Exploring Flexibility in Hydroelectric Projects: a case study of Ethiopia

Application Portfolio Final Report

ESD.71: Risk and Decision Analysis / Engineering Systems Analysis for Design

Submitted

By

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To

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This project would not have been possible without the help of several key individuals. I would first like to extend my gratitude to Professor Ken Strzepek who gave me the idea to pursue this particular project and has been an immeasurable help along the way. I would also like to thank Michel-Alexandre Cardin for his continual support in this project, his help to keeping me clear of pitfalls and ensuring that I stayed on track. Tremendous thanks are also in order to Dr. Paul Block of the Columbia International Research Institute for Climate and Society. Dr. Block's willingness to share his time, expertise and data has been a great help. And finally, I would like to thank Professor de Neufville for his support in this endeavor and for his salient introduction to thinking about flexibility in the design of engineering systems.

Executive Summary

There are plans to construct four hydroelectric dams, Karadobi, Border, Mabil and Mendaia, along the upper Blue Nile River in Ethiopia. The primary use for these dams is to supply much needed electricity to the Ethiopian population, but two of the proposed dams will also be used for irrigation. A recent model developed by Block and Strzepek (2010), IMPEND, has been developed to calculate the net benefits for this particular project based on stream flow conditions, climate variability, climate change, and construction options (either build all four dams at once or stagger construction by 7 years). The model assumes a constant price of electricity.

This analysis adapts the work of Block and Strzepek to consider uncertainty in the price of electricity as well as the multiple construction sequences. Despite the sophistication of IMPEND, it is computationally expensive. This analysis, therefore, develops a simplified model of net benefits based on dam specifications, stream flow and a variable price of electricity. Both costs and benefits are discounted using a 10 % discount rate.

The price of electricity, rather than being fixed, is assumed to grow exponentially over time dependent upon five fixed growth rates.

There are three components to this analysis. First, the analysis considers a fixed construction sequence under a deterministic electricity price path. The second component of the analysis analyzed the fixed construction sequence under uncertain price of electricity. Uncertainty is described using geometric Brownian motion model with a volatility of 5 %. A Monte Carlo simulation of 1000 samples is run. The results of this analysis therefore consider 1000 different possible projections of the electricity price for each electricity growth rate. In the final component of the model, the value of flexibility is explored by investigating the net benefits of alternative construction sequences.

The results of the analysis suggest that greater net benefits are possible by pursing construction sequences that do not conform to the initial fixed design.

There are two salient lessons derived from this project. The first is that the assessment criteria with which one chooses to analyze a project will have a potentially significant impact on the overall conclusions. The second lesson is relates to the importance of developing a decision rule that actually makes sense given the uncertainties of the project. The paper concludes with a discussion regarding where the flexible approach to design is of most value.

CONTENTS

1 System Description

Part of Ethiopia's development strategy is the construction of four hydroelectric dams along the upper Blue Nile River in the northwest portion of the country (Block and Strzepek, 2010). By name, the proposed dams are, from west to east (refer to Figure 1) Border, Mendaia, Mabil and Karadobi. Figure 1 illustrates the location of the proposed dams.

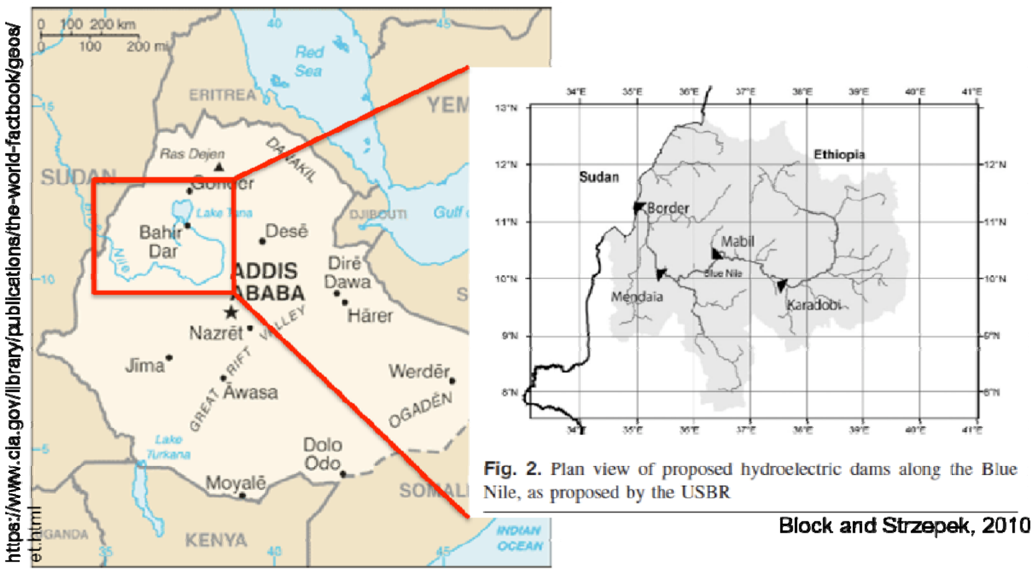

Figure 1: Illustration of the location of the four proposed dams

As noted by Block and Strzepek (2010) Ethiopia has a virtually untapped hydropower potential, and the electricity generated by any future hydropower would greatly benefit Ethiopian citizens. Other system benefits noted by Block and Strzepek are a constant supply of irrigation water, flood control downstream, and, by storing water in the Ethiopian plateau rather than the arid climate of the High Aswan dam, decreased evaporative losses from the reservoirs created by the dams (Block and Strzepek, 2010).

