts as opposed to one optimum criteria (Lempert and Collins, 2007). Secondly, RDM is based on either scenario without probability distributions, or it considers imprecise probability distributions. Later there can be a probability covering a range of values (Means et al., 2010). In contrast to sensitivity analysis, it provides a mechanism for controlling the sensitivity and is therefore not only a reactive approach.

An RDM analysis for hydropower design basically follows the following working steps (see also Cervigni et al., 2015):

1. List of possible future states
2. Selection of design alternatives
3. Simulation of performance for different future states: During this working step the performance for many different future states are simulated.
4. Sensitivity and vulnerability: The trade-offs among the design alternatives and the performance across the different futures are analyzed in order to identify the sensitivity

and to characterize the vulnerabilities. A differentiation between sensitivity and vulnerability is useful, as some projects may be sensitive to harsh futures but will not be very vulnerable as the overall performance is very high.

5. Ranking of design alternatives: Design alternatives are ranked based on a selected robust decision rule or a combination of them.

These working steps can lead to a final design decision or to a preliminary robust design, which can be used as a new starting point for additional iterations through the process.

Robust Decision Rules

The selection of a design alternative is based on a robust decision rule. For hydropower design three different rules have been suggested (see Table 29). All rules are based on a measure of regret, which is defined as the difference between the performance of a design alternative in some future and the performance of the best design alternative for that future (Cervigni et al., 2015).

The mini-max regret criterion was introduced by Savage (1950) and has often been applied for decisions under deep uncertainty. This approach has become more and more widely discussed in the literature in decision-making that incorporates the uncertainties of climate change (e.g. Cervigni et al., 2015; Harry, 2008; Willows et al. 2003; Lempert and Collins, 2007). The mini-max regret is easy to implement, but can be unduly influenced by extreme cases.

The domain criterion defines a robust design as one that performs reasonably compared to the alternatives across a wide range of plausible futures. The aim is to reduce the interval of plausible futures over which a strategy performs poorly (Lempert and Collins 2007).

If some probabilistic information on the relative likelihood exists, the third criterion can be applied. That can be done by excluding the most extreme alternative futures (e.g. driest or wettest hydrology projections).

Depending on the robustness criteria applied, a satisficing criterion has to be defined. A possible satisficing criterion is to define those of the design alternatives that exceed a certain economic performance parameter (threshold figure). An alternative satisficing criterion can be the design alternative that performs better than all other plausible design alternatives, in other words a measure of regret.

The choice of design parameters can vary according to the applied robustness criteria.

Table 29: Robustness Criteria (Source Cervigni et al. 2015)

Robustness Criteria	**References**
Minimize maximum regret	Savage, 1950
Domain criteria: satisfice over a wide range of future conditions	Rosenhead 2001; Lempert et al., 2006; Lempert and Collins, 2007
Satisfice over a wide range of likelihoods for future conditions	Lempert and Collins, 2007; Nassopoulos et al., 2012

9.4.2 Recent Application to Hydropower Design

Nassopoulos et al. (2012) apply RDM to dam dimensioning in the water management sector. In that paper the "regret" (or error cost) is calculated if the dam is designed using one of the climate scenarios, while another one is the "correct" one. The reservoir volume with the potential for smallest regret is found to be the best concept.

Cervigni et al. (2015) applied the RDM method to five hydropower projects in Sub-Saharan Africa. The test projects cover different types of schemes (run-of-river and storage schemes) and different project purposes (hydropower, irrigation and water supply). The RDM methodology was used to structure the analysis and to identify potentially robust project configurations. In this study three different robustness criteria (see Table 29) were applied. All of the applied criteria include a measure of regret.

9.4.3 Application to the Case Study

The RDM method was applied to the hydropower project in the Swiss Alps described in Chapter 8. The objective is to select a robust design discharge by considering a wide range of possible future states of inflow and energy prices.

The selected design alternatives cover a range of design discharges between 2 m^3/s and 6 m^3/s.

The hydrological study considering various climate projections suggests a range of plausible changes of the inflow to the planned hydropower intake. The model projections indicate an increase of the annual inflow in the near future (2035) from 2% to 10%. The range of inflow projections in the far future (2085) is 7% to 19%.

The reference period selected for the inflow was the long-term recorded discharge. The records cover the period from 1961 to 2013.

As well as the inflow, the energy price is a highly uncertain parameter. Three scenarios were assumed for future states of the energy price. The "High" energy price scenario corresponds to 120 CHF/MWh, the "Central" energy price scenario assumes 65 CHF/MWh, and the "Low" energy price scenario is based on a mean energy price of 30 CHF/MWh.

Sensitivity to Climate Change and Energy Price

The climate change analyses conducted for different projection periods show that the energy production is sensitive to future climate (see Figure 44).

All climate change projections for the near up to far future predict an increase of the annual energy production compared with the long-term reference period 1961-2013. In the near future, the climate change may result in an increase up to about 10%. Additional increase can be expected for the periods referenced as 2060 (up to plus 19%) or 2085 (up to plus 28%).

The alternative with the smallest design discharge has the highest sensitivity of the annual energy production to climate change, whereas design alternatives in the middle range (Qd4 and Qd5) show less sensitivity.

Figure 45 presents the value of the produced energy for each design alternative relative to the reference scenario. For the reference scenario, the central energy price scenario and the long-term recorded discharge were assumed. The energy value for the High energy price scenario is shown as blue dots, the Central energy price scenario is marked red and the Low energy price scenario is plotted green.

The range of the climate change projections is shown by a range plot. The top edges show the maximum, the central dot the median and the bottom edges the minimum value of the chances of the energy value as a function of the climate change projections.

The energy price analyses show a very large sensitivity of the energy value to the energy price scenarios. Because of the large range of assumed energy prices, the value of the produced energy can vary significantly, depending on whether it is the low, central or high energy price scenario.

Compared with the energy price scenario, the climate change projections have a very small influence on the energy value.

In relation to the reference scenario, the highest increase of the energy value can be expected for the smallest design alternative (Qd2), with an increasing effect over time from the near future to the far future (see Figure 45).

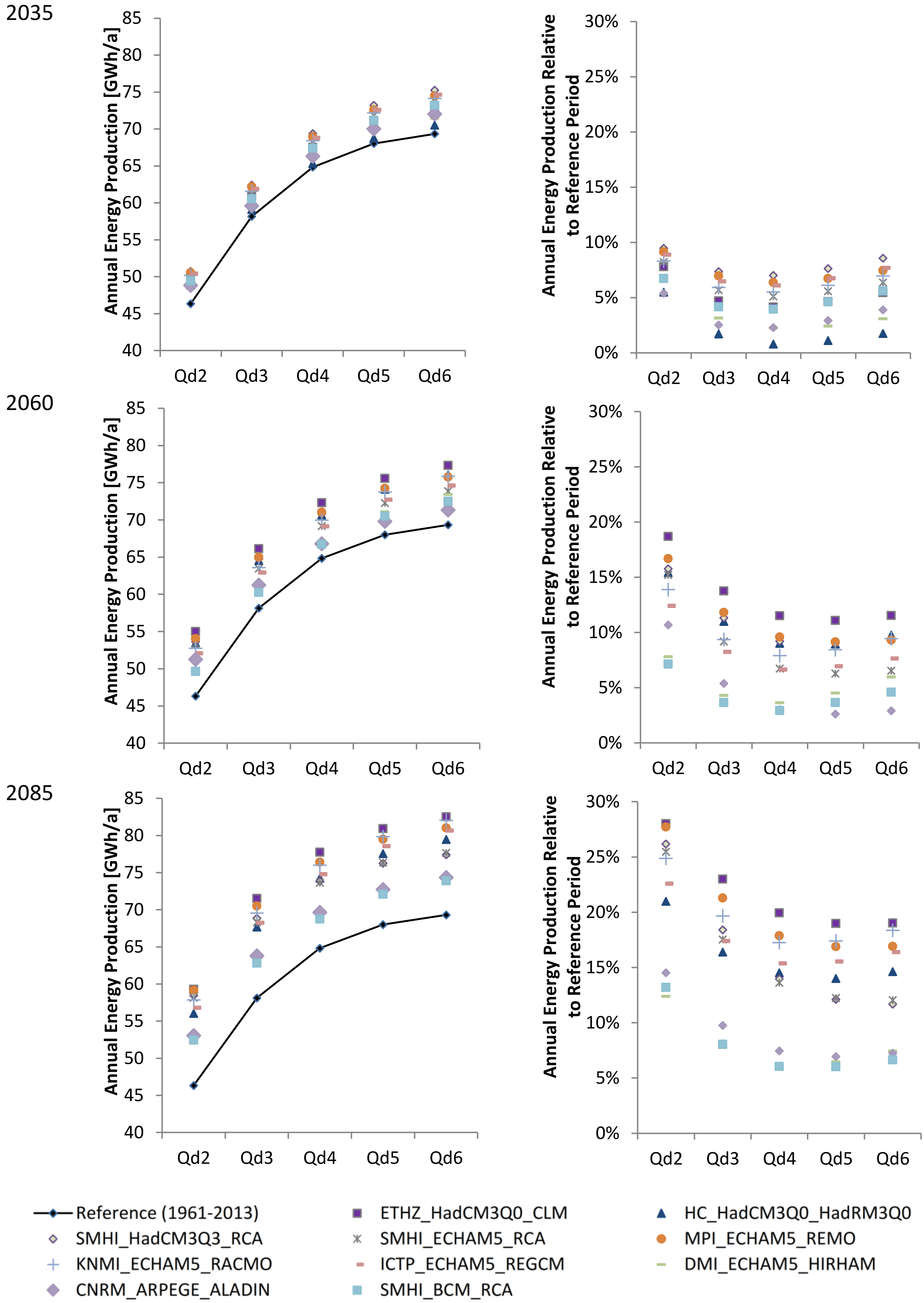

Figure 44: Sensitivity of energy production based on 10 climate change projections for the future periods 2035, 2060 and 2085. Left plots: Annual energy production for different climate change projections. Right plots: Relative variation of energy production compared with the reference period.

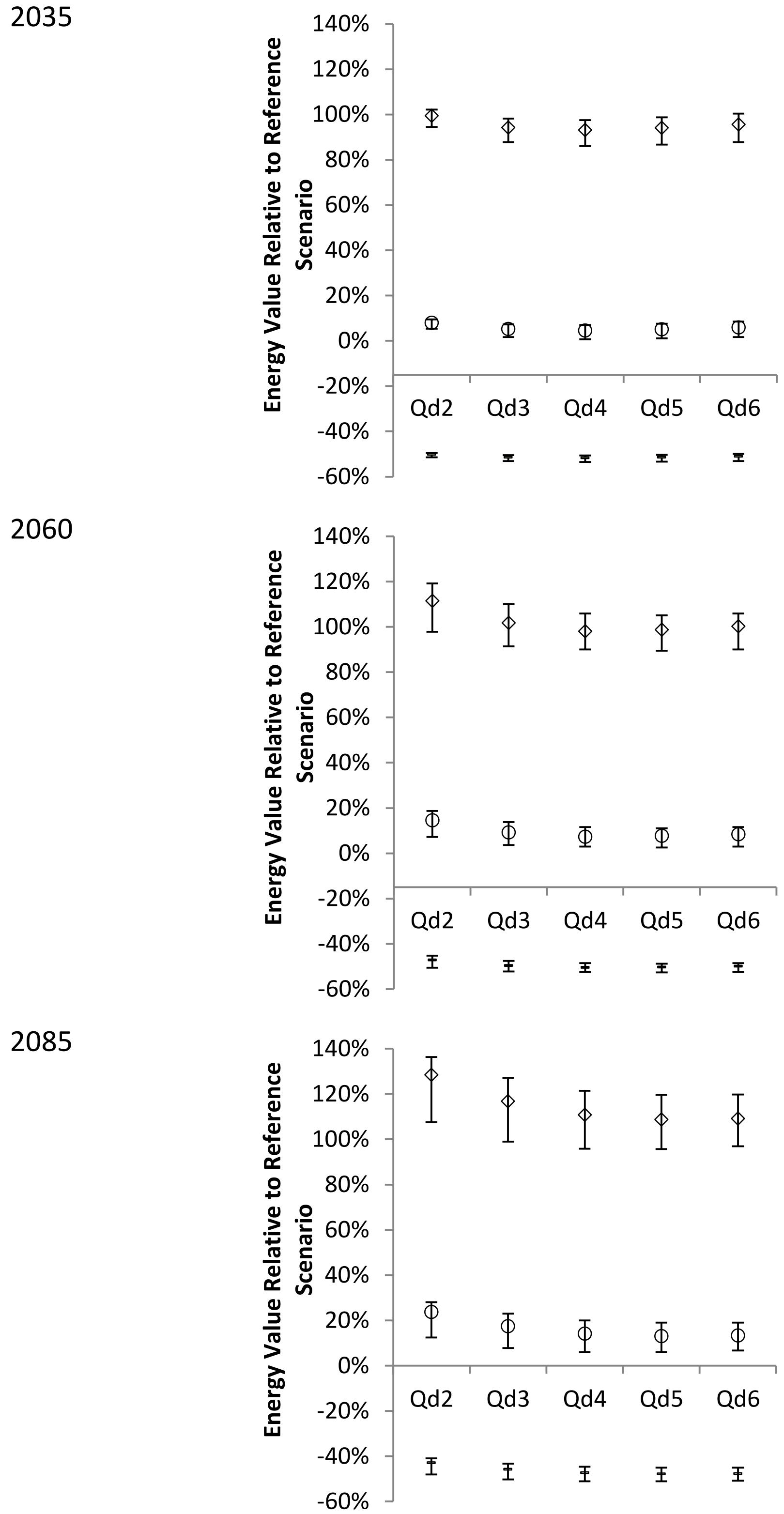

Figure 45: Variation of energy value as compared with the reference scenario as a function of climate change projections and energy price scenarios for the different design alternatives (Qd2 to Qd6). Upper plot for future period 2035, middle plot for future period 2060 and lower plot for future period 2085. Each plot shows the results of the three energy price scenarios: high (diamond), central (circle) and low (horizontal line). Range of results depending on climate change projections are shown as whiskers. Central mark indicates median, whisker extends to the most extreme data points of climate change projections for each energy price scenario.