Block and Strzepek (2010) have developed a model, IMPEND, to investigate the net benefits of this development strategy from the year 2000 to 2100. IMPEND runs an optimization method to maximize net benefits of the project over this time frame. The model considers stream flow variability, several climate change scenarios, downstream flow effects, construction staggering options and the time the dam takes to fill after completion of the dam, referred to as the transient filling stage by the authors (the authors note that the standard approach is to ignore the transient filling stage; this, however, over states the benefits of the system). Though highly sophisticated, IMPEND is also computationally expensive. The analysis presented below is much indebted to IMPEND, its authors and the underlying data, but does not expressly employ IMPEND in the analysis.

The purpose of the following analysis is, by developing a simplified model of net benefits, investigate the impact of a non-constant and uncertain price of electricity as well as alternative construction sequence scenarios, on top of those investigated by Block and Strzepek (2010).

2 Principal Design Levers

There is one primary design lever over which system designer has control. This design lever is the sequence of dam construction. Options relevant to dam construction are whether to build a dam, when to build the dam, and in what sequence to build the dams. Block and Strzepek in their analysis compare two cases; case 1 considers impacts of the four dams built all at once. Case 2 considers the dam construction to be staggered in seven-year increments in the following order; Karadobi, Border, Mabil and Mendaia[1]. One key difference between the two analyses is that in case 1, the authors ignore the transient filling stage, whereas in case 2, the transient filling stage is not ignored.

Another potential design lever is flow policy. Flow policy refers to the allotment of Nile River flow granted to Ethiopia. Block and Strzepek (2010) investigate two flow policies in their analysis. The first flow policy would allow Ethiopia to retain some share of the

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[1] This is not a totally arbitrary order of construction. Block et al. (2007) cite that prior work suggested this order would capitalize on hydroelectric potential.

annual flow while the second policy would allow Ethiopia to retain any flow in excess of some historical percentile. I have considered this a potential design lever since the system designer will not necessarily have complete control over the flow policy. In fact, it is highly unlikely that the system designer will have complete control over the flow policy as such policy will be subject to international politics.

The analysis in this report employs a much-simplified NPV model of each dam. The simplified model does not consider any downstream flow effects and therefore is not able to consider flow policies. When analyzing results of this model, one should keep in mind that applying flow policies would add an additional constraint on the model and likely reduce the calculated net benefits.

3 Sources of Uncertainty

3.1 Price of Hydropower

The main source of uncertainty considered in this analysis is the price of electricity. Block and Strzepek (2010) assume that electricity would sell at $0.08 / kWHr, and that this value stays fixed throughout the life of the project (100 years). Electricity prices, however, have not been constant over time, at least in the US. The EIA report of historical prices of electricity by end use sector suggests that electricity prices have been increasing over time in the United States.

The EIA's Annual Energy Outlook (AEO), following the trend displayed in Figure 2, forecasts future increases in electricity price in real terms for the next 25 years for the United States under five possible scenarios; a reference case, low price of oil case, high price of oil case, low economic growth rate case and high economic growth rate case (AEO 2010). The projections are illustrated in Figure 3 below. The electricity price growth rate is calculated by computing the percent difference between the 2008 price and the 2035 projected price. The electricity price growth rates are presented below in Table 1.

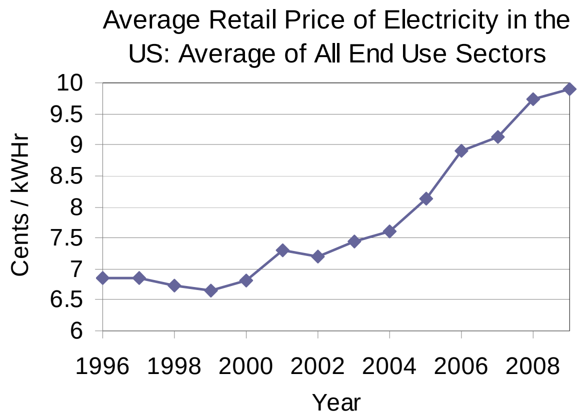

Figure 2: Historical electricity prices reported by the EIA for the United States[2]

Table 1: Electricity Growth Rate Scenarios (AEO 2010)

Scenario	Growth Rate: 2008 to 2035 [%]
Reference	0.13
Low Oil	0.0
High Oil	0.25
Low Growth	-0.2
High Growth	0.37

The electricity price projections are for the United States, and there are sure to be differences between Ethiopia and the US. Block and Strzepek, however, use as their electricity price \$ 0.08 / kWHr which is comparable to the 2010 prices presented by the EIA for the United States. Since Block and Strzepek (2010) use a price for electricity that is comparable to the US electricity price, it seems not inappropriate to assume that electricity price growth rates for the United States would reflect electricity price growth rates for Ethiopia.

[2] Source: EIA

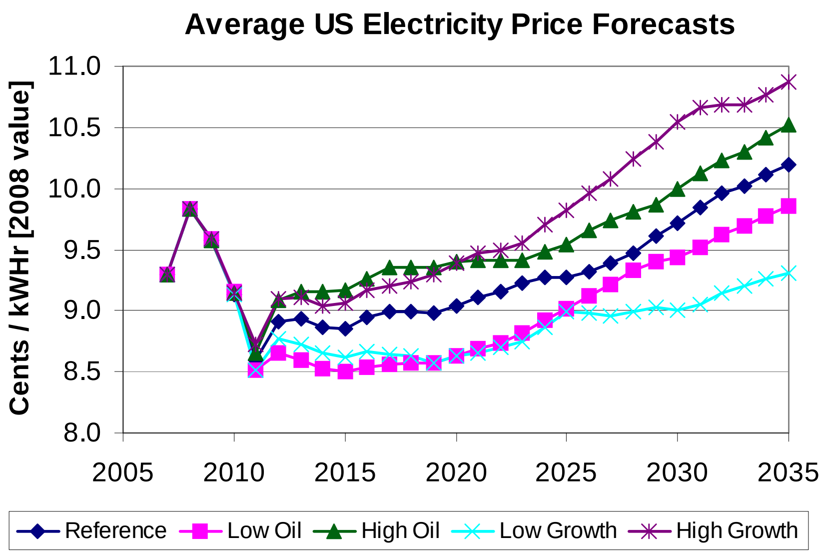

Figure 3: Electricity price forecasts for the United States reported by the EIA AEO

3.2 Variability in Stream Flow

Stream flow is another source of uncertainty in this system, due to natural climatic variability as well as potential impacts due to climate change (Block and Strzepek 2010). Stream flow tends to be distributed log-normally (K. Strzepek 2010, pers. comm., November). Ideally, historical flow rates at each dam site – Karadobi, Border, Mabil and Mendaia – would be used to develop parameters for describing a site specific lognormal distribution at each dam site. The distribution could then be used to project stream flow at each site for the next 100 years.

Site specific flow data, however, does not exist at the four dam sites (P. Block 2010, pers. comm., December 8). In the place of flow data, this analysis uses site specific monthly flow estimates for 30 years from the model CliRun II (Strzepek et al., 2008). These flow estimates have been provided me by Dr. Paul Block and are presented in yearly estimates in the Appendix.

A standard normal distribution can be modeled in Excel using the log inverse ("LOGINV") and random number generator ("RAND") functions as well as the mean and standard deviation of the distribution using the syntax shown in the final row of Table 2.

The mean and standard deviation for the distribution of stream flow at each dam site was calculated using the site specific flow estimates from CliRun. The parameters are displayed below in Table 2.

Table 2: Parameters for describing log normal distribution of stream flow

Units: $m^3 \times 10^6$	**Karadobi**	**Border**	**Mabil**	**Mendaia**
Mean	2.664484	2.135984	1.756704	2.781596
STDEV	0.209376	0.149156	0.212537	0.117529
Syntax in MS Excel	=LOGINV(RAND(),Mean,STDEV)			

Site specific stream flow projections were made using the parameters in Table 2 and a data table to recalculate stream flow over 100 years. Figure 4 illustrates the resulting site specific stream flow projections. This analysis, for the sake of simplicity, only considers the one stream flow projection shown in Figure 4.

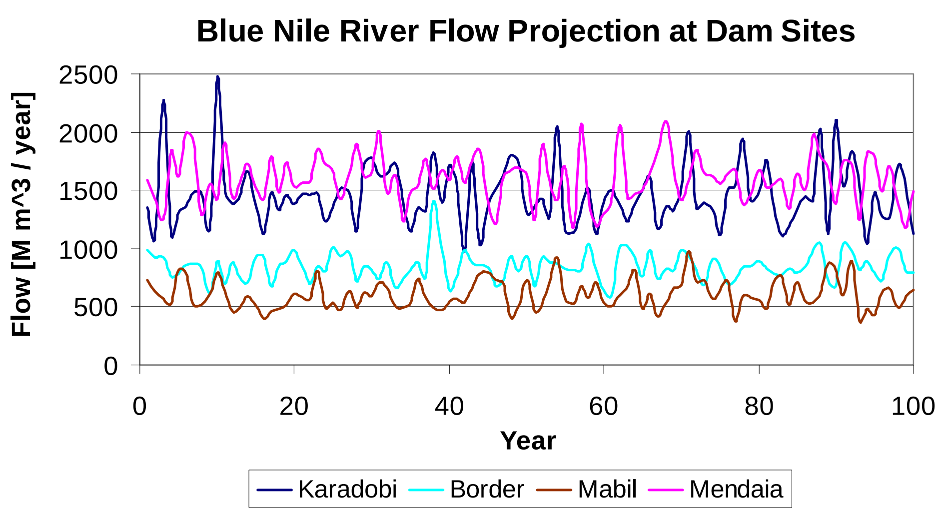

Figure 4: 100 year projection of stream flow at the four possible dam locations

3.3 Other Sources of Uncertainty

In calculating benefits, IMPEND also considers the added benefit from increased agricultural output due to the irrigation potential of the project. Like the price of electricity, a constant agricultural commodity price is used for the life of the project. This price is subject to variability. This analysis, however, does not consider the impact of agriculture, mainly for the purpose of simplicity.

4 Structure of the Analysis

There are three components of this analysis. The first component of the analysis investigates a fixed system design operating under a deterministic electricity price growth rate. Following the analysis of Block and Strzepek (2010), the fixed design dictates the construction start date of Karadobi, Border, Mendaia and Mabil in years 0 (beginning of the project), 7, 14 and 21 respectively; i.e. all dams are built in seven-year increments. The fixed design is not the product of an optimization scheme and simply reflects one possible construction sequence (P. Block 2010, pers. comm., December 6) though prior work has suggested that specific benefits are attributable to this unique construction scheme (Block et al. 2007). This analysis described in this report is an attempt to build upon the work of Block and Strzepek (2010) and for this reason takes the construction sequence described above as the reference construction path to which alternative construction sequences are compared. For the purposes of this report, this construction sequence is called the fixed design.

The second stage of the analysis investigates the fixed design under uncertainty in the price of electricity. Uncertainty is modeled using a geometric Brownian motion with 5 % variability about the growth rate trend. For each of the five electricity price growth rates, a Monte Carlo simulation of 1000 samples is run so that many 100 year projections in the price of electricity are considered rather than only one.

The third and final stage of analysis investigates the value of including flexibility by relaxing the constraint on the construction sequence. Three alternative construction sequences are explored and compared to the reference fixed design.