Vulnerability to Energy Price Scenarios and Climate Change Projections

In general, some projects can lead to benefits and revenues so high that the chance for negative performances is low, even under harsh futures.

Means et al. (2010) defines vulnerability in the context of water planning and dealing with climate change as the degree to which a system is susceptible to an adverse effect.

In the discussed case study, all climate change projections lead to an increase in energy production. Consequently, the only adverse effect stems from an energy price below the reference estimate. The analyses of the vulnerability as defined in terms of NPV show a significant impact on the economic performance of all of the design alternatives.

Table 30 summarizes the vulnerabilities of the design alternatives. Compared with the reference scenario, a decrease of the NPV between 2749% and 379% can be expected. Qd2 has the highest relative vulnerability because of the lowest NPV in the reference scenario.

Relative vulnerability, which is defined as the difference between the most adverse performance and the estimates of the reference periods, seems to be less important for decision-making than absolute vulnerability.

For a low energy price, all design alternatives lead to a negative NPV and very high relative and absolute vulnerabilities. The absolute vulnerability increases with increasing project costs (higher design discharge).

Table 30: Absolute vulnerability and relative vulnerability of design alternatives

		Qd2	Qd3	Qd4	Qd5	Qd6
NPV	[CHF million]	1.32	10.36	13.66	13.30	11.37
Lowest NPV	[CHF million]	-34.90	-35.83	-38.09	-40.93	-43.77
Absolute vulnerability	[CHF million]	-36.22	-46.19	-51.74	-54.23	-55.13
Relative vulnerability	[%]	-2749%	-446%	-379%	-408%	-485%

Figure 46 shows the NPVs across energy price scenarios for the five design alternatives. In addition, the most advantageous design alternative for each energy price scenario is indicated as "best design alternative" (marked yellow). For the reference inflow and the central energy price scenario, the design alternative Qd4 would be the preferred option. In case high energy prices are assumed, Qd5 will lead to the highest NPV. On the contrary, the smallest design will limit the maximum loss in case of an adverse energy price.

Figure 47 shows the NPVs, taking into account the energy projection as well as the climate change projections. The range of the climate change projections are shown as a range plot. Similar to the observed influence of climate change on the energy value, the climate projections give a very small effect on the NPV compared with the energy price scenarios.

For all future climate projections and in case of the High energy price scenario, the largest design alternative Qd6 would be the preferred option.

For the Central energy price scenario, a shift from Qd5 in the near future to Qd4 in the far future can be observed. One explanation can be that the increase of the energy production in smaller design alternatives is relatively larger than that of project alternatives having a higher design discharge as shown in Figure 44.

Assuming the Low energy price scenario, Qd2 would minimize the economic loss, independently of the climate change projections.

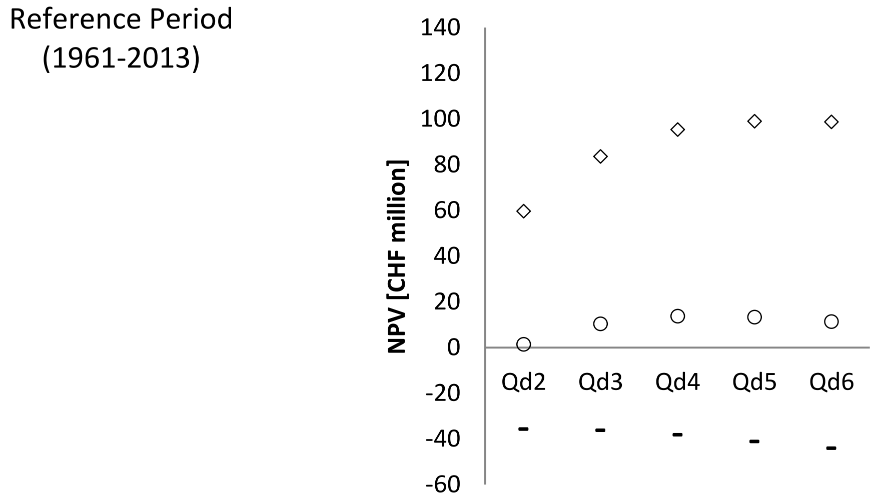

Figure 46: NPVs of different design alternatives (Qd2 to Qd6) for high (diamond), central (circle) and low (horizontal line) energy price scenarios. Calculations are based on inflow in the reference period (1961-2013).

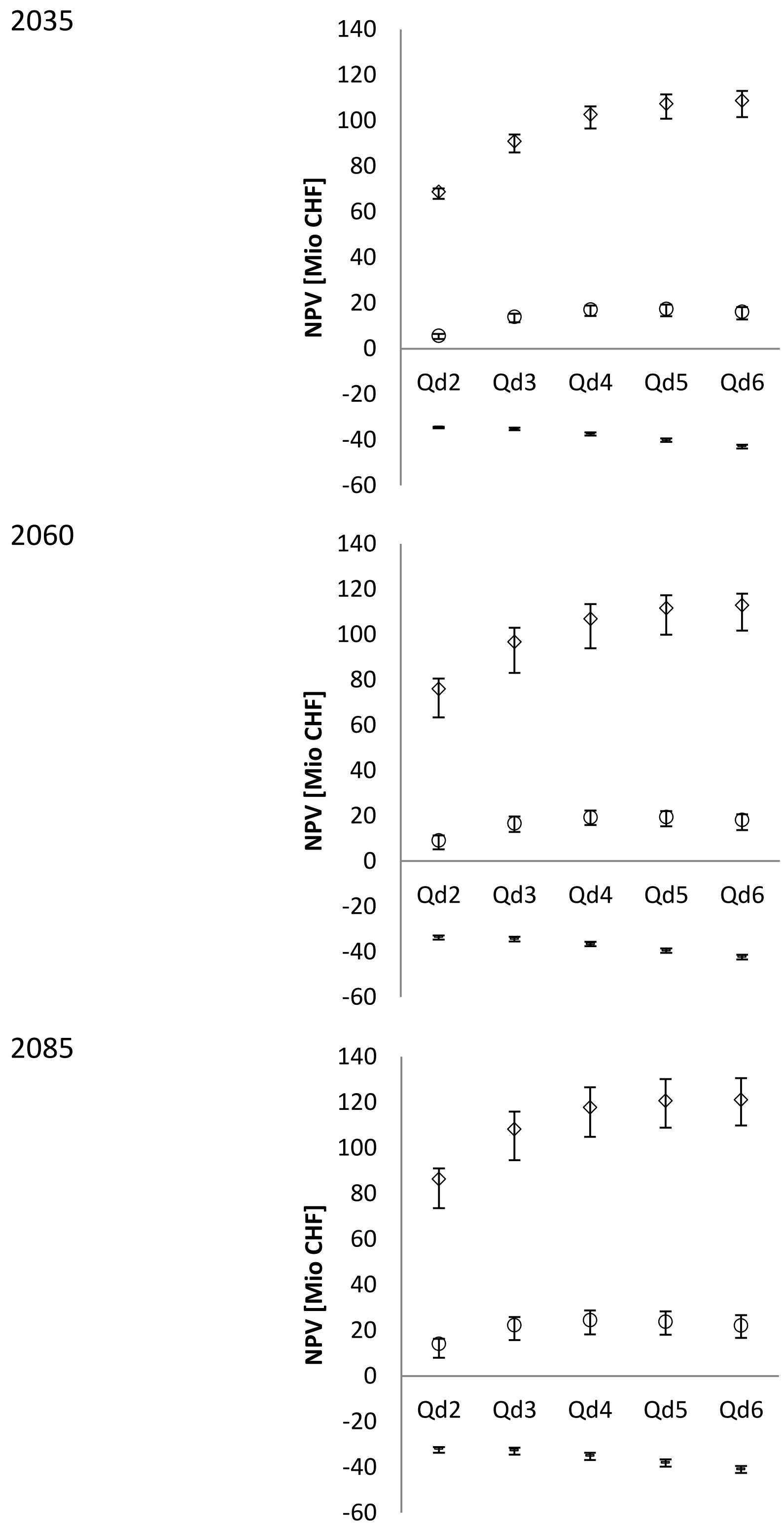

Figure 47: NPV of different design alternatives (Qd2 to Qd6) for high (diamond), central (circle) and low (horizontal line) energy price scenarios. Range of NPVs depending on climate change projections are shown as whiskers. Central mark indicates median, whisker extends to the most extreme data points of climate change projections for each energy price scenario.

Ranking of Design Alternatives

As shown by the sensitivity and vulnerability analyses, the various design alternatives have different vulnerabilities and lead to different NPVs depending on the future states. However, the analyses do not provide the information necessary to frame and make a decision.

In the following sections, the “minimize maximum regret” decision criterion and the domain criterion are discussed.

Minimize Maximum Regret

As shown in the NPV plots over a wide range of future states, larger designs perform better in case of high energy prices and the smallest design alternative has the highest NPV in case of the Low energy price scenario.

Table 31 summarizes the maximum regrets of each design alternative depending on the climate projections and the energy price scenarios. Figure 48 shows the regrets of all analyzed future states.

The minimize maximum regret criterion leads to the choice of the design alternative Qd5 when all energy price scenarios are considered (see Table 31 and Figure 48). Climate projections in the near future and in the far future do not influence this design choice, which is determined by the energy price scenarios. If high energy prices occur, Qd5 leads to better performance than Qd4, and for low energy prices, Qd5 will reduce losses in comparison with Qd6.

The results summarized in Table 31 show that in case of high energy prices the “cost” of selecting the small design alternative (Qd2) will be 6-7 times higher than the regret in a case where the largest design alternative (Qd6) was selected and low energy prices will occur.

From a project developer’s perspective, the project will most probably be stopped if the low energy price scenario is considered to be a likely scenario. Also when neglecting the low energy price scenario, Qd5 is the most robust concept for the near future. However, if the project is postponed and the central and high energy price scenarios are considered, the ”minimize maximum regret” criterion will lead to Qd4.

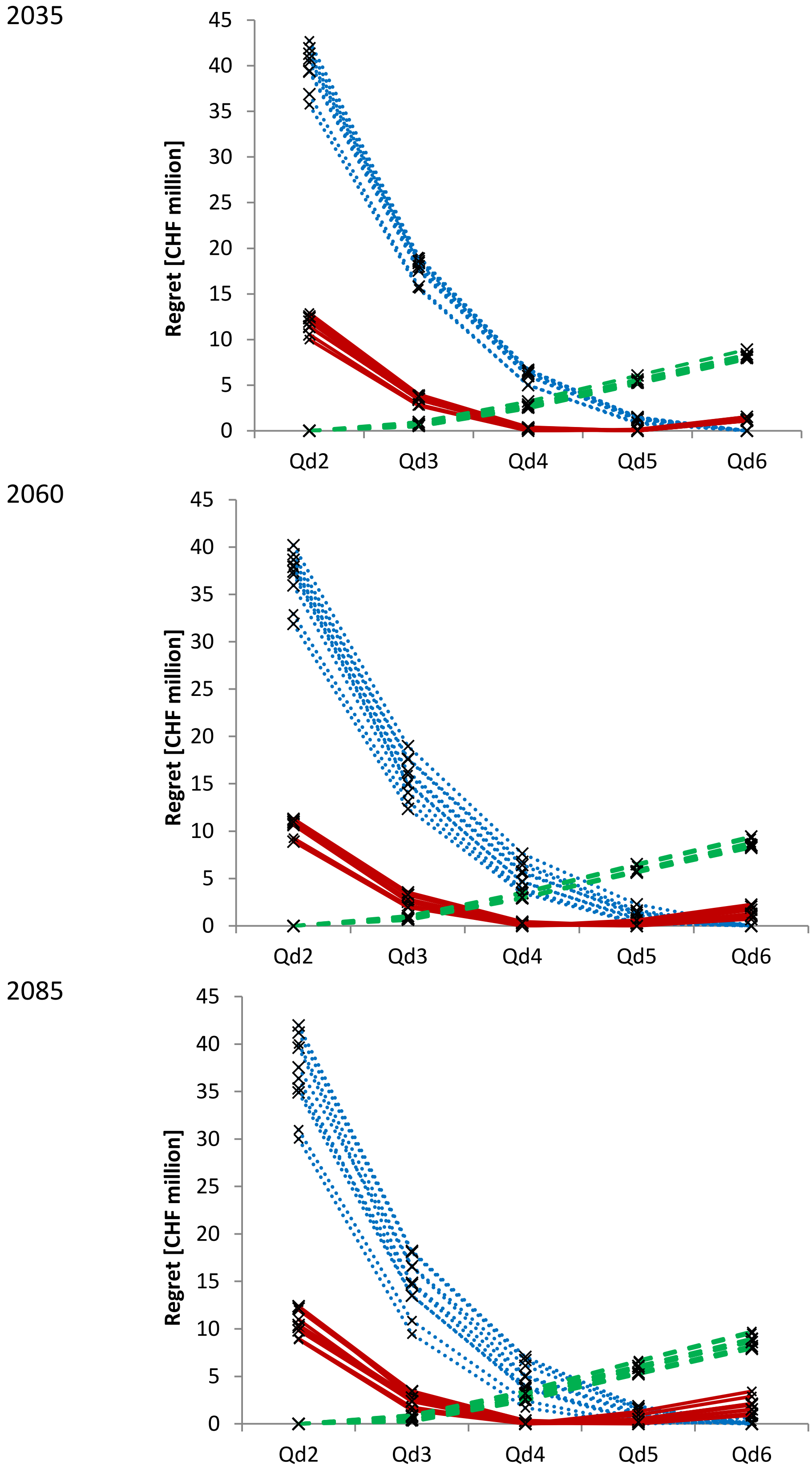

Figure 48: Regret of climate change projections and energy price scenarios for the design alternatives (Qd2 to Qd6) in the climate change projections for the near (2035), middle (2060) and far (2085) futures. Regrets based on the high energy price scenarios are shown as blue dotted lines. Red continuous lines refer to the central energy price scenario and green dashed lines represent the results of the low energy price scenarios. Each line stands for a climate change projection.