5 NPV Model: Estimating Costs and Benefits

The IMPEND model developed by Block and Strzepek (2010) estimates the NPV of the proposed dam project in Ethiopia. Though highly sophisticated, it is also computationally expensive. In order to more easily perform the analysis described above, a simplified model of the costs and benefits of the proposed dam project is developed and described below. Following the analysis of Block and Strzepek, a discount rate of 10 % is used to translate all future costs and benefits in to present value terms. I am indebted to Dr. Paul Block for providing me with his IMPEND model, cost data, dam specifications, and other data relevant to developing my simplified model of net benefits.

5.1 Estimating Cost

The upfront capital costs and operational costs of construction for Karadobi, Border, Mabil and Mendaia are shown below in Table 3. The upfront costs are spread out over the seven year construction period and allocated each year by a percentage of the total upfront costs. The allocation percentage is the same for each dam. These percentages are presented in Table 4.

Table 3: Parameters for projecting the price of hydro power

Dam	Fixed Cost [Mil USD]	O&M Cost [Mil USD]
Karadobi	2,213	15.9
Border	1,985	17.2
Mabil	1,792	13.5
Mendaia	2,114	17.9

Table 4: Distribution of fixed costs

Construction year	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Portion of fixed cost [%]	10	15	20	20	20	10	5

Fixed costs presented in Table 3 are therefore distributed across seven years according to Table 4. After the construction is complete, the cost associated with each dam is the operational costs presented Table 3. These costs remain fixed throughout the 100-year life of the project.

5.2 Estimating Benefits

One of the key insights of Block and Strzepek (2010) is the necessity of considering what the authors call the transient filling stage. The transient filling stage refers to that period of time after construction has finished but before the reservoir is sufficiently full to allow for electricity generation. Block and Strzepek (2010) note that many analyses significantly overestimate benefits by ignoring the transient filling stage. In order to avoid overestimating benefits, the analysis described in this report does consider the transient filling stage (albeit in a simplified manner) by not allowing electricity generation until the in flow has filled the reservoir to 10 % of its capacity. Reservoir capacity is presented in Table 5.

Once the reservoir has filled to 10 % of capacity, benefits begin to accrue. Benefits are a function of capacity, generation efficiency, and price of energy:

$$B = C_{\mathrm{dam}} * P_{\mathrm{hydro}} * \eta \qquad \text{Eq. 1}$$

where C_{dam} represents the capacity in MW of the particular dam in question (refer to Table 5), P_{hydro} represents the projected price of hydropower in USD / kWHr and η represents the efficiency of the electricity generation. In this analysis, efficiency of 65 % is used (K. Strzepek, 2010, pers. comm., November 23).

Table 5: Reservoir capacity in billion cubic meters and power capacity in MW[3]

Dam	Reservoir Capacity [10^9 x m^3]	Power Capacity [MW]
Karadobi	32.5	1,350
Border	11.1	1,400
Mabil	13.6	1,200
Mendaia	15.9	1,620

The model estimates benefits by assuming that once the reservoir is filled to 10 % capacity, each hydropower plant begins to generate electricity at its maximum capacity (refer to Table 5). Realistically, maximum energy will not be achieved until the reservoir is completely full, and for this reason, the above assumption will actually overstate benefits to some degree. That being said, overall net benefits estimated by this model

[3] Source: Block et al. (2007) and pers. comm. with P. Block

seem to comport with the net benefits presented by Block and Strzepek (2010) and thus whatever impact this simplification has, it does not appear to be very significant.

Comment [MAC1]: Good

Net benefits are calculated by subtracting total discounted costs from total discounted benefits. The discount rate, as stated previously, is 10 %.

6 Analysis

6.1 Fixed Design – No Uncertainty in Electricity Price

Using the model of net benefits described in section 5 above, the NPV of the fixed design is analyzed for each electricity growth rate listed in Table 1. The results of the analysis are presented below in Table 6. Costs are equal across all electricity price growth rate scenarios. The price of electricity impacts the estimation of benefits only, so we expect the costs to be consistent across electricity price growth rate scenarios. By way of comparison, Block and Strzepek (2010) report net benefits at 2,760 Mil USD for what this analysis calls the fixed design. Since Block and Strzepek (2010) consider a constant price of electricity, 2,760 should be compared to the "Low Oil" case in Table 6, 2,441. One possible reason for the underestimation of this analysis compared to the analysis of Block and Strzepek is that this analysis ignores agricultural benefits.

Table 6: Costs, benefits and NPV of the fixed design under no uncertainty

Growth Rate Scenario	Costs [Mil $]	Benefits [Mil $]	Net Benefits [Mil $]
Reference (0.13 %)	3,280	5,904	2,624
Low Oil (0 %)	3,280	5,721	2,441
High Oil (0.25 %)	3,280	6,080	2,799
Low Growth (-0.2 %)	3,280	5,452	2,172
High Growth (0.37 %)	3,280	6,262	2,981

6.2 Fixed Design Under Uncertain Price of Electricity

As indicated by Figure 2, there is a degree of variability in historical prices of electricity. Despite the variability, electricity prices still seem to follow an upward trend. Geometric Brownian motion (GBM) is one method of modeling variability about a trend and is the method chosen here to describe the uncertainty in the price of electricity. The

GBM model is developed in Excel using a volatility of 5 %. By way of illustrative example, Figure 5 shows one 100-year projection of the in price of electricity for the EIA AEO's low economic growth rate scenario.