Table 31: Regrets of climate projections and energy price scenarios for the design alternatives

Maximum Regret [CHF mill.]						
Climate Projection	Energy Price Scenario	Qd2	Qd3	Qd4	Qd5	Qd6
2035	High	42.74	19.08	6.73	1.51	**0.00**
2035	Central	12.91	3.98	0.39	**0.16**	1.54
2035	Low	**0.00**	0.96	3.21	6.06	8.89
2035	Low-High	42.74	19.08	6.73	**6.06**	8.89
2060	High	40.21	18.99	7.63	2.27	**0.00**
2060	Central	11.32	3.56	**0.44**	0.59	2.26
2060	Low	**0.00**	1.04	3.52	6.52	9.43
2060	Low-High	40.21	18.99	7.63	**6.52**	9.43
2085	High	41.97	18.22	7.07	1.87	**0.66**
2085	Central	12.40	3.45	**0.38**	1.30	3.42
2085	Low	**0.00**	0.92	3.48	6.68	9.72
2085	Low-High	41.97	18.22	7.07	**6.68**	9.72

Satisfice over a Wide Range of Future Conditions

The domain criterion defines a robust design as one that performs reasonably compared to the alternatives across a wide range of plausible futures. The aim is to reduce the interval of plausible futures over which a strategy performs poorly (Lempert and Collins 2007).

A possible approach is to count the cases having the minimum regret and to select the design alternatives having the highest number of minimum regrets. However, this approach can lead to questionable results, as the criterion is highly sensitive to the selected scenarios and simulation intervals.

When simulating a few scenarios at large intervals only, the criterion can lead to unreliable results. This case study gives preference to design alternatives on the extreme side (Qd2 and Qd6). The smallest design has low regrets for low energy prices, whereas the largest design is preferred for high energy prices, as shown in Table 32.

Table 32: Number of minimum regret cases

No of Minimum Regret Cases Inflow Projection	Energy Price Scenario	Qd2	Qd3	Qd4	Qd5	Qd6
2035	High	0	0	0	0	**10**
2035	Central	0	0	2	**8**	0
2035	Low	**10**	0	0	0	0
2035	Low-High	**10**	0	2	8	**10**
2060	High	0	0	0	0	**10**
2060	Central	0	0	**6**	4	0
2060	Low	**10**	0	0	0	0
2060	Low-High	**10**	0	6	4	**10**
2085	High	0	0	0	2	**8**
2085	Central	0	0	**7**	3	0
2085	Low	**10**	0	0	0	0
2085	Low-High	**10**	0	7	5	8

An alternative to analyzing the domain criteria is to map the regrets over the future states. Figure 49 shows the regrets against the inflow volume and the energy price. The inflow volumes represent the climate change projections. In this case, the mapping shows almost vertical isolines of regret, indicating that the regret is mainly sensitive to the energy price scenarios.

Qd4 has low regrets in the area of the central price estimations. Larger design alternatives have low regrets for higher energy prices, whereas small design alternatives perform better for low energy prices.

In general, the regret criterion does not differentiate between more harsh or more opportune futures. In Figure 49, “A” indicates the area with higher inflow and higher energy prices compared to the reference scenario. All climate projections result in higher inflow volumes than those in the reference period thereby leading to a vertical split of the plots. A comparison between the areas A in each of the various plots shows that a selection of Qd5 is mainly driven by more opportune futures. A robust design choice with focus on more harsh future states would be Qd4.

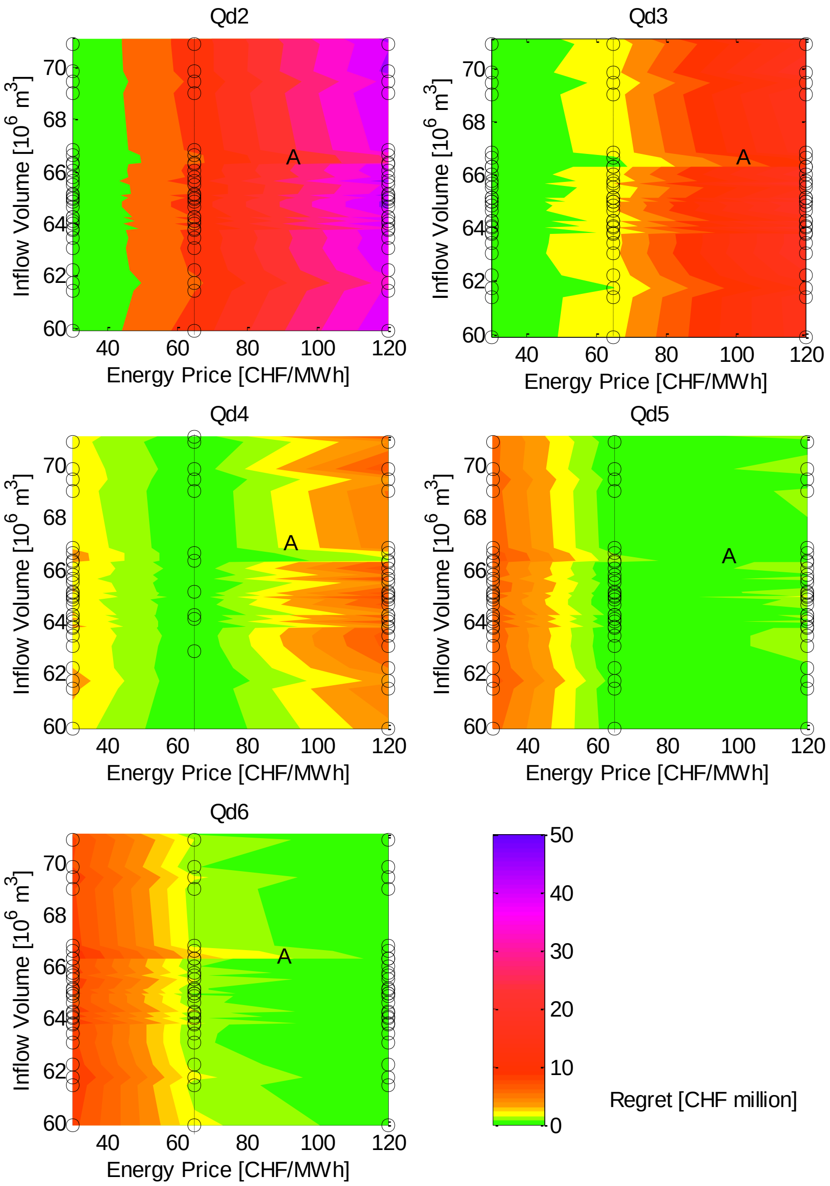

Figure 49: Regrets over the simulation range for the analyzed design alternatives (Qd2 to Qd6), "A" indicates the area with higher inflow and higher energy prices compared to the reference scenario

9.4.4 Discussion

The Robust Decision Making method provides information on the performance of scenarios across large ensembles of plausible futures. Potential vulnerabilities can be identified and this can help to identify better design concepts.

A main advantage of Robust Decision Making is that various scenarios can be directly, i.e. without further simplification, integrated into the procedure. Therefore, this seems to be particularly valuable in cases where climate change scenarios have to be considered.

A limitation of the method is that a large set of simulation runs is required.

Another disadvantage is that the results depend on the selected design alternatives and future states. The identification of key scenarios in a systematic and transparent way can be a major challenge for a project team.

The approach to count the cases with minimum regrets and then to select the design alternative having the highest number of minimum regrets can lead to misleading design choices. A better approach to analyze the domain criterion is mapping of the regret.

9.5 Conclusions and Recommendations

The classical approach of selecting the design alternative with the highest NPV and neglecting uncertainties of climate change and energy price fluctuations leads to Qd4.

This design choice is basically confirmed by the Info-Gap Decision Theory method. For a risk-averse project team, Qd4 would be the preferred solution. This design alternative gives a positive NPV also under harsher futures. If more attention is given to opportuneness, Qd5 or Qd6 could be selected, but Qd6 is found to be attractive only if there is a projected increase in energy price and inflow.

Robust Decision Making tends to favor the larger design discharge. The minimize maximum regret and domain criteria lead to the choice of the design alternative Qd5. However, as shown by the mapping of the regret, this design selection is mainly driven by the regrets of more opportune futures. A robust design choice with focus on harsher future states would be Qd4.

In addition, Robust Decision Making shows that the project is highly vulnerable to dropping energy prices, whereas the plant is not vulnerable to climate changes. The absolute vulnerability is higher for larger design alternatives, as they require higher upfront investment costs. But the analyses show that in case of high energy prices the “cost” of selecting the small design alternative (Qd2) will be 6-7 times that of the regret if the largest design alternative (Qd6) is selected and energy prices are low.

The classical approach, Info-Gap Decision Theory and Robust Decision Making reached similar results. The classical approach as well as the robustness curves of the Info-Gap Decision Theory promote Qd4. Robust Decision Making suggests the larger design alternative Qd5, but only if the decision gives the same weight to more harsh and more opportune futures.

The application of the methods leads to the following main findings: Firstly, the classical approach can lead to robust design choices also if the uncertainties are not incorporated into the decision finding process. Secondly, Info-Gap Decision Theory and Robust Decision Making help to assess the robustness of the different design alternatives of a hydropower project and lead to similar but not entirely matching results. The final selection depends primarily on the risk attitudes of the decision makers and less on the applied method. Both methods suggest Qd4 in cases where the focus is placed on more adverse conditions, whereas Qd5 is suggested in cases where attention is also given to the opportuneness.

Current research in respect to climate change and hydropower design has mainly focused on Robust Decision Making, whereas Info-Gap Decision Theory has not been applied for hydropower design so far.

The observation that the design choice derived by the classical approach can also lead to a robust design is essential for the next steps in developing design methods considering uncertainties. It highlights the priority placed on providing methods that can be efficiently applied to check the robustness of a design choice derived via the classical approach. Based on the finding of this study, Info-Gap Decision Theory is a very promising method for this purpose.

Therefore, a two-step approach for hydropower projects is suggested. In a first step the classical approach can be applied, and in a second step Info-Gap Decision Theory is used to prove the robustness. Especially in early design stages, where several design choices have to be made within limited time and with limited resources, this procedure could be applied.

In addition, comprehensive forecast scenarios and climate change projections are not often available in an early design stage. Info-Gap Decision Theory can be applied with best estimates of the uncertain factors. It allows identification of the uncertainty level at which a different design choice leads to a better performance. It is suitable to check the robustness of various design choices derived by the classical approach.

For later design stages and larger projects both methods may be applied. However, it has to be noted that several overlapping working steps are required for the application of Info-Gap Decision Theory and Robust Decision Making. Therefore a combined procedure is proposed, which is shown in Figure 50. The combined procedure requires 10 working steps and achieves the following advantages:

- Reduction of working steps
- Direct incorporation of scenarios
- Including sensitivity and vulnerability analyses
- Analysis of switch of design preferences
- Differentiation between robustness and opportuneness
- Regret over complete range

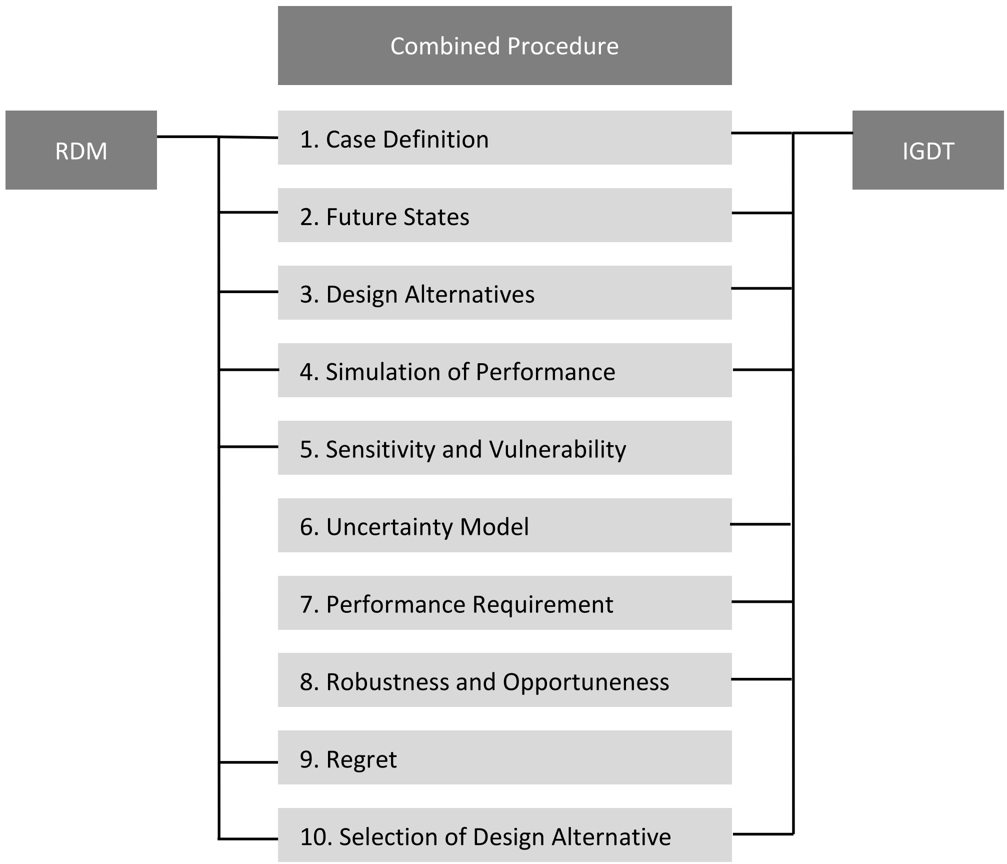

Figure 50: Working steps for combined Robust Decision Making (RDM) and Info-Gap Decision Theory (IGDT) procedure

Chapter 10 Versatility

10.1 Introduction

The concept of versatility covers a wide field of possible applications and the finally selected approach depends significantly on the specific hydropower project. The derivation of a general procedure to achieve versatility is therefore not seen as helpful. However, in order to provide a comprehensive overview on different methods applicable in hydropower design, this chapter describes the general concept and possible methods to achieve versatility. In addition, a summary of previous studies in the hydropower sector is given.

In this work, versatility is defined as the ability of the hydropower scheme to provide additional services not originally included to the same extent in the requirements definition, without any structural adjustments. Compared to flexibility or interoperability, it is a non-structural measure (see Figure 33).

For hydropower projects, versatility can be achieved by the adaptation of operation rules or by portfolio planning. Adaptation of operation rules focuses on pure hydropower projects, whereas portfolio planning could be applied for multipurpose schemes.

10.2 Adaptation of Operation Rules – Previous Studies

In general, operation rules are defined during the planning phase and are followed over the entire operation period. A driving factor for the adaptation of operation rules can be a changing demand for services to be provided by a hydropower scheme during the operation period. In other words, changing energy market conditions can emphasize a rethinking of the operation rules. Several Swiss and European utilities have started to analyze their current operation rules in the wake of the drop of energy prices in 2008.

Adaptation of the operation rules can also increase the performance of a scheme in a case where the effective inflow is not matching the estimated inflow originally defined for the construction project.

The possibilities of adjustment of the operation rules are constrained by the technical characteristics of a power plant, such as minimum operation level, full supply water level, flood water levels, capacity of outlet structures and waterways, limits of transient conditions in the waterways, or regulations on water releases. In addition, existing agreements and regulatory constraints are often strongly limiting the range of potential adjustments.

Project designs that select versatility to manage uncertainties need to identify options for widening the respective limits in order to increase the production flexibility for future conditions.

A few studies were carried out to analyze the challenges of reservoir management and operation rules for various climate change projections.

The value of an adaptive management of the operation rules has been clearly demonstrated by Arsenault et al. (2013). The study compares the possibilities of adding an additional turbine to an existing power plant and adapting the operation rules of this power plant for a wide range of climate change projections. The study concludes that power production can be increased both by adding turbines and by optimizing the operation rules. The concept of adapting the operating rules is found to be sufficient to reap most of the benefits of increased water availability.

Georgakakos et al. (2012a, b) highlight the value of adaptive reservoir management in the context of climatic change for Northern California. The study shows that adaptive management can be an effective mitigation measure for climate change and improve the performance of the scheme in terms of water supply, energy, and environmental water.

Minville et al. (2010) evaluate the water resource system of the Peribonka River in Canada under various hydrological regimes using different climate change scenarios. In this climate change context, adaptive operation rules are used and compared with the historical operation rules.

Veijalainen et al. (2010) studied the climate change impact on hydrology and water resources in the Vuoksi watershed in Finland in order to assess the possibilities of adapting lake regulation to the projected changes. The study concludes that a modification of the regulation practices and limits is an effective way to adapt to climate change.

10.3 Portfolio Planning

Versatility is also related to the concept of portfolio planning. The principal concept of portfolio planning is that by providing a greater portfolio of services the uncertainties can be better absorbed. This concept could be valuable for multi-purpose projects. Multipurpose projects can provide a wide range of services, such as:

- Energy production:
  - base load energy
  - peak energy
  - reserve energy
- Irrigation
- Industrial water supply
- Municipal water supply
- Water supply for fire fighting
- Navigation
- Flood control
- Drought control
- Aquaculture
- Tourism

A kind of hedging could be provided by diversifying the service portfolio of a multi-purpose project into services that are not affected by the same uncertainties.

To the knowledge of the author, this approach is currently not in use for hydropower design. Some studies (Means et al., 2010) indicate its potential for application in the water sector or more specifically in the hydropower sector.

10.4 Conclusions

Versatility is a hydropower scheme's ability to provide additional services not originally included in the requirements definition. The concept focuses on the adaptation of the operation without any structural adjustments. Previous studies on the adaptation of operation rules (e.g. Arsenault et al., 2013; Georgakakos et al., 2012a, b) underline the value of this design objective for hydropower storage schemes.

Multipurpose projects would also allow for portfolio planning. However, there is a lack of experience in the formulation and application of portfolio planning in the hydropower sector.

Chapter 11 Flexibility

11.1 Introduction

A hydropower project is a flexible system with several options, such as:

- Increase of the storage capacity by dam heightening or additional storage
- Upgrade of the installed capacity
- Extension by an additional diversion scheme
- Change of a storage scheme to a pump storage scheme, or
- Investment timing

Many hydropower projects have undergone reconstruction or upgrading to better match the observed conditions and the forecasted scenarios for the next decades. Shifts in the electric supply market, hydrology, sedimentation or ecological preferences have changed the definition of what effective designs are, and so the originally constructed scheme was adjusted or the option was identified, but not realized. Some examples of design options in hydropower are summarized in Table 33.

However, the original design of most of these projects did not consider a possible future structural adaptation. Especially extensions of waterways can lead to significantly higher costs if the possibility of an extension was not included in the original design. In addition, considering the value of an option to extend a project can increase the value of a scheme. Finally, this can also have an influence on the selection of design alternatives for greenfield projects. In some cases, smaller concepts with an extension option for changing conditions in the future might turn out to be the better design alternatives.

Table 33: Examples of flexibility in hydropower projects

		
KW Bürglen, Switzerland	Göscheneralp dam, Switzerland	KW Forbach, Germany
The Bürglen power plant started operation in 1964. After about 50 years of operation, the option to install an additional turbine was analyzed with the aim to reduce the spill. Finally, an additional unit with an installed capacity of 3.5 MW was added, leading to a total installed capacity of 24.5 MW. Because of the available space in the power house only minor adjustments were necessary, i.e. no adjustments were required on the headworks and the main waterway.	The Göscheneralp dam is a 155 m high earth-core rockfill dam which forms the 75 million m^3 reservoir for the Göschenen hydropower plant with a 164 MW installed capacity. The dam was constructed between 1955 and 1962 and was the highest earth-core rockfill dam in Europe at the time. About 50 years later, the market conditions changed and a further increase in peak energy was expected. Therefore, the option of heightening the dam to increase the reservoir volume by about 15% was investigated. The dam heightening project was not realized and finally abandoned, partly due to the significant drop of the electricity prices after 2008.	The Forbach power plant is part of the German hydropower scheme known as Rudolf-Fettweis-Werk. The scheme was constructed between 1914 and 1926. Already at the time of construction, an alignment for an additional penstock was foreseen to make allowance for a more cost-efficient installation of an additional penstock should the project be expanded.

One approach to analyze the flexibility of hydropower or, more generally, of infrastructures is the Real Option Analysis. Real option in engineering is conceptually similar to financial options. Both financial and real options are rights but not obligations to future actions. The analysis of financial options is a well-established discipline in financial economics based on a detailed theoretical foundation. In addition, several application tools have been developed and are increasingly applied also in engineering. Some research studies show that this method is promising also for hydropower plants. An overview on these studies is provided in Chapter 11.2.

However, according to de Neufville and Scholtes (2011), the theory of financial options is of limited value in the context of engineering projects. This is because the context of engineering projects differs significantly from that of financial transactions. Financial option theory is based on assumptions and on a context that makes their application questionable for engineering systems. The context differences or financial, design and, more specifically, hydropower options are summarized in Table 34.

Another approach for design flexibility in engineering projects, which includes different tools and analysis techniques, has been proposed by de Neufville and Scholtes (2011). The proposed method focuses on large-scale, long-lasting projects with irreversible investment decisions. It holds the promise that a project's value can be enhanced by recognizing the fact that the future is inevitably uncertain and that by creating flexible designs one can adapt to eventualities. This method can be summarized under the term "Flexible Design".

In general, it is not possible to make a final and conclusive recommendation as to whether the Real Option Analysis or the Flexible Design approach is more appropriate for hydropower projects. For a pure hydropower project, which will trade its electricity on the market, Real Option Analysis can be applied. In cases where the project is located in a country without electricity market or where additional services, such as water supply, flood protection etc. are or can be provided in the future, Flexible Design is the preferred approach.

Table 34 Context differences between financial and design options. Source of content of the columns "Financial option" and "Design option in engineering systems": de Neufville and Scholtes (2011).

Financial option	**Design option in engineering systems**	**Design options in hydropower**
Asset is widely replicated (company stock, commodities, financial assets)	*Asset is unique (a bridge, a building, a new product)*	Hydropower plants are unique structures
There is a market for such assets	*No market in general (maybe for a product such as for copper from mine)*	An electricity market exists in some countries. Typically, no market exists for other services that can be provided by a multipurpose project (irrigation water, flood protection, municipal water supply etc.)
A replicating portfolio can be created	*Unlikely to be able to create replicating portfolio (maybe in short term, as for traded commodities such as copper, but unlikely over years of option)*	In countries having an electricity market, energy supply can be traded. Very unlikely for other services that can be provided by a multipurpose project.
Option valid for months	*Option for years, even decades*	Options for several decades
Market data available	*Data spotty, maybe unavailable*	Market data for electricity are available in some countries. Apart from the market data, inflow data may be unavailable or very limited
Recent market data credible for anticipation of market variations over life of option	*Historical data do not anticipate trend breakers likely to occur over long life of option*	Historical data of long-term inflow and electricity prices can have a limited reliability for anticipating future variations. Climate changes and unpredictable events on the energy markets make it questionable to base an assessment entirely on historical data.
Option characteristics well defined (strike price, time of maturity, payoffs)	*Option characteristics may be unclear and change over time (indefinite life of option, indefinite exercise type, size, and price)*	Options of hydropower plants are often highly unclear. As well as technical issues (variation of technical lifetime), contractual or political constraints can influence the characteristics of an option.

11.2 Real Option Analysis

11.2.1 Description of Method

The Real Option Analysis method was developed by Black and Scholes (1974) for the financial sector. It recognizes that the decisions that determine project cash flows are made sequentially over many episodes and that the value of a project can be increased if uncertainties are faced by flexibility.

Real Option Analysis holds the promise that the value of flexibility can be evaluated also for an engineering system. Consequently, the economic value of a project at a stage where it is still relatively unformed is often greater than the discounted present value of the estimated future cash flow. Embedding flexibility in infrastructure systems already optimized for performance under traditional deterministic concepts has reportedly led to substantial savings in numerous cases (de Weck et al., 2004; Priemus et al., 2008)

Real options can be divided into those that are either "on" or "in" projects. Real options "on" projects are financial options, in which the engineering system itself is treated as a black box. Real options "in" projects focus on the flexibility of an engineering system. Therefore, engineering knowledge to design appropriate options is required (de Neufville, 2004).

Different methods have been established to evaluate real options. According to Mun (2002), the methods mostly used are closed-form solutions, partial differential equations, and binomial lattice trees. Closed-form solutions, such as the Black Scholes model, are exact and easy to implement. But they are also very specific in nature and have limited modelling flexibility. Dixit and Pindyck (1994) provide a comprehensive overview on methods based on partial differential equations and their theoretical background for investment under uncertainty.

Compared to those methods, the binomial lattice approach has several advantages for the application in hydropower projects. The binomial lattice method, which was originally proposed by Cox et al. (1979), is highly flexible and easy to understand and can provide good approximation. According to Mun (2002), the binomial lattices have been accepted by the industry for application in real option analysis, mainly because of their transparency and simplicity, which can be essential for the development of a project strategy involving different decision makers.

11.2.2 Application to Hydropower Design

Michailidis and Mattas (2007) applied the real option approach to an irrigation dam in Greece. The analyzed option is delay in investment time. One of the main findings is that new advanced methodologies could significantly diminish the weakness of the discounted cash flow techniques.