There are, of course, an infinite number of possible electricity price projections. Instead of using just one electricity price projection incorporating uncertainty, many possible electricity projections are explored through a Monte Carlo simulation of 1000 samples. The results are compared using the ENPV, CAPEX and RoI (return on investment; defined here as the ENPV divided by CAPEX) assessment criteria. To check for stability, a simulation of 100 samples considering the low growth scenario (Table 1) is run and compared to the similar 1000 sample simulation. Similar results were achieved, indicating a stable solution. The results of this analysis are shown below in Table 7.

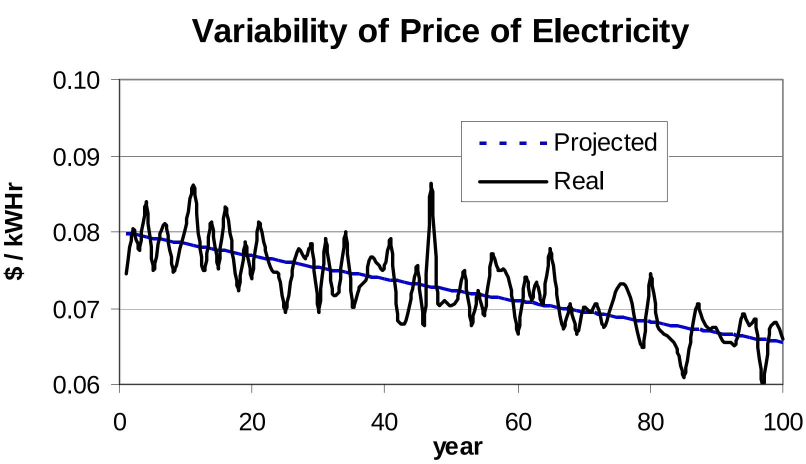

Figure 5: Example of variability of price of electricity in cents / kWHr (-0.2 % growth rate scenario)

The results in Table 7 suggest the introduction of uncertainty does not alter the system very much at all. This suggests that the price of electricity, as it is described in this analysis, does not have a great impact on overall system net benefits.

Table 7: ENPV, CAPEX and RoI of the fixed design under uncertainty

Growth Rate Scenario	ENPV [Mil $]	CAPEX [Mil $]	RoI
Reference (0.13 %)	2,624	3107	0.84
Low Oil (0 %)	2,440	3107	0.79
High Oil (0.25 %)	2,798	3107	0.9
Low Growth (-0.2 %)	2,173	3107	0.7
High Growth (0.37 %)	2,979	3107	0.96

6.3 Flexible Design Under Uncertain Price of Electricity

In this final component of the analysis, flexibility is introduced by relaxing the constraint on the sequence of construction. This is accomplished by considering three alternative construction sequences. The first sequence, All At Once (AAO), describes commencement of construction simultaneously in year 0 of the project; in other words, all dams are built at once. This is similar to the Case 1 scenario considered by Block and Strzepek (refer to section 2). The one key difference is that here, an attempt has been made to consider the transient filling stage whereas Case 1 does not consider the transient filling stage. Despite the fact that such a scheme of building all dams at once is not terribly realistic (Block and Strzepek 2010), the goal of including the AAO scenario in this analysis is to develop some insight in to the impact of building all dams at once while not ignoring the transient filling stage.

The second construction sequence, ‘KaBo’, describes constructing Karadobi and Border in year 0 and the remaining two dams in year 7. The third sequence, ‘MeBo’ describes constructing Mendaia and Border in year 0 and the remaining two dams in year 7. The ‘MeBo’ construction sequence is an initial attempt at exploring the possibility of constructing the dams in an order different from proposed in Block and Strzepek (2010).

The analysis performed for the fixed design described in section 6.2 above is repeated for each construction scenario described here. Results are presented below in Table 8[4]. Three criteria are used to compare the fixed design to the alternatives; ENPV,

[4] It is interesting to note that the analysis of Block and Strzepek (2010) report NPV of over 9,000 Mil USD for their Case 1 scenario (very similar to the AAO scenario described here). I am not convinced that this is

CAPEX and RoI. If the construction sequences are compared just on the basis of ENPV, where the goal is the maximization of ENPV, the results indicate that AAO is preferred to all other scenarios, while the fixed design yields the lowest net benefits. The VARG curve for the reference electricity growth rate scenario is shown below in Figure 6. The VARG curves for the remaining electricity growth rate scenarios (refer to Table 1) are very similar to the reference curve, are illustrated in Figure 7.

Table 8: ENPV, CAPEX, and RoI for the fixed design and alternative designs under uncertain electricity price scenarios

Reference (0.13 %)	**ENPV [Mil $]**	**CAPEX [Mil $]**	**RoI**
Fixed Design	2,624	3,107	0.84
AAO	6,366	6,312	1.01
KaBo	4,620	4,831	0.96
MeBo	5,283	4,793	1.10
Low Oil (0 %)	**ENPV**	**CAPEX**	**RoI**
Fixed Design	2,440	3,107	0.79
AAO	6,071	6,312	0.96
KaBo	4,362	4,831	0.90
MeBo	5,023	4,793	1.05
High Oil (0.25 %)	**ENPV**	**CAPEX**	**RoI**
Fixed Design	2,798	3,107	0.9
AAO	6,656	6,312	1.05
KaBo	4,874	4,831	1.01
MeBo	5,540	4,793	1.16
Low Growth (-0.2 %)	**ENPV**	**CAPEX**	**RoI**
Fixed Design	2,173	3,107	0.7
AAO	5,609	6,312	0.89
KaBo	3,975	4,831	0.82
MeBo	4,632	4,793	0.97
High Growth (0.37 %)	**ENPV**	**CAPEX**	**RoI**
Fixed Design	2,979	3,107	0.96
AAO	6,955	6,312	1.10
KaBo	5,121	4,831	1.06
MeBo	5,804	4,793	1.21

just due to the inclusion of the transient filling stage in my simplified model. Neglecting agriculture could also play in to the discrepancy as well. At the very least, it suggests an area for future investigation.