Bockman et al. (2006) present a real options-based method to define investment timing and optimal capacity choice for small hydropower projects. Additionally, an optimal trigger price for initiating an investment is estimated. The method is illustrated at the example of three small hydropower projects in Norway.

Wang (2008) provides a comprehensive overview on real options applied in river basins. His work shows that applying real options allows the net benefit to be increased and/or the downside risk to be reduced.

Elverhøi et al. (2010) present a decision support framework for hydropower producers with production facilities due for rehabilitation. Real Option Analysis was used to evaluate the investment opportunities.

Fertig et al. (2013) analyzed optimal investment timing and capacity choice for a pumped hydropower storage scheme in Norway. In total five capacity alternatives of the hydropower scheme with arbitrage in the German spot market are analyzed. Real Option Analysis was used to value the investment opportunity in order to account for uncertainty of the electricity market and intertemporal choice.

11.3 Flexible Design

Flexible Design focuses on the methods and tools that will lead to a flexible system able to adapt to future needs and opportunities and therefore able to increase its long-term expected value, compared with traditional procedures for developing and implementing projects (de Neufville and Scholtes, 2011). The basic procedure consist of the following working steps:

- Estimating the distribution of future possibilities
- Identifying candidate flexibilities
- Evaluating and choosing flexible design
- Implementing flexibility

De Neufville and Scholtes (2011) provide a detailed description of each working step and of the methods and tools generally applicable to engineering projects. In contrast to robust design or versatility, flexibility analyzes structural adjustment.

Designing flexibility is a kind of engineering thinking rather than a clearly defined procedure or method. Therefore, several methods or tools that are used in Flexible Design, such as Monte Carlo simulations or dynamic forecasting, are applied also in other design methods for uncertainty.

In contrast to real option analysis, which is strongly influenced by the financial option approach, the methods for Flexible Design have been adjusted to develop engineering projects.

11.4 Application to the Case Study

A Flexible Design approach has been selected for the case study. The hydropower plant on which the case study was carried out is described in Chapter 8.

The objective of the IGDT and RDM methods is to increase robustness by selecting the best design alternative and not to anticipate any structural adjustments during the operation phase of the project. In contrast thereto, the following design methods include the possibility of structural adjustment of the power plant during the operation phase.

The option of expanding the plant size by installing an additional turbine if future changes is analyzed. It is assumed that the design discharge can be increased should the plant owner decide to do so.

The best case of a one-stage project leading to the highest ENPV is the design alternative Qd5.

Two multi-stage strategies have been analyzed. One possibility would be to construct a smaller project (Qd4) in a first stage and to allow for adding a turbine if future conditions lead to better production conditions. This concept anticipates an increase to a total capacity equal to the capacity of Qd5 or Qd6. This extension strategy is referred to as ExtQd4.

The second extension strategy foresees the construction of Qd5 and possible extension to the installed capacity of Qd6, referenced as ExtQd5.

11.4.1 Modeling Framework

For the evaluation of different design alternatives, it is necessary to derive the expected net present value (ENPV) and other distribution of outcome indicators such as VaG and VaR. The results finally allow a comparison of the different design strategies and are the final point of multiple steps of methodologies (see Figure 51). In principal, the structure reflects the basic working steps required to calculate the economic performance parameter of a hydropower project, with the difference that distributions of future possibilities of the main factors are considered.

The study focuses on the uncertainty of inflow and thus on the uncertainty of both energy production and electricity price. Factors for which uncertainty was considered in modelling are marked red in Figure 51.

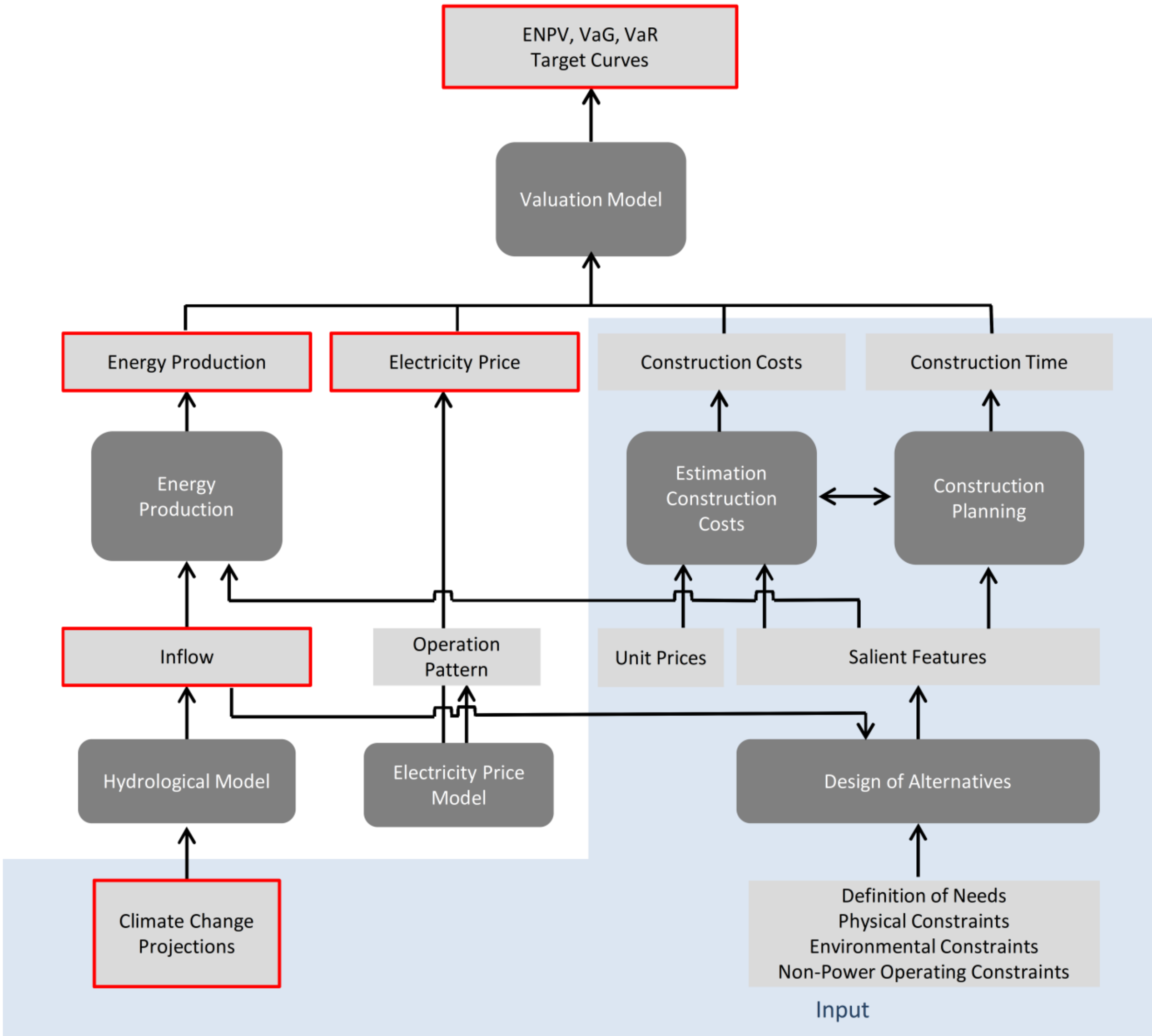

Figure 51: Model cascade used for this case study

11.4.2 Climate Change –Inflow – Energy Production

Different climate change projections were considered to reflect the uncertainties of the future inflow as derived by the methodology described in Chapter 8.3. The inflow series simulated by the hydrological model were used in energy production simulations with daily simulation time steps (see Chapter 8.4). In order to cover the assumed economic lifetime (50 years), the climate change projection for the period from 2021 to 2050 was extended by the first 20 years of the projections of the 2060 period. The operation rules of the hydropower plant are simple as it is a run-of scheme in which only the ecological flow has to be released while the remaining inflow can be used for energy production as long as it is below the maximum discharge capacity. The annual energy productions over the 50-year simulation period for the different climate change projections and for selected design alternatives are shown in Figure 52. An annual trend of about 5% can be observed for all of the design alternatives. The design alternatives show the following average energy productions: Qd4 is 68.3 GWh, Qd5 is 71.9 GWh, and Qd6 is 73.9 GWh.

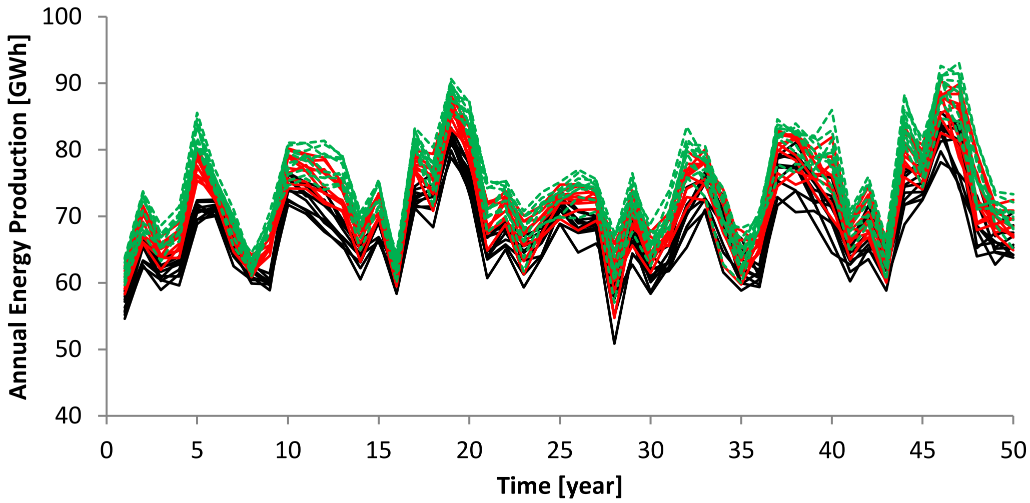

Figure 52: Annual energy production considering the climate change projections for the design alternatives Qd4 (black lines), Qd5 (red lines) and Qd6 (green lines)

11.4.3 Electricity Price

For long-term investments, a possible approach to describe the electricity prices in an electricity market is the Geometric Brownian Motion. This model reflects only long-term variation, whereas short-term variations are neglected. However, Smith and Schwartz (2000) claim that for long-term investments the long-term factor is the determining one. Also Pindyck (2000) argues that, when considering long-term investments, a geometric Brownian motion description of the price will not give large errors. Besides that, also other studies analyzing long-term investment decisions in the energy sector rely on this approach (e.g. Fleten et al., 2007). Based on the foregoing aspects and due to the simplicity of the approach, the geometric Brownian motion was selected for the case study.

The change of the electricity price *dS* is defined by the geometric Brownian motion as:

$$dS = \mu \, S \, dt + \sigma \, S \, dz \qquad (15)$$

where μ is the annual risk-adjusted growth rate and σ is the annual volatility of the electricity price. The last term *dz* is the Wiener process, a special diffusion process. For details on this approach and possible applications see Dixit and Pindyck (1994).

In this study, cash flow calculations with annual time steps are applied.

For the simulation of this process, the electricity price at discrete time steps can be solved according to Brigo et al. (2007) as follows:

$$S(t_{i+1}) = S(t_i) \, exp\left(\left[\mu - \frac{1}{2}\,\sigma^2\right](t_{i+1} - t_i) + \sigma\sqrt{t_{i+1} - t_i}\, Z_{i+1}\right) \qquad (16)$$

Where $Z_1, Z_2, \ldots Z_n$ are independent random draws from standard normal distribution.

The model is to represent the long-term electricity price and not short-term deviations. Therefore, model parameters are often derived from forward contracts with longest time to maturity. One possibility would be to analyze Phelix futures prices, the physical electricity index in the EEX spot market for Germany and Austria. However, there is a very limited trading volume for long-term contracts and therefore it will not reflect the market conditions (Fertig et al., 2016).

Thus, a sensitivity analysis was carried out, analyzing the effect of volatility on the value of the flexible design alternatives. To limit the sensitivity analysis to a plausible range, the annual volatility estimated by Fleten et al. (2007) on the basis of over-the-counter contracts in Norway with time periods longer than 3 years was used as a benchmark. The study estimated an annual volatility of 0.103. The sensitivity analysis was carried out for an annual volatility from 0.05 to 0.20.

In order to allow a comparison between these results and the findings from the RDM and IGDT methods, a starting electricity price (S_0) of 65 CHF/MWh was assumed. This value corresponds to the best estimate or 'Central' electricity price scenario assumed for the IGDT or RDM approach, respectively.

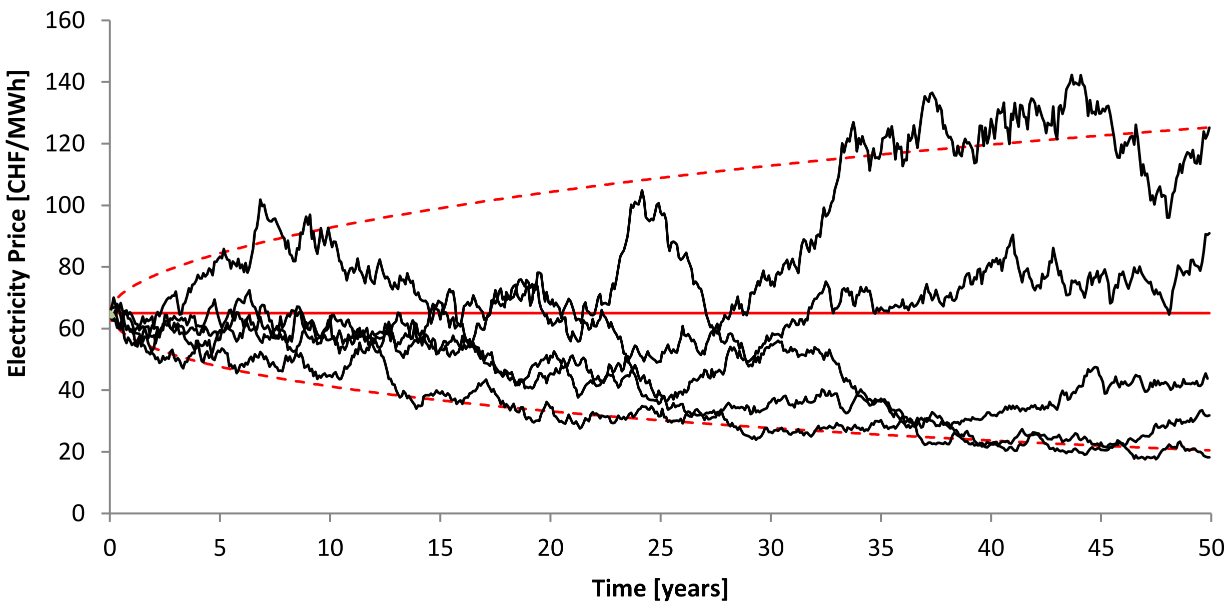

Figure 53: Geometric Brownian Motion of electricity price (μ=0, σ=0.10, S_0=65). Mean path (red), 5 sample paths (black), 10% and 90% percentile paths (red dashed)

11.4.4 Identifying Candidate Flexibilities

The flexibility of the power plant is limited to a potential scaling of the installed capacity. Starting from the static evaluation of the different design alternatives, the analyzed design alternatives cover design discharges within a range from 4 m^3/s (Qd4) to 6m^3/s (Qd6).

Other design flexibilities, such as constructing a reservoir, can be excluded because of the physical constraints at the project site.

11.4.5 Valuation Model

The valuation model has to consider the possibility of design changes and their effects. De Neufville and Scholtes (2011) argue that the rules for exercising flexibility should mimic what decision makers would do if they ever had to deal with a situation.

Power plant owners often base their decisions on historical data covering the last few years. Therefore, it was assumed that a decision on whether or not to make an extension is triggered by the average of the electricity price and inflow over the last three years before the decision on a potential expansion is made. Based on the three-year average electricity price and inflow, the annual income, and finally in consideration of the investment costs for the additional turbine, the NPV is calculated. If the NPV of the extension project turns out to be positive for the remaining lifetime, the decision will be to install the additional turbine, ignoring the fact that a later investment may be more beneficial.

Because of the limited space in the power house, the upgrade project can be realized only once in the project’s lifetime.

The decision-making process does not necessarily lead to an optimal choice, as revenue may decrease over the following years and finally lead to a non-profitable investment. However, it was found that such a decision rule was the best way to mimic decision-making for mid-size hydropower plants.

The valuation model finally calculates the expected net present value for the project without and with the extension by simulating 1000 runs.

A discount rate of 3% and water royalties of 110 CHF/kW for the gross capacity were assumed. The other input parameters for the economical calculations are summarized in Table 35.

Another important assumption is that the additional turbine will be installed during the winter months and will not cause any energy production loss to the base project. Also, it is assumed that the additional turbine will start full operation shortly after installation in the same year and can generate the full annual production of the respective year.

Table 35: Economical input parameters for valuation model, extension project ExtQd4

	Base Project	Extension Project ExtQd4	
Parameter	Qd4	Extension to Qd5	Extension to Qd6
CAPEX	CHF 47.1 million	CHF 3.2 million	CHF 5.8 million
OPEX	1% of CAPEX, plus CHF 50‘000/year	1% of CAPEX	1% of CAPEX
Re-investment in E&M equipment	35 years after start of operation	35 years after start of operation	35 years after start of operation
Construction period	3 years	-	-
First year of operation	4th year	same as year of installation	same as year of installation
Economic lifetime	50 years	end of base project	end of base project

Table 36: Economical input parameters for valuation model, extension project ExtQd5

	Base Project	Extension Project ExtQd5
Parameter	Qd5	Extension to Qd6
CAPEX	CHF 50.1 million	CHF 2.8 million
OPEX	1% of CAPEX, plus CHF 50‘000/year	1% of CAPEX
Re-investment in E&M equipment	35 years after start of operation	35 years after start of operation
Construction period	3 years	-
First year of operation	4th year	same year as installation
Economic lifetime	50 years	end of base project

11.4.6 Evaluating and Choosing Flexible Design

The results show a low value for flexible design strategies. Compared with the best one-stage project Qd5, the multi-stage project ExtQd4 leads to a less than one percent increase of the ENPV for an annual volatility σ = 0.10. If the volatility is equal to 0.20, an increase of about 3.6% can be expected (see Table 37).

Upgrading the design alternative Qd5 to Qd6 is even less attractive and gives no increase of the ENPV.

The measures of distribution of the best single-stage project Qd5 and the two multi-stage projects for an annual volatility of 0.20 are shown in Table 38. Also, the comparison of the Value at Gain (VaG) and Value at Risk (VaR) of the one-stage and multi-stage projects underlines the low value of flexibility in this hydropower plant.

Table 37: Relative change of ENPV compared to Qd5

σ	ExtQd4	ExtQd5
0.05	-1.2%	0.0%
0.10	0.4%	0.0%
0.15	2.2%	0.0%
0.20	3.6%	0.0%

Table 38: Measures of distribution of outcomes of Qd5, ExtQd4 and ExtQd5 for σ = 0.20

Metric	Qd5	ExtQd4	ExtQd5
VaG (P 90%)	114.4	113.6	114.4
ENPV	17.8	18.4	17.8
VaR (P 10%)	-54.8	-51.8	-54.8

11.5 Discussion

Flexible Design can be useful to identify a flexible strategy that leads to a higher project value, including a balanced assessment of the investment risk.

The method can be applied and adjusted to consider different uncertain parameters with probability information being required for each of them. Especially, the elaboration of an electricity price model for long-term future projections is a difficult task. This was found to be the major limitation of this approach as regards its application in engineering practice. Long-term stochastic electricity price models are not often available for hydropower projects, especially for smaller hydropower plants

In addition, the decision-making process should mimic the decision of the power plant's management. For the case study, it was assumed that the management decision was based on short-term historical data. However, this may vary between responsible managers and can change over the lifetime of a project. In contrast, real option valuation does without such an assumption on the decision-making process. It optimizes the value of flexibility independently of management preferences, which is an advantage in cases where available information on management preferences is limited.

11.6 Conclusions and Recommendations

For large uncertainties and for hydropower projects having a substantial flexibility, real options or more generally flexible design strategies can lead to a more valuable project. However, the value of expansion in this case study is low.

For hydropower plants, additional important aspects have to be considered and this clearly limits the attractiveness of a flexible concept.

As mentioned by Gaudard et al. (2016), the regulatory framework can limit the plant operator's flexibility and often makes it difficult to adopt a real-option approach.

In Switzerland as well as in most countries, a structural modification or an extension requires a revision of the existing concession agreement on the water rights or conclusion of a new agreement. This can be a long process which may take several years. It has to be considered that public preferences can change in the future and might finally lead to an opposition to a project's expansion. Consequently, it has to be considered that the expansion can be rejected or that the construction can be delayed. Depending on the remaining technical lifetime or concession period, a delay of the construction project can eventually have a significant impact on its profitability.

Chapter 12 General Conclusions and Outlook

12.1 Uncertainties of Small and Large Hydropower Projects in Switzerland

A main objective of this study is to assess uncertainties of hydropower projects in Switzerland. The outside view has been applied to analyze cost overruns and performance of energy production forecasts for large and small hydropower projects in Switzerland (see Chapter 5).

12.1.1 Construction Costs

The results show that the range of cost overrun incurred by small hydropower projects is on average quite similar to that of large projects. However, the chance that small projects will exceed the estimated costs is much smaller than for large projects. Costs for small hydropower plants were underestimated in about 1 out of 2 projects, whereas 67% of the large projects suffered a cost overrun.

Small projects tend to have more extreme cost overruns than large facilities. The density trace of small plants shows a much longer tail to adverse outcomes. This long tail indicates a potential for improvement, especially in terms of the methods applied for estimating the construction costs, including quality of design, and in terms of appropriate approaches to controlling actual construction costs.

Compared to previous research studies on cost overrun of large hydropower schemes, the results for Swiss projects show that the average cost overrun is significantly below the figures derived from global databases. The data sample of Swiss projects shows an average cost overrun of 15%, whereas previous studies presented figures in the range from 27% up to 96%. The chance that a large project will suffer a cost overrun is in a similar range as what previous studies indicated. The main reason for the difference most probably is that the present study analyses Swiss projects only and the project faced much lower commercial and political uncertainties compared with some of the other countries.

12.1.2 Energy Production

The analyses of mid-term energy production of small hydropower plants show in general a high tendency for energy production to be overestimated. In 7 out of 10 projects, the estimated energy production was below actual generation, leading to an average production overestimation of 14%.

The projects show a relatively poor performance in the first production year then followed by a decrease in production overestimation. This indicates frequent early-life failures of the small power plants.

To provide an indication of how accurate long-term forecasts for small hydropower plants are, an additional data sample was established. The production was slightly overestimated also in the long term. Production overestimation was 5% on average, and about 20% of the projects in the sample achieved less than 80% of the estimated long-term production. This tendency for production overestimation in small hydropower projects supports the findings from mid-term production data.

In contrast, the production of large hydropower projects in the long term was on average 8% higher than the estimated figures. About 80% of the projects reached or exceeded the production targets.

12.1.3 Policy Implications

The analysis of cost overruns of small hydropower plants reported in this study indicates potential for improvement, especially in terms of the methods applied for estimating the construction costs, including quality of design, and in terms of appropriate approaches to controlling actual construction costs.

From a technical perspective, no explanation can be given why very high cost overruns, which led to a long tail to adverse outcomes, were avoided for large projects but not for small facilities. Most probably, this is related to lower risk awareness or maybe to higher risk acceptance by the project teams responsible for small hydropower projects.

Another crucial finding of this study is that the Swiss large power plants in our sample have faced significantly less cost overrun than projects from previous international studies. In addition, the long-term energy production target was exceeded. The assumption that large hydropower schemes are generally highly risky structures must be questioned.

12.1.4 Implication for Design and Planning

The study allowed to establish statistical distributions of the uncertainties of construction cost estimations and energy production forecasts. These distributions can be applied in the evaluation process for hydropower projects if the conditions expected for such projects are similar to those of the projects in the data sample. The reference class forecast methods and the evaluation based on the metrics Expected Net Present Value (ENPV), Value at Gain (VAG) and Value at Risk (VAR) were applied. The latter is found to be more suitable for hydropower projects.

12.1.5 Discussion and Limitations

The present study is the first study to focus on cost overrun and performance of production estimation of small hydropower projects. In a nutshell, it can be stated that “small hydropower projects are not always beautiful”.

However, a limitation of the present study is that no detailed project information was available. Especially for projects with poor estimates, specific information (including cost breakdown of each study phase and technical reports) would have been beneficial. Also, it would have been useful to know the project team’s explanations and reasoning on the differences between estimates and actual figures to increase the reliability of the results.

The results for large Swiss projects provide useful indications on the historical cost overruns and performance of energy production forecasts. However, only a limited sample size could be established and, similar to the data group of small hydropower plants, no detailed project information was available. Considering the high variability of cost overruns and the difference to previous studies, it would be beneficial for future studies to include and consider detailed project information as has been recommended for future work on small hydropower plants.

Using the derived distributions for the evaluation of hydropower projects implies the assumption that future uncertainties will be similar to the uncertainties represented in the sample. This is especially crucial for energy production forecasts as it is questionable whether the climate of the historical period will still be relevant for the operation time of the new hydropower plant. This issue is getting more and more important in the light of the climate change and limits the possibilities of application.

12.2 Project-Specific Assessment

A performance-oriented register of uncertainties potentially affecting hydropower projects was elaborated (see Chapter 6). The elaborated register can be used as a basis for the preparation of project-specific assessments of uncertainties.

The uncertainties listed in the register are linked to the key economic performance parameter, such as NPV or IRR, and allow the uncertainty assessment to be directly incorporated into the performance evaluation.

The method is considered to be more suitable for larger projects as several experts and an adequate budget will be required to elaborate a project-specific assessment.

Beside the application aspects, the register gives a comprehensive overview of the wide range of potential uncertainties that can have an impact on the performance of a hydropower projects.

12.3 New Design Methods for the Management of Uncertainties

This part of the study focused on the formulation, application and evaluation of new design methods which allow for management of uncertainties.

12.3.1 The Proposed Framework

In a first step, a framework for hydropower projects was developed to allow a straightforward selection of the design objective and the required design method (see Chapter 7). It includes methods that have to be carried out during the planning phase as well as methods that are more suitable for power plants in operation. Importance is given to the question whether or not structural adjustments are required, as this can be a critical item for a project team’s decision whether or not to follow up on certain possibilities.