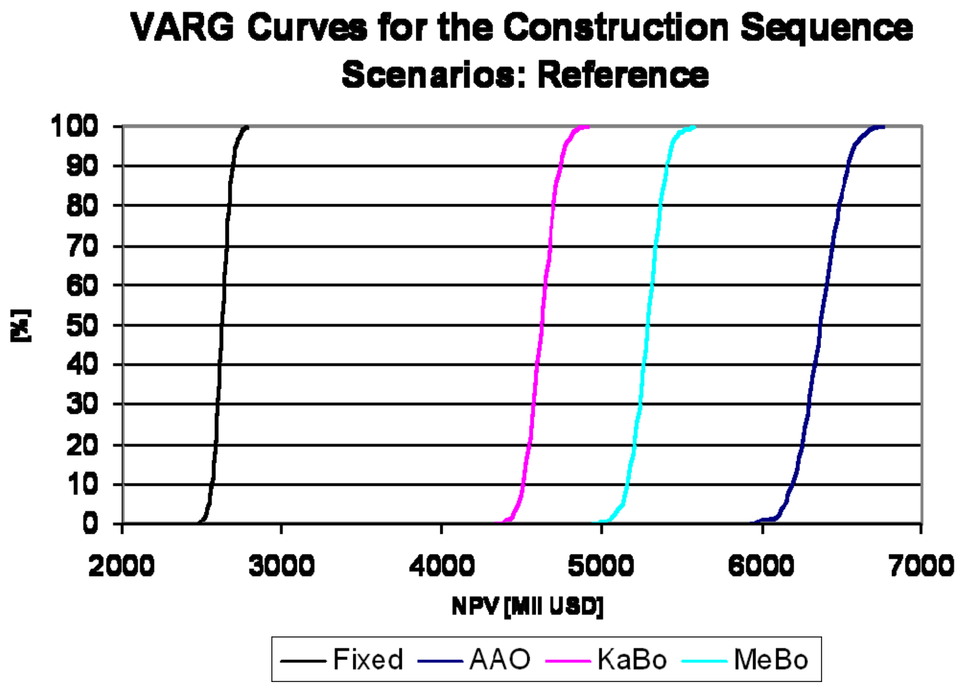

Figure 6: VARG curve for the reference electricity growth rate

The VARG curves illustrate that the standard deviation of the distribution of net benefits for each construction sequence considered is relatively small. This is perhaps not a great surprise when considering that the volatility in the electricity price was only 5 %. There is, however, some variation in the standard deviations between the construction sequence options. The smallest standard deviation (from a visual inspection) is demonstrated by the fixed construction sequence and the largest standard deviation is observed in the AAO construction sequence. This result is due to when benefits begin to accrue. For the AAO construction sequence, benefits for each dam come on line within the first 10 years, whereas it takes on the order of 30 years for all benefits to begin to accrue for all dams. Later benefits, due to discounting, will be less sensitive to variability in the price of electricity. Earlier benefits, by implication, are more sensitive to variation in price. Since more benefits exist earlier in the AAO construction sequence, it is expected that the spread of values for the AAO would be greatest.

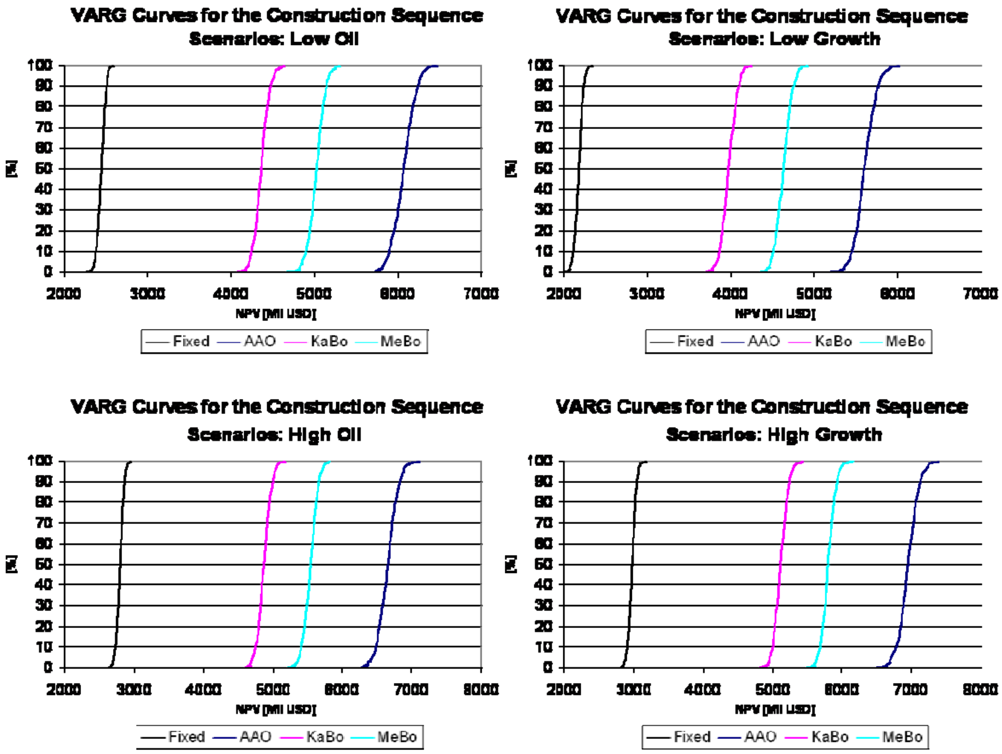

Figure 7: VARG curves for the low and high oil and low and high economic growth rate electricity price growth rate scenarios.

The conclusions regarding the preferred construction sequence change when one additionally considers the CAPEX and RoI assessment criteria. First consider CAPEX, where the goal is the minimization of the initial capital expenditure. The conclusions are opposite those conclusions obtained by employing the ENPV assessment criteria. The fixed design is clearly preferred to all other designs, while what was preferred under the ENPV criteria, AAO, is now the least preferred construction sequence.

That AAO produced the highest ENPV but the lowest CAPEX should come as no surprise. In the AAO scenario, all the dams are built beginning in year 0. Therefore, initial capital costs are paid in the first seven years of the project lifetime and are therefore subject to the least possible discounting. This will lead to high initial capital costs. By delaying construction, to be sure, one is delaying benefits, but one is also delaying large initial investment. From the perspective of today, the cost of building a dam tomorrow is less than the cost of building a dam today. So, if the primary metric of concern is cost, the option that builds the most dams the furthest in to the future will reveal itself to be preferred. In this analysis, the option that builds the most dams furthest in the future is the fixed design. For this reason, from the perspective of initial capital cost alone, the fixed design is the most preferred.

System designer and planners tend to care about more than just cost[5]. And whereas ENPV will indicate whether a project's overall benefits exceed overall costs, ENPV does not indicate how efficiently the money was spent, or to put it another way, ENPV does not indicate the "bang for the buck" the project achieved. To assess the efficiency with which the money was spent in the project, one could use the return on investment (RoI) defined as the ENPV divided by the CAPEX. The goal is to maximize RoI.

As in the case of the ENPV assessment metric, the fixed design has the lowest RoI. The construction alternative with the highest RoI, however, is not the AAO construction scenario but rather the 'MeBo' construction scenario. The RoI assessment criterion favors those projects that maximize net benefits at a minimum cost. It is, in some sense, a measure of the balance between maximizing ENPV on the one hand and minimizing initial capital costs on the other. One would not expect the AAO construction sequence to be the preferred sequence on the basis of RoI, since little attention is paid to minimizing costs. In addition to highlighting the importance of evaluating projects by multiple criteria, this RoI analysis suggests that there are other orders in which to build the dams, outside of the order presented in Block and Strzepek (2010), that may be preferred and that should be explored.

On account of the similarities between Figure 6 and Figure 7, the results suggest that net benefits are not terribly sensitive to the electricity price growth rate or variability. It should be noted, however, that the electricity growth rates analyzed in this analysis are not large, nor is the volatility especially great. To develop some idea of how robust the conclusions related to preference rank are to the assumptions of growth rate and

[5] If the *only* metric of concern in a project is cost, then the rather myopic "best" option is always to build nothing, unless of course the costs of inaction exceed the costs of the least expensive action.

volatility, consider Figure 8. These VARG curves were generated considering very low and very high growth rates (-2 % and 2 % respectively) and a volatility of 20 %. Not surprisingly, the ENPV's for each construction sequence are either lower or higher depending upon the growth rate, and some of the tail of the distribution of fixed design net benefits drops below zero. This being understood, the AAO scenario is still stochastically dominant, and relative to the other scenarios, the AAO's distribution of net benefits still has the largest standard deviation. And since the rankings of the construction sequence based on ENPV and CAPEX remain unchanged, ranking based on RoI will also remain unchanged.

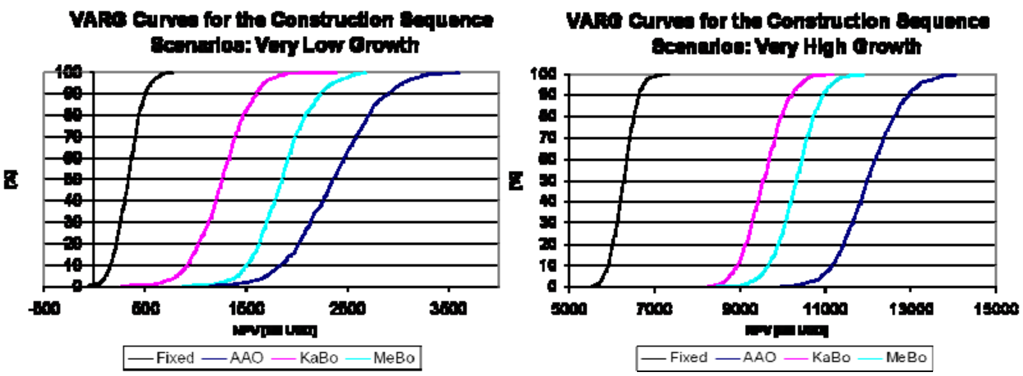

Figure 8: VARG curves of extreme values for electricity price growth rate (+/- 2 %) and volatility (20 %)

The salient point from this exercise is that the general conclusions with respect to rank and relative size of the standard deviation of the distribution of net benefits remain unchanged, and therefore the conclusions with respect to ranking of the construction sequences developed from the above analysis seem to be robust to the assumptions of electricity growth rate and volatility in the price of electricity.

7 Discussion: Insights and Lessons Learned

Using a simplified model for calculating the net benefits of the 4-dam proposal, the analysis above essentially provides a sort of screening model that begins to develop insight in to what parameters are important and what parameters are unimportant for further investigation. One insight is that the construction sequence originally outlined in Block and Strzepek (2010) is not necessarily the best sequence. Building each dam simultaneously produces the highest net benefits, but initial upfront costs are high. The simplified model also suggested that there are construction sequences that more efficiently spend money by not being fixed to the Karadobi-Border-Mabil-Mendaia construction order.