12.3.2 Application of the New Design Methods

Robust Decision Making, Info-Gap Decision Theory and Flexible Design were formulated and applied to a real hydropower project (see Chapter 9 and Chapter 11).

The selected case is representative of a typical design problem. The task is to select an adequate plant size determined by the design discharge. But energy price forecasts are highly uncertain and there is also some uncertainty about anticipated inflow. The inflow is expected to increase in the future as the catchment area is partly covered by glaciers. Therefore, the classical approach, which is to select the design discharge on the basis of the highest NPV without taking uncertainties into account, may not lead to an optimum selection of the design discharge.

To take uncertainty of climate change into account, a hydrological model was established and climate change projections were generated. Based on these climate change projections, the energy productions for a wide range of possible futures were simulated.

Uncertainty of electricity prices was reflected by three scenarios. The "High" energy price scenario corresponds to 120 CHF/MWh, the "Central" energy price scenario assumes 65 CHF/MWh, and the "Low" energy price scenario is based on a mean energy price of 30 CHF/MWh.

The classical approach of selecting the design alternative with the highest NPV while neglecting the uncertainties of climate change and energy price fluctuation leads to a plant size in the middle range (Qd4). This design choice is confirmed by the Info-Gap Decision Theory for a risk-averse project team. Qd4 leads to a positive NPV also under harsher futures. If more attention is given to opportuneness, larger design alternatives could be preferred.

Robust Decision Making tends to favor a larger design discharge. The minimize maximum regret and domain criteria lead to the choice of the design alternative Qd5. However, as shown by the mapping of the regret, this design selection is mainly driven by the regrets of more opportune futures.

In such case, the classical approach, Info-Gap Decision Theory and Robust Decision Making reached similar although not entirely matching results. The classical approach as well as the robustness curves of Info-Gap Decision Theory support Qd4. Robust Decision Making suggests the larger design alternative Qd5, but only if the decision gives the same weight to both more harsh futures and more opportune futures.

Application of the methods leads to the following main findings: Firstly, the classical approach can lead to a robust design choice although uncertainties are not incorporated into the decision-finding process. Secondly, Info-Gap Decision Theory and Robust Decision Making help assess the robustness of the different design alternatives of a hydropower project and lead to similar but not entirely matching results. The final selection depends primarily on risk attitudes of the decision makers rather than on the method applied.

Current research on climate change and hydropower design has mainly focused on Robust Decision Making, whereas Info-Gap Decision Theory has not been applied in hydropower design so far. The observation that the design choice derived by the classical approach may also lead to a robust design is essential for the next steps of developing design methods considering uncertainties. It highlights the priority of providing methods that can be efficiently applied to check the robustness of a design choice derived via the classical approach. Based on the findings of this study, Info-Gap Decision Theory is a very promising method for this purpose.

In addition, flexible design strategies were evaluated for the same hydropower plant. The option of expanding the power plant by installing an additional turbine was analyzed. In this particular hydropower case, flexibility has a low value.

12.3.3 Limitations of the Applications of the New Design Methods

A limitation of this work lies in the assumptions about the long-term mean electricity prices and the stochastic electricity price model. Simplified approaches were selected to determine the input required to apply the different design methods. This is found to be a major limitation also for the application in the engineering practice. Long-term stochastic electricity price models are not often available for hydropower projects, especially for smaller hydropower plants.

In addition, more comprehensive quantitative studies on the accuracy of historical long-term electricity price forecasts would be beneficial. A possible approach has been used in this study (see Chapter 4.3.2 and Chapter 4.3.5). The difference between the projected electricity price and the actual electricity price was analyzed and characterized by the mean percentage error and the mean absolute percentage error. However, only mid-term electricity price forecasts could be obtained. Surprisingly, no study on this issue for the Swiss or European electricity market could be identified.

As the new design methods were applied to just one real hydropower project, further experience with their application has to be gathered. For further development of the design methods, their application to virtual cases is not seen as a major improvement. It is recommended to formulate and apply the design method to real hydropower projects. As discussed in this work, hydropower projects cover several planning phases, often with an engagement of stakeholders and limiting physical, environmental and non-power operating constraints. Typically, the range of design alternatives in each planning phase is further reduced and, additionally, legal frameworks can limit the application of robust or flexible design concept. Such limiting constraints or preferences are difficult to reflect by a virtual model.

In addition, it is recommended that all main uncertainties should be considered, similar to the work carried out in this study. The exclusive focus on climate change may be convenient due to general availability of climate change projections, but may lead to questionable results as it cannot be excluded that other uncertainties will be more dominant for the selection of a design.

12.4 Recommendations for Engineering Practice

For small hydropower projects, more attention has to be paid to potential cost overrun, low performance of energy production forecasts, and relatively high chance of early life failures.

Major uncertainties should be integrated into the design process. This should be contemplated not only for performance evaluation, but also for the selection of technical design parameters.

In early study phases, the evaluation of the performance of project or design alternatives can be based on the Expected Net Present Value (ENPV), Value at Gain (VAG) and Value at Risk (VAR). The calculation of these economic key metrics can be based on the statistical distributions of the uncertainties of construction cost and energy production forecasts described in Chapter 5.7.2.

It has to be noted that the distributions are based on historical data of Swiss projects and that an application of these methods implies the assumption that future uncertainties will be similar to the uncertainties represented in the sample. This is crucial especially for energy production forecasts. Their application in projects outside Switzerland is questionable, as political or commercial uncertainties can be very different.

For international projects where no statistical distributions for the performance of construction costs and energy production are available, and for all projects in a later design stage (from Feasibility Study onwards), it is recommended to develop a project-specific assessment of the uncertainties as outlined in Chapter 6.

Long-term uncertainties, such as uncertainty of long-term inflow or energy price, can also be managed by adjusting the technical design of a hydropower project. The proposed framework includes guidance on the selection of one of the new design methods (see Chapter 7).

In general, it is recommended to combine the classical approach, i.e. deterministic approach of estimating the key economic parameters (e.g. NPV), with the new design methods for the hydropower sector while incorporating the uncertainties.

If the selected design objective is robustness, Info-Gap Decision Theory is regarded as a useful method. Robust Decision Making and Info-Gap Decision Theory can be applied in later design stages and larger projects. However, it should be noted that the methods include several overlapping working steps and so a combined approach can be applied (see Chapter 9.5) to reduce the number of working steps.

In case flexibility is selected as a project's design objective, particular attention and consideration should be given to whether or not it is appropriate to make a structural adjustment to the legal framework of a hydropower project.

12.5 Future Research

The following two research needs were identified with regard to an analysis of uncertainties in realized hydropower projects (see Chapter 5):

- Increase in data sample size: First data samples for the two reference classes of small and large hydropower projects were built within the scope of this work. This should be followed up with an increase in the size of the data samples and with an analysis of the empirical data. Previous studies have set up global data bases. Due to the large number (i.e. population) of small and large hydropower projects around the world and the high variability of the main outcomes, preference should be given to country specific assessments.

- Project-specific evaluations: The reliability of the outcomes should be improved based on a project-specific analysis. A systematic analysis should be carried out, including a review of project documents and interviews of project owner and engineers, especially for projects with poor estimates.

To ensure the application of a project-specific assessment as described in Chapter 6, it would be advantageous to place the focus of research on the following issues:

- Development of country-specific sets of guide values or benchmarks regarding likelihoods or frequencies of political and commercial uncertainties.

- Analysis of commercial, political and project uncertainties and their interactions. Therefore, a Bayesian belief network would be a promising model in order to visually represent the probabilistic relationships among the uncertainties and to analyze the wide range of uncertainties potentially affecting hydropower projects.

Finally, for further development of the design methods incorporating uncertainties, the following research issues should be investigated:

- The proposed framework as described in Chapter 7 should be applied to actual projects and further developed on the basis of expert interviews. Also, it would be beneficial to conduct expert interviews in order to analyze the acceptance of the proposed framework in the hydropower sector.

- Additional actual hydropower projects should be analyzed by including the design objectives of robustness, versatility, flexibility, or interoperability in the engineering design process.

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Appendix

A) Protocol Large Hydropower Projects – Cost Overrun

No	Hydropower Plant	Reference	Phase	Installed Capacity MW	Construction Costs million CHF current	Construction Costs million CHF constant (2015)	CC_{act} or CC_{est}	Ccact/CC_{est} current CHF	Ccact/CC_{est} constant CHF(2015)
1	Aarberg	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1960	Planning Phase	14	32	131			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1963	Planning Phase	14	32	119	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1968	Construction Phase	15	50	156			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1969	Operation Phase	15	55	168			
		"Kollaudation des Kraftwerkes Aarberg der BKW AG" Bull. SEV 59 (1968) 24.	Operation Phase	15	55	172	CC_{act}	1.72	1.44
2	Airolo-Piotta	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1964	Planning Phase	11	25	90			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1965	Planning Phase	12	25	87	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1966	Construction Phase	13	28	93			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1967	Construction Phase	13	28	90			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1968	Construction Phase	13	28	87			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1969	Operation Phase	12	28	85			
		www.aet.ch/azienda/stalvedro.htm (11/8/2002)	Operation Phase	13	30	94	CC_{act}	1.20	1.08
3	Aletschwerk (Massa)	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1947	Planning Phase	16	13	62	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1950	Operation Phase	16	12	57			
		Geschäftsbericht Aletsch AG 1965.	Operation Phase	16	9	39	CC_{act}	0.69	0.63
4	Bannwil - Neu	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1963	Planning Phase	17	35	131			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1964	Planning Phase	23	69	249			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1965	Planning Phase	23	71	248	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1966	Construction Phase	24	85	283			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1967	Construction Phase	24	85	272			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1968	Construction Phase	24	85	266			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1969	Construction Phase	24	85	259			
		"Das neue Kraftwerk Bannwil der BKW" Wasser- und Energiewirtschaft Nr. 7/8 1969	Operation Phase	24	85	258	CC_{act}	1.19	1.04

No	Hydropower Plant	Reference	Phase	Installed Capacity MW	Construction Costs million CHF current	Construction Costs million CHF constant (2015)	CC_{act} or CC_{est}	Ccact/CC_{est} current CHF	Ccact/CC_{est} constant CHF(2015)
5	Birsfelden	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1947	Planning Phase	64	80	379	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1950	Construction Phase	62	113	530			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1952	Construction Phase	62	113	494			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1953	Construction Phase	82	113	497			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1954	Construction Phase	53	113	494			
		"Das Kraftwerk Birsfelden", Wasser- und Energiewirtschaft Nr. 5/6/7 1954	Operation Phase	88	145	636	CC_{act}	1.81	1.68
6	Bürglen II	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1963	Planning Phase	17	24	89	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1964	Construction Phase	20	48	171			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1965	Construction Phase	20	48	166			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1966	Construction Phase	20	48	158			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1967	Operation Phase	20	48	152			
		"KW Bürglen", EW Altdorf, Broschüre 1967	Operation Phase	22	45	144	CC_{act}	1.88	1.61
7	Kirel/ Filderich	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1953	Planning Phase	15	15	66			
	Simmentaler Wasserkraft	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1954	Planning Phase	15	15	66	CC_{est}		
		"Einweihung des Kraftwerkes Kirel/Filderich", Bull. SEV Bd. 50 (1959) Nr. 22	Operation Phase	17	20	83	CC_{act}	1.33	1.26
8	Fätschbach	Ausbau der Wasserkräfte, 1947	Planning Phase	15	10	47	CC_{est}		
		"Das Fätschbachwerk", Schweiz. Bauzeitung Nr. 18 1951	Operation Phase	15	14	64	CC_{act}	1.42	1.35
9	Les Clées II	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1947	Planning Phase	18	18	85			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1950	Planning Phase	20	18	85			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1952	Planning Phase	20	18	79			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1953	Planning Phase	21	18	79	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1954	Construction Phase	21	18	79			
		"Nouvelle centrale des clées", Bull. Schweiz. Elektrotechn. Verein 46 / 1955.	Operation Phase	24	22	95	CC_{act}	1.22	1.20

No	Hydropower Plant	Reference	Phase	Installed Capacity MW	Construction Costs million CHF current	Construction Costs million CHF constant (2015)	CC_{act} or CC_{est}	$Ccact/CC_{est}$ current CHF	$Ccact/CC_{est}$ constant CHF(2015)
10	Mauvoisin	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1950	Planning Phase	265	370	1743			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1952	Planning Phase	265	370	1622	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1953	Construction Phase	265	400	1764			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1954	Construction Phase	310	425	1864			
		"Chute de Mauvoisin", le génie civil, 78e année, no.9, 1958	Operation Phase	310	450	1852	CC_{act}	1.22	1.14
11	Miéville-Salanfe	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1947	Planning Phase	60	70	331	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1950	Construction Phase	60	70	330			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1952	Construction Phase	80	70	307			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1953	Construction Phase	80	70	309			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1954	Operation Phase	80	70	307			
		www.salanfe.ch	Operation Phase	80	77	338	CC_{act}	1.10	1.02
12	Morobbia (rimodernamento)	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1967	Planning Phase	12	11	34			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1968	Planning Phase	15	14	45	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1969	Construction Phase	15	14	44			
		"Entrata in funzioni del rinnovato impiante della Morobbia", Rivista tecnica de la Svizzera Italiana 61 (1970) 9.	Operation Phase	13	14	42	CC_{act}	1.00	0.94
13	Rheinau	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1950	Planning Phase	34	60	283			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1952	Planning Phase	57	60	263	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1953	Construction Phase	34	60	265			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1954	Construction Phase	40	92	403			
		"Das KW Rheinau im Vollbetrieb", Bull. Schweiz. Elektrotechn. Ver. Bd. 48 (1957) Nr. 4	Operation Phase	34	92	386	CC_{act}	1.53	1.47