Working through the analysis above leaves me with two primary lessons learned. The first lesson (and perhaps this lesson is rather obvious; but such lessons always seem to carry more weight when experienced first hand) is that the value of a project will in large part depend upon what the analyst or ultimate decision maker values most. For example, under the high growth scenario in Table 8, the preferred construction sequence depends upon the assessment criteria. ENPV recommends AAO, CAPEX recommends the fixed design while RoI recommends the MeBo construction sequence. Each assessment criteria emphasizes a different component to the value of a project; ENPV emphasizes overall net benefits, CAPEX emphasizes up front costs while RoI places value on how efficiently money is used. Depending upon what the decision maker values most, a different construction sequence would be chosen. This discussion should also highlight the responsibility that analysts have to perform a multi-criteria assessment. Since each assessment criteria emphasizes a different component of a project, only performing one assessment based on one criterion is presenting an incomplete story.

The second lesson I have drawn from this project is the necessity to adopt an appropriate decision rule. During an initial stage of this analysis, I attempted to program in to my net benefits model a decision rule that would relax the constraint of beginning construction on the dams in seven year increments. I sought to develop a decision rule that would guard against the “bad” outcome of price for electricity dropping very low and staying low, potentially rendering the construction of an additional dam a poor financial decision. The initial decision rule was as follows: in the first year after the first dam’s completion, only build a new dam if the electricity price growth rate at year “t + 7” is greater than the growth rate then at year “t”. The rational behind the rule was to guard against building a new dam if the price of electricity had been declining over time. Under uncertainty in electricity price, this decision rule produced some curious results; ENPV of the fixed design was greater than ENPV of the flexible design for a zero and negative electricity price growth rate scenarios[6]. Further investigation in to the source of this unexpected result revealed that it is in fact preferable to begin to build dams as soon as possible. Allowing for the remaining three dams to begin construction simultaneously yielded higher NPV than the initial decision rule. This “discovery” if you will, led me to investigate in the final analysis the various scenarios (Fixed, AAO, KaBo and MeBo) presented here instead of attempting another similar decision rule.

Because electricity prices are modeled using geometric Brownian motion the electricity price will always follow an up or down trend. A decision rule that attempts to guard against the possibility of a sudden dive in electricity price doesn’t make sense under a GBM assumption, since the price will eventually bounce back up and any intermediate losses caused by a dip below the trend in electricity price will likely be made up in a corresponding spike above the trend in electricity prices. The decision rule that I initially tried to implement may have had more success with uncertainty in stream flow which might, on account of climate change, take a relatively large downward turn over the next 100 years and remain low. In this study, however, only one stream flow analysis was considered and in this particular stream flow projection, the flow never decreases and then remains low.

In closing, I consider the question of where flexibility seems to have the most value. The ENPV values in Table 8 demonstrate that as the electricity growth rate increases, the difference in ENPV between the fixed design and the three alternatives increases. This suggests that the greater the electricity growth rate, the more valuable the alternative construction scenarios become, from the perspective of ENPV[7]. If further research indicates that the price of electricity in Ethiopia may increase drastically, then an exploration in to many more construction scenarios seems appropriate. While

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[6] The electricity growth rates in this initial stage of analysis were different than those presented here, though the insight is still apropos to the situation.

[7] From the perspective of CAPEX, construction sequence scenarios that build dams early would be discouraged.

investigating this design space, however, it also seems that attention should be paid to stream flow variability. If climate change does cause a significant decrease in stream flow, one can imagine that system designers may want the flexibility to refrain from building one or more dams, or perhaps not building the dams to their original specifications. In the face of possible reduced stream flow, it may even be prudent to build the dams initially low with the capability of increasing their height if it turns out that stream flow is not as low as predicted. This is, however, an area for future work.

8 References

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APPENDIX

The table below presents the stream flow data from which the parameters in Table 2 were derived.

Table A1: Stream flow data (Mm^3 / year)

Year	Karadobi	Border	Mabil	Mendaia
1	1029.961	677.131	362.911	1413.543
2	1164.264	690.18	488.5	1388.103
3	1602.115	969.506	645.727	1741.712
4	2456.293	1089.807	902.528	1893.952
5	1788.451	851.784	665.078	1669.617
6	1249.025	1134.716	552.502	1869.188
7	853.817	615.605	336.693	1161.374
8	1076.722	833.476	437.034	1628.345
9	1234.069	845.377	517.253	1695.662
10	1567.872	727.21	568.59	1461.025
11	1541.525	774.602	595.601	1614.044
12	1505.997	903.613	658.507	1711.475
13	1470.162	835.999	596.805	1640.885
14	1729.607	868.959	706.467	1778.803
15	1412.08	811.036	593.953	1770.518
16	1525.504	794.042	566.785	1588.103
17	1767.988	987.79	662.829	1663.908
18	1616.591	934.55	782.87	1779.366
19	1555.879	1014.653	688.635	1929.492
20	1255.135	934.164	557.117	1779.445
21	1319.593	899.895	565.642	1628.713
22	1323.981	879.951	555.272	1685.927
23	1311.232	916.371	578.91	1677.472
24	1550.712	719.019	519.229	1394.181
25	1742.996	1004.972	694.132	1751.405
26	1242.396	629.608	459.817	1262.652
27	1340.089	792.476	538.988	1499.181
28	1575.3	889.528	712.638	1640.507
29	1990.849	843.093	752.161	1593.769
30	1206.033	797.56	487.33	1434.529

The data presented above was calculated from a monthly time flow series given me by Dr. Paul Block. The monthly flow data was loaded in to GAMS, summed over every twelve months with result being the table above.