No	Hydropower Plant	Reference	Phase	Installed Capacity MW	Construction Costs million CHF current	Construction Costs million CHF constant (2015)	CC_{act} or CC_{est}	Ccact/CC_{est} current CHF	Ccact/CC_{est} constant CHF(2015)
14	Schaffhausen	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1950	Planning Phase	21	49	228			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1952	Planning Phase	21	49	213			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1953	Planning Phase	21	49	214			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1954	Planning Phase	25	53	230			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1960	Planning Phase	22	52	212	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1963	Construction Phase	28	70	260			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1964	Operation Phase	28	75	270			
		"Fakten und Zahlen", Broschüre Kraftwerk Schaffhausen AG, Stand 2001.	Operation Phase	26	90	288	CC_{act}	1.73	1.36
15	Wildegg-Brugg	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1947	Planning Phase	42	95	450	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1950	Construction Phase	46	95	448			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1952	Construction Phase	44	95	414			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1953	Construction Phase	46	95	417			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1954	Operation Phase	46	95	414			
		NOK Broschure "Kraftwerk Wildegg-Brugg"	Operation Phase	50	87	380	CC_{act}	0.91	0.85
16	Oberhasli (Oberaar)	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1947	Planning Phase	27	100	473	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1950	Construction Phase	32	95	448			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1952	Construction Phase	32	95	416			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1953	Construction Phase	32	95	419			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1954	Construction Phase	32	95	417			
		"KW Oberaar-Denkschrift über den Bau 1949-1953", KWO 1954	Operation Phase	43	95	417	CC_{act}	0.95	0.88

No	Hydropower Plant	Reference	Phase	Installed Capacity MW	Construction Costs million CHF current	Construction Costs million CHF constant (2015)	CC_{act} or CC_{est}	$Ccact/CC_{est}$ current CHF	$Ccact/CC_{est}$ constant CHF(2015)
17	Grande Dixence (Vollausbau)	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1954	Planning Phase	690	1000	4385	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1960	Construction Phase	684	1400	5717			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1963	Construction Phase	684	1600	5947			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1964	Construction Phase	684	1600	5768			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1965	Construction Phase	690	1600	5578			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1966	Construction Phase	690	1600	5325			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1967	Operation Phase	690	1625	5197			
		"Die Wasserkraftnutzung im Wallis unter besondererer Berücksichtigung der finanzwirtschaftlichen Auswirkungen auf Kanton und Gemeinden", Felix Walker, Diss. Uni. FR. Schweizerischer Wasserwirtschaftsverband 1967.	Operation Phase	735	1600	5118	CC_{act}	1.60	1.17
18	Kraftwerke Hinterrhein	Data base M. Balmer	Planning Phase		590	2521	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1960	Construction Phase	645	600	2450			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1963	Operation Phase	645	600	2230			
		www.khr.ch	Operation Phase	640	624	2075	CC_{act}	1.06	0.82
19	Saas-Almagell (Zermeiggern) & Stalden	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1960	Planning Phase	233	380	1552	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1963	Construction Phase	234	400	1487			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1964	Construction Phase	234	400	1442			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1965	Construction Phase	234	420	1464			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1966	Construction Phase	234	450	1498			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1967	Construction Phase	236	480	1535			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1968	Construction Phase	236	480	1499			
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1969	Construction Phase	236	480	1463			
		Broschure "Kraftwerke Mattmark AG"	Operation Phase	236	490	1493	CC_{act}	1.29	0.96
20	Gondo	Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1950	Planning Phase	30	25	118	CC_{est}		
		Eidg. Amt für Wasserwirtschaft, Ausbau der Wasserkräfte, 1952	Construction Phase	44	25	110			
		"L'équipement électro-mécanique de la centrale de Gondo", Bull. SEV 44 (1953) Nr. 22	Operation Phase	32	32	141	CC_{act}	1.28	1.20

B) Protocol Large Hydropower Projects – Energy Production

Large Hydropower Plants

No.	Name Powerplant	Year of Last Commissioning	Installed Capacity [MW]	Estimated Production (P_{est}) Reference Author	Title, Date	P_{est} [GWh]	Actual Production (P_{act}) Reference Author	Title, Date	P_{act} [GWh]	P_{act}/P_{ect}	Prod. Overestimation
1	Sedrun 1	1968	147	SWV	Wasser und Energiewirtschaft, 1965	253	BFE	Statistik der Wasserkraftanl. der Schweiz, 2010	261	1.03	-3%
2	Tavanasa (KVR)	1962	176	SWV	Wasser und Energiewirtschaft, 1965	505	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	563	1.12	-12%
3	Sarelli	1978	88	SWV	Wasser und Energiewirtschaft, 1970	157	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	180	1.15	-15%
4	Schaffhausen	1964	25	SWV	Wasser und Energiewirtschaft, 1965	162	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	174	1.07	-7%
5	Rheinkraftwerk Säckingen	1966	72	SWV	Wasser und Energiewirtschaft, 1965	404	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	480	1.19	-19%
6	Montbovon	1972	29	SWV	Wasser und Energiewirtschaft, 1969	78	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	79	1.01	-1%
7	Aarberg	1968	14	SWV	Wasser und Energiewirtschaft, 1965	69	BFE	Statistik der Wasserkraftanl. der Schweiz, 1991	85	1.22	-22%
8	Flumenthal	1970	22	SWV	Wasser und Energiewirtschaft, 1966	144	BFE	Statistik der Wasserkraftanl. der Schweiz, 2009	139	0.97	3%
9	Bannwil	1970	24	SWV	Wasser und Energiewirtschaft, 1966	148	BFE	Statistik der Wasserkraftanl. der Schweiz, 1996	152	1.03	-3%
10	Arniberg	1969	13	SWV	Wasser und Energiewirtschaft, 1969	43	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	47	1.10	-10%
11	Bürglen (Unterschächen)	1967	25	SWV	Wasser und Energiewirtschaft, 1965	96	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	99	1.03	-3%
12	Bisisthal	1962	15	SWV	Wasser und Energiewirtschaft, 1965	47	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	55	1.16	-16%
13	Wernisberg	1966	20	SWV	Wasser und Energiewirtschaft, 1965	65	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	76	1.16	-16%
14	Bremgarten-Zufikon	1975	20	SWV	Wasser und Energiewirtschaft, 1972	99	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	106	1.07	-7%
15	Tierfehd (Limmern)	1964	255	SWV	Wasser und Energiewirtschaft, 1965	287	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	284	0.99	1%
16	Linthal	1964	34	SWV	Wasser und Energiewirtschaft, 1965	60	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	81	1.35	-35%
17	Fieschertal	1975	60	SWV	Wasser und Energiewirtschaft, 1972	110	BFE	Statistik der Wasserkraftanl. der Schweiz, 1996	110	1.00	0%
18	Lötschen	1976	110	SWV	Wasser und Energiewirtschaft, 1973	312	BFE	Statistik der Wasserkraftanl. der Schweiz, 2007	327	1.05	-5%
19	Chippis-Rhône	1971	46	SWV	Wasser und Energiewirtschaft, 1970	259	BFE	Statistik der Wasserkraftanl. der Schweiz, 1996	253	0.98	2%
20	Stalvedro (AET)	1968	13	SWV	Wasser und Energiewirtschaft, 1966	64	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	55	0.87	13%
21	Grono	1965	36	SWV	Wasser und Energiewirtschaft, 1965	98	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	94	0.96	4%
22	Morobbia	1970	15	SWV	Wasser und Energiewirtschaft, 1968	41	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	42	1.03	-3%
23	Bavona	1966	124	SWV	Wasser und Energiewirtschaft, 1965	275	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	324	1.18	-18%
24	Pradella	1970	288	SWV	Wasser und Energiewirtschaft, 1965	923	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	1020	1.11	-11%

C) Protocol Small Hydropower Projects – Energy Production

Small Hydropower Plants

No.	Name Powerplant	Year of Last Commissioning	Installed Capacity [MW]	Estimated Production (P_{est}) Reference Author	Title, Date	P_{est} [GWh]	Actual Production (P_{act}) Reference Author	Title, Date	P_{act} [GWh]	P_{act}/P_{ect}	Prod. Overestimation
1	Ladral	1973	5.6	SWV	Wasser und Energiewirtschaft, 1972	14	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	16	1.11	-11%
2	Thusis	1968	4.6	SWV	Wasser und Energiewirtschaft, 1968	21	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	18	0.88	12%
3	Wunderklingen	1968	0.4	SWV	Wasser und Energiewirtschaft, 1968	3	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	2	0.96	4%
4	Lessoc	1973	8.0	SWV	Wasser und Energiewirtschaft, 1969	22	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	22	1.00	0%
5	La Jougnenaz	1970	2.1	SWV	Wasser und Energiewirtschaft, 1969	6	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	6	1.00	0%
6	Arni, Engelberg	1966	2.4	SWV	Wasser und Energiewirtschaft, 1965	10	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	6	0.61	39%
7	Ruosalp	1962	4.5	SWV	Wasser und Energiewirtschaft, 1965	19	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	19	1.03	-3%
8	Glattalp	1970	9.0	SWV	Wasser und Energiewirtschaft, 1970	21	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	16	0.80	20%
9	Trübsee	1967	8.4	SWV	Wasser und Energiewirtschaft, 1966	19	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	19	1.02	-2%
10	Waldhalde	1967	2.7	SWV	Wasser und Energiewirtschaft, 1966	16	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	16	1.02	-2%
11	Aegina	1967	9.2	SWV	Wasser und Energiewirtschaft, 1965	20	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	22	1.08	-8%
12	Balavaud	1971	0.5	SWV	Wasser und Energiewirtschaft, 1971	3	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	2	0.85	15%
13	Giumaglio	1967	8.7	SWV	Wasser und Energiewirtschaft, 1966	32	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	25	0.79	21%
14	Silvaplana	1973	1.4	SWV	Wasser und Energiewirtschaft, 1973	5	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	5	0.98	2%
15	Arosa-Litzirüti	1969	5.0	SWV	Wasser und Energiewirtschaft, 1968	20	BFE	Statistik der Wasserkraftanl. der Schweiz, 2016	23	1.13	-13%

Notation

Latin symbols

P	power output of all units	[W]
g	acceleration of gravity	[m/s^2]
Q_d	design discharge of power plant	[m^3/s]
Q_{max}	maximum generation discharge	[m^3/s]
H_n	net head	[m]
PF_A	annual plant factor	[-]
P_A	average annual energy	[kWh]
P_t	theoretical maximum annual energy production	[GWh]
P_{act}	actual average annual energy	[GWh]
P_{est}	estimated average annual energy	[GWh]
IC	installed capacity	[kW] or [MW]
NPV	Net Present Value	[CHF]
C_t	net cash flow at time t	[CHF]
i	discount rate	
T	total number of time periods	
$LCOE$	Levelized Cost of Electricity	[CHF/MWh]
PV_{costs}	present value of the total costs	[CHF]
$CAPEX$	capital expenditure	[CHF]
$OPEX$	operational expenditure	[CHF]
PV_{PA}	Present Value of the total energy production	[CHF]
$NPVc$	critical NPV	[CHF]
$ENPV$	Expected Net Present Value	[CHF]
$WACC$	Weighted Average Cost of Capital	
VaR	Value at Risk	[CHF]
VaG	Value at Gain	[CHF]
MPE	Mean Percentage Error	[-]
$MAPE$	Mean Absolute Percentage Error	[-]
n	sample size	
$S.D.$	standard deviation	
IQR	interquartile range, Q3-Q1	
$Q1$	first quartile	
$Q3$	third quartile	
r_{Qmax}	ratio of the simulated and observed design volumes	[-]
V_{Qmax}^{sim}	simulated volume for a specific maximum generation discharge	[m^3/year]
V_{Qmax}^{obs}	observed volume for a specific maximum generation discharge	[m^3/year]
h	horizon of uncertainty	
$\hat{h}$	robustness of design alternative	
d	design alternative	
dS	change of the electricity price	
dz	Wiener process	
S_0	starting electricity price	[CHF]

Z_n	independent random draws from standard normal distribution	

Greek symbols

ρ	density of water	[kg/m^3]
η	overall efficiency of all units (including efficiency of turbines, generator, transformer)	[-]
$\tilde{u}$	best estimate	
σ_l	lower boundaries	
σ_r	upper boundaries	
ω_l	scaling factor, left-hand side	
ω_r	scaling factor, right-hand side	
$\hat{\beta}$	opportuneness of design alternative (d)	
μ	annual risk-adjusted growth rate	
σ	annual volatility of the electricity price	

Acronyms

EPFL	Ecole Polytechnique Fédérale de Lausanne
BFE	Bundesamt für Energie
WCD	Word Commission on Dams
SIA	Swiss Society of Engineers and Architects
CPI	Swiss Consumer Price Index
WB	World Bank
IDA	International Development Association
SHP	Small Hydropower Projects
LHP	Large Hydropower Projects
DCF	Discounted Cash Flow
IGDT	Info-Gap Decision Theory
RDM	Robust Decision Making
Qdx	Design alternative, indices x design discharge
ExtQd4	Extension project with base project Qd4
ExtQd5	Extension project with base project Qd5

